Energy flows and potential energy development strategies in RoRo ports

A study based on the Port of Trelleborg

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Abstract

The recent push for decarbonization in the maritime sector presents an opportunity for ports to strengthen their position as energy hubs. This work studies the existing energy flows in the Port of Trelleborg, one of Europe's biggest roll-on, roll-off ports, and proposes some energy-related development strategies. The current energy flows directly concerning the port are for the most part electricity and fuel used in the port's rolling equipment, with a smaller energy flow in the wastewater collected from the ferries. The electricity is currently mostly used to power the port's buildings, lighting and equipment, with a smaller portion dedicated to shore-to-ship power. The latter is however predicted to increase significantly as environmental regulations get stricter. It is also possible to use auxiliary data to deduce that there are significant flows of fossil fuel sold to trucks passing through the port, as well as used to bunker ships. While not currently directly tied to the port, these energy flows should be monitored as they are likely to evolve in the near future as alternative fuels get adopted in both the road and maritime transport industry.

Multiple development strategies were analyzed throughout this paper. For emissions reduction, the conversion of the port's rolling equipment to electric power was deemed the most promising, whether in the form of battery electric or fuel cell vehicles. However, this would require a significant investment in the infrastructure to support the new propulsion methods. On-site power generation opportunities have been found to be plentiful and promising. Techno-economic analysis of both photovoltaic and wind power installations netted staggeringly positive results. The electricity produced by these installations has the potential to be used to cover the port's own needs, with the surplus being sold to the grid or used to produce fuels on-site such as hydrogen. Hydrogen production via electrolysis was studied and proved potentially profitable, though contingent on market interest. A tri-generation fuel cell solution producing electricity, hydrogen and heat from biogas was also analyzed for the port, as its output ratios are well matched to the port's interests and would greatly increase the port's energy resilience. The study showed that such a solution would likely need external gas sources other than the port's production from wastewater, as the volume from the latter couldn't support it. Due to this, the profitability of the solution was highly dependent on the price of gas. Finally, wave generation was briefly looked at. While not ideal in the Port of Trelleborg due to the low energy nature of the local sea, the technology might prove useful in other ports thanks to its good base load generation potential.

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Contents

List of Figures

List of Tables

Acronyms

AC Alternating Current.

BEV Battery Electric Vehicle.

BOD Biological Oxygen Demand.

CAPEX Capital Expenditure.

CCS Carbone Capture and Storage.

COD Chemical Oxygen Demand.

DC Direct Current.

ETS Emissions Trading System.

FC Fuel Cell.

FCEV Fuel Cell Electric Vehicle.

GHG Greenhouse Gases.

GWA Global Wind Atlas.

HDV Heavy Duty Vehicle.

HFO Heavy Fuel Oil.

HVO Hydrotreated Vegetable Oil.

ICE Internal Combustion Engine.

IMO International Maritime Organization.

LCOE Levelized Cost of Electricity.

LFO Light Fuel Oil.

LNG Liquefied Natural Gas.

LPG Liquefied Petroleum Gas.

MGO Marine Gas Oil.

NPV Net Present Value.

NREL National Renewable Energy Laboratory.

O&M Operation and Maintenance.

OPEX Operational Expenditure.

pe Population Equivalent.

PV Photovoltaic.

PVGIS European Commission Photovoltaic Geographical Information System.

R&D Research and Development.

RoRo Roll-on, Roll-off.

SAM System Advisory Model (Software).

SMHI Swedish Meteorological and Hydrological Institute.

TMY Typical Meteorological Year (File).

WEC Wave Energy Converter.

WWTP Wastewater Treatment Plant.

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Chapter 1

Introduction

1.1 Overview

Every year, logistics become ever more important to the functioning of society. The rise of globalization has meant that a large part of the population relies on the efficient transport of goods, some of which might originate from the other side of the globe. This is reflected in the ever-growing size of the sector, with no forecasted stall (Placek, 2022). Within the logistics sector, ships occupy a crucial role. In fact, according to UNCTAD (2022b), ships carry over 80% of the volume of global trade. Nevertheless, the majority of customers obtain their goods through land transport, whether it be last-mile or longer. The interface between these two forms of transport is provided by ports. This makes ports a critical part of the system, which will have to evolve to accommodate the broadening needs of the sector. This provides ample opportunities for development, and calls for innovation to best utilize such valuable areas. Freight is not the only resource moving through ports every day. In fact, commercial ports see large amounts of energy flowing through them as well, rivaling those seen in power stations and distribution centers. Thus, ports can be seen not only as trading but also energy hubs. This work aims to study these energy flows based on data from the Port of Trelleborg, one of the largest RoRo[1] ports in Europe and the second largest commercial port in Sweden (Trelleborgs Hamn AB, 2023b). Furthermore, some strategies for the energy development of ports based on the collected data are presented, with the aim of capitalizing on ports' potential as future clean energy hubs.

[1]Roll-on, Roll-off.

1.2 Objectives

This thesis has two main objectives:

1. Inventorying the energy flows in the Port of Trelleborg, with a subsequent visualization and analysis.
2. Proposing development strategies related to clean energy for the Port of Trelleborg based on the collected data, market forecasts and present knowledge.

To be able to achieve these overarching objectives, some minor goals were set and fulfilled:

- Collect all the available relevant data regarding the port's activities and compile it in a readable database.
- Categorize and visualize the current energy flow data in order to recognize strengths, bottlenecks, and opportunities more easily.
- Create a rough forecast of the future landscape of the sectors and technologies which will influence ports the most, based on available literature, market studies and interviews with contacts within the relevant fields.
- Perform an in-depth literature review to gain a deeper understanding of the technologies that might be best suited for adoption in ports, as well as those that might influence development decisions.
- Perform a techno-economic analysis of the most promising energy-related developments to be installed in the port in the near future based on the data and the literature review.

1.3 Method

Data was provided mainly by the Port of Trelleborg, but also by some external sources as outlined through the thesis.

Most of the data processing was performed in Microsoft Excel. The energy flow graph was created using SankeyMatic to better visualize the origin and destination of the many resources involved.

Simulations of the performance of potential installations were mainly performed in System Advisory Model (SAM), a techno-economic software model optimized for the renewable energy industry developed by the NREL. Details on the specific models utilized for each simulation will be provided in the relevant sections. In some cases the economic analysis was expanded in Microsoft Excel.

Chapter 2

Theoretical background

Given the role of ports as an interface hub, much research was done regarding a multitude of topics. The different fields researched are becoming increasingly interconnected as the logistics industry develops and more efficient operation is sought. The research will be divided into three main areas. The first area, covered by Chapter 2.1, concerns the maritime sector. The current trends in the field are presented, and how they may affect ports. Special attention was given to ferries, as the vessels which moor at the Port of Trelleborg. Chapter 2.2 covers the land transport sector, in particular heavy-duty trucks. Chapter 2.3 explores sustainable electricity generation and storage technologies relevant to the port.

2.1 Maritime sector

2.1.1 Current outlook

The maritime sector has held a central role in human society for centuries. For many generations, maritime transport has allowed our species to travel long distances and move goods and people across the globe. In modern society, this has not changed, and the maritime transport sector is more important than ever. As UNCTAD (2022b) reports, ships haul over 80 % of the world's trade. With markets becoming increasingly global, and manufacturing processes becoming more and more decentralized, the role of shipping is ever more important to society. This was highlighted during the COVID-19 pandemic, when maritime trade was heavily impacted, experiencing shortages of raw material, lead time issues, blank sailings, port closures, reduced working hours, equipment and labor shortages, and truck and inland transport capacity constraints (UNCTAD, 2022a). The knock-on effect of this disruption had grave consequences, with almost all market sectors being impacted. This was reflected in worldwide shortages and price hikes on numerous products (Austin, 2021). While the maritime shipping industry has since recovered

(UNCTAD, 2022a), the crisis showed firsthand how central the sector has become to the world's economy.

A topic that has been the focal point of many industries in the past years is climate change. As the Earth's temperature keeps rising, and greenhouse gas (GHG) emissions continue to increase, it has become clear that action is needed to preserve the wellbeing of our planet (United Nations, 2023a). Central to the discourse on climate change is the topic of GHG emission reduction, as greenhouse gases in the atmosphere are the main driver for the increased temperatures seen across the globe (European Commission, 2023c). The maritime transport sector plays no small part in the emissions, with it accounting for 1.7 % of the world's total GHG emissions in 2016, as visible in Figure 2.2 (Ritchie, Roser, and Rosado, 2020). Because of this, it is important for the industry to focus on emission reduction in order to achieve the goals set by the UN for 2050. This would entail an almost 15 % reduction in emissions from 2021 to 2030 (IEA, 2022f).

One factor that is rather unique about the shipping sector is the long service life of equipment. Ships can operate commercially for over 30 years, with studies showing that as of 2022, the average age of all ships in the world merchant fleet was just over 20 years (Dinu and Ilie, 2015; Statista, 2023; UNCTAD, 2022b). Moreover, this number has been steadily rising (UNCTAD, 2022b). This is both a symptom and a cause, as many shipowners are uncertain about future technological developments and the most cost-effective fuels going into the future, as well as changes in regulations and carbon pricing (Opportimes, 2022). Given the large investment required in purchasing and constructing a new vessel, many are deciding to extend their existing fleet's operational lifetime instead. At the same time, this is slowing down the adoption of low carbon fuels, and consequently governing bodies are looking for other ways to expedite the reduction of the industry's carbon footprint without needing a replacement of the existing fleet. The environmental policies being considered and enacted have the main objective of increasing ships' efficiency, both in terms of design and operation, and thus reducing their carbon impact (UNCTAD, 2022b). On top of this, policies and incentives are being proposed to promote the transition to alternative fuels and propulsion modes (Warborn, Andresen, and Wölken, 2023).

2.1.2 Clean propulsion and alternative fuels

It is clear that alternative fuels are pivotal in the future of the maritime transport sector. According to the IMO[1], the EU, and the DNV, they will play a key role in reducing the industry's emissions. Moreover, the uncertainty about which fuels will be most readily available is also the driving force behind the reluctance of shipowners to invest in a renewal of their fleets (UNCTAD, 2022b).

DNV GL (2018) has identified LNG[2], LPG[3], methanol, biofuel, and hydrogen as the most

[1] International Maritime Organisation

[2] Liquefied natural gas.

[3] Liquefied petroleum gas.

promising alternative fuels. Additionally, it is believed that technologies such as battery systems, fuel cells and wind-assisted propulsion may also offer potential for ship applications.

Of these, LNG has already seen some adoption, in no small part thanks to it overcoming the hurdles of international legislation. Methanol and biofuels are also predicted to do so soon. On the other hand, hydrogen and LPG had not been covered by appropriate regulations within the IMO IGF[4] code as of 2019 (DNV GL, 2018). According to the 2022 report filed by the IMO on fuel consumption data, which all operating commercial ships are obliged to report to, 93.95% of the fuel oil used by ships of 5 000 Gt and above during 2020 was either heavy fuel oil, light fuel oil or diesel/gas oil. However, a growing percentage of the fuel consumed was LNG, amounting to 11 974 761 tons in 2020 and 12 623 121 tons in 2021 (5.95 % of the reported fuel tonnage). This number has been increasing every year since 2019. For comparison, all the other fuel types combined only amounted to around 220 000 tons in 2021. However, when looking at the usage data divided by area a different picture arises: the bulk of LNG was used in LNG and gas carriers, while its consumption in other types of ships was much smaller, amounting to 527 458 tons. While still much more common than other types of alternative fuels, the difference in adoption is not as staggering as it may seem at first glance (IMO, 2022a). Reports also show that 30% of the gross tonnage of ships on order is capable of LNG operation, and 3% capable of running on methanol and LPG, showing the increased adoption of alternative fuels in the sector (DNV GL, 2022).

Focusing on RoRo vessels, in 2021 98.5% of the fuel consumed was either diesel, HFO[5] or LFO[6]. LNG consumption amounted to 117 863 tons or 0.94%, with other fuels making up the remaining 0.11% (13 465 tons) (IMO, 2022a).

Looking at the future, DNV GL (2022) predicts major changes in the fuel mix if the maritime shipping sector is to achieve the goal set by the IMO of 100% decarbonization by 2050. They predict LNG to see an uptake to around 20% to 30% of the fuel mix before rapidly declining by mid-century as carbon-neutral fuels become more widely adopted. The latter would have to constitute 40% of the fuel mix in 2050 to satisfy the IMO's goals. Within carbon-neutral fuels, it is hard to identify clear winners, as there are uncertainties on price, availability, and safety. The preferred fuels would be bio-LNG, bio-MGO[7] and bio-methanol, due to their high energy density. However, there are concerns about the availability of biomass for their production given the competition with the aviation and electricity production sector. Due to this, the prices of biofuels are expected to be uncompetitive with those of electrofuels and blue fuels[8]. The availability of electrofuels will heavily depend on the availability of renewable electricity to produce hydrogen by

[4]International Code of Safety for Ships using Gases or other Low-flashpoint Fuels.

[5]Heavy fuel oil.

[6]Light fuel oil.

[7]Marine gas oil.

[8]Carbon-neutral fuels produced from fossil energy. Usually achieved through carbon capture and storage (CCS) (DNV GL, 2022).

electrolysis, as well as the availability of sustainable carbon to produce e-MGO, e-LNG or e-methanol in order to increase the fuels' energy density. If sustainable carbon will not be widely available and affordable, e-ammonia may be the preferred fuel. Blue fuels may be another option, but their availability will depend on the effectiveness of carbon capture and the infrastructure for the storage of the captured carbon. Assuming high availability, blue ammonia would be the preferred fuel. The use of CCS on fossil fuel powered ships is also a viable and realistic possibility, as well as the use of drop-in fuels such as bio-LNG, e-LNG, bio-MGO and e-MGO depending on the pace of decarbonization and strictness of environmental regulations. Drop-in fuels may retain good economic value in spite of their likely higher price compared to ammonia or methanol due to avoiding the need to switch fuel-systems completely. It is expected that annual fuel costs would increase by 70% to 100% compared to today in the scenario of full decarbonization (DNV GL, 2022).

The adoption of alternative fuels will hinge heavily on the availability of infrastructure for their production, distribution, and storage. Thus, significant investments are required and expected in ports to further strengthen their role as energy hubs and provide ships with fuels and shore-to-ship electricity. It is believed that decarbonization will truly hasten once the availability of alternative fuels is widespread and the supporting infrastructure is well-established (DNV GL, 2022).

2.1.3 Environmental legislation

The rapid pace of change required to meet the climate goals set by the Paris Agreement[9] has meant that the environmental policy and legislation space has been in constant evolution in the last decade. As a significant contributor to global emissions, the maritime transport sector is not excluded from these measures.

In Europe, both regulations set by the IMO and the European Union are enforced. The latter has recently taken action due to a dissatisfaction with the slow progress in the evolution of the IMO's approach to address GHG emissions (European Commission, n.d.[b]). In this section, the regulations enforced by the IMO will be described, before delving into the policies adopted and proposed by the EU.

The IMO adopted its first set of international measures to improve ships' energy efficiency in 2011 (IMO, 2011), which entered into force in 2013 (IMO, n.d.). These regulations mandated the Energy Efficiency Design Index for new ships, and the Ship Energy Efficiency Management Plan for all ships. In 2016, the IMO adopted mandatory requirements for ships of 5 000 gross tonnage and above, which account for around 85% of CO2 emissions from international shipping, to collect consumption data for each type of fuel oil they use (IMO, n.d.). This data was to be used as a basis on which to build future environmental measures. More recently, in 2018 it introduced its 'Initial GHG Strategy', "setting

[9] A global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C.

out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible" (IMO, n.d.) to comply with the Paris Agreement temperature goals. It mainly provided a framework for future strategies to reduce GHG emissions in international shipping, setting out the levels of ambition of the organization, identifying barriers and supportive measures and including candidate measures with possible timelines. The measures mainly target energy efficiency, driving new ships to be adopt more energy efficient designs, and existing ships to have energy efficiency management plans encompassing "improved voyage planning, cleaning the underwater parts of the ship and propeller more often, introducing technical measures such as waste heat recovery systems, or even fitting a new propeller." (IMO, n.d.). It also encouraged voluntary cooperation between ports and the shipping sector to contribute in reducing GHG emissions from ship, through actions such as the provision of onshore power supply, bunkering of alternative fuels, and optimization of port calls (IMO, n.d.). The first of the proposed measures entered into force in 2022. These mandate all ships to calculate their Energy Efficiency Existing Ship Index, a measure of their energy efficiency compared to a baseline, and to report on their annual operational carbon intensity indicator (CII), which links GHG emissions to the amount of cargo carried over distance traveled (IMO, 2022b). Ships with unsatisfactory ratings will have to enact corrective action plans and may incur in penalties, and thus encourage shipowners to guarantee more environmentally conscious operation of their ships (DHL, n.d.). In July 2023 a revision of the Initial Strategy from 2018 is set to be adopted at the Marine Environment Protection Committee.

The European Union has stated its interest in reducing GHG emissions from the shipping industry multiple times, starting in 2013 with the development of an initial strategy (European Commission, 2013). The strategy resembled the one later developed by the IMO, consisting of three steps: monitoring, reporting and verification of CO2 emissions from large ships using EU ports; setting greenhouse gas reduction targets for the maritime transport sector; adopting further measures, including market-based ones, in the medium to long term (European Commission, n.d.[b]). Later, in 2018, the commission reiterated on the importance of acting on shipping emissions in the amendment to the EU Emissions Trading System (ETS) Directive (European Commission, 2018). The directive also called for regular review of IMO action, and active effort by either institution to address shipping emissions from 2023. Also starting in 2018, ships over 5 000 gross tonnage were mandated to monitor and report their related CO2 emissions and other relevant information, similarly to the 2016 IMO ruling (European Commission, n.d.[b]). In 2021, as part of the 'Fit for 55' package the European Commission made several proposals to address maritime transport's climate impact to deliver the European Green Deal:

- Extending the EU Emission Trading System[10] to maritime transport.
- Setting a maximum limit on GHG content of energy used by ships to encourage

[10]The EU ETS is a 'cap and trade' system limiting the total amount of certain greenhouse gases that can be emitted within the system. Within the cap, operators can buy or receive emission allowances. Each operator must surrender enough allowances to cover all its emissions at the end of each year, lest they be fined heavily. The cap is reduced over time to lower total emissions (European Commission, n.d.[a]).

zero-emission technology at berth and boost demand for marine renewable and low carbon fuels.

- Boosting alternative fuel infrastructure, as well as setting mandatory targets for shore-side electricity supply at ports.
- Revising the Renewable Energy Directive to increase the target share of renewable energy sources in the overall energy mix, with a focus on sectors where progress has been slower, such as transport.
- Revising the Energy Taxation Directive to remove outdated exemptions such as those for intra-EU maritime transport and align the taxation of energy products with the European Union's climate objectives. (European Commission, n.d.[b])

As of the 27th of February 2023, the Parliament and Council agreed on the aforementioned position on the EU ETS Directive, now awaiting formal adoption before the legislation is published and entered into force. If the agreement is adopted, the EU ETS will include emissions from maritime transport starting in 2024, with a phase-in approach to ease the transition in the first three years. If the legislation is entered into force, it will economically incentivize the reduction of emissions, starting with cutting where it costs least to do so and promoting investment in innovative, low-carbon technologies. Furthermore, the EU supports the IMO energy efficiency project with a contribution of € 10 million, which encompasses the Energy Efficiency Design Index and the Ship Energy Efficiency Management Plan among other initiatives (European Commission, n.d.[b]).

2.1.4 Port equipment

Multiple studies have shown that the electrification of port equipment can lead to a significant reduction in emissions (H. Zhang, 2022; Gan et al., 2021). However, many of these studies focus on cranes and equipment seen in container ports. In RoRo ports, the main equipment used is yard tractors and, to a lesser extent, reach stackers. The vehicles are shown in Figure 2.1. According to Kim, Rahimi, and Newell (2012) electrification of yard tractors could lead to significantly reduced emissions on a per-vehicle basis, but given the predicted increase in container traffic, it is unlikely to lead to an overall reduction of emissions.

Studies have been conducted on the feasibility of hydrogen fueled heavy duty yard trucks for RoRo operations, finding that this solution could be effective and could lead to significant emissions reduction by replacing diesel fueled yard tractors (Ilio et al., 2021). A pilot project is being launched in the Port of Valencia to prove the viability of hydrogen technology for port handling equipment. One yard tractor and one reach stacker, both fuel cell powered, will be run daily for two years of real operational activities. The port will be outfitted with the necessary hydrogen distribution infrastructure (Ballester and Fúnez, 2019) and the powertrain of the vehicles will be based on previous studies (Di Ilio et al.,

(a) Yard tractors in the Port of Trelleborg

(b) A reach stacker in the Port of Trelleborg

Figure 2.1: Examples of the main rolling equipment in RoRo ports (Trelleborgs Hamn AB, 2023a)

2021). The project is part of the H2Ports initiative, and aims to raise the awareness of this technology as an option for ports (H2 Ports, n.d.).

When it comes to battery electric port handling equipment, fewer studies have been conducted. While there have been some studies on yard tractors for container ports (Heo et al., 2016; Sato et al., 2022), no studies have been found focusing on RoRo ports. Similarly, companies in the sector have offerings for battery electric yard tractors for container terminal applications (BYD USA, 2023; Kalmar Global, 2022; MAFI Transport-Systeme GmbH, 2023; Orange EV, 2023; Terberg Special Vehicles, 2023), with some being adopted in ports already (Terberg Special Vehicles, 2022), but none offer solutions for RoRo ports. RoRo ports have special requirements as the slopes that the trucks must tread to board the ferries are steep and require a significant amount of power and traction. Furthermore, certain functions of the tractors such as a revolving cabin are required for efficient and precise operations and are missing from the current offerings (Terberg Shunters, 2023). Tests performed by the port of Trelleborg have shown that the current offerings are not suitable for RoRo operations, and specialized equipment is needed (Sonesson and Folkunger, 2023).

2.2 Road transport sector

The road transport sector is crucial to modern human society. The rise of automotive vehicles has made rapid and reliable transport available to most of the population, leading to a more interconnected world. Vehicles are generally used to transport passengers, goods, or both. Narrowing the scope to ports, they primarily interface with two types of road transport vehicles: passenger cars and cargo trucks.

The industry, both for passenger and cargo vehicles, has been using predominantly fossil fuels since its inception (Rae and Binder, 2023). Consequently, given its size, the sector accounted for 11.9 % of global GHG emissions in 2016 as shown in Figure 2.2 (Ritchie, Roser, and Rosado, 2020). Thus, the recent global push to lower GHG emissions to combat climate change heavily involves the sector, and has meant that alternative fuels and propulsion methods are being steadily studied and developed. The main ones are electricity, hydrogen (to be used either in fuel cells or internal combustion engines (ICEs)), alcohols (methanol or ethanol), natural gas, biomethane, and liquefied petroleum gas (European Commission, 2023b; OAR US EPA, 2022).

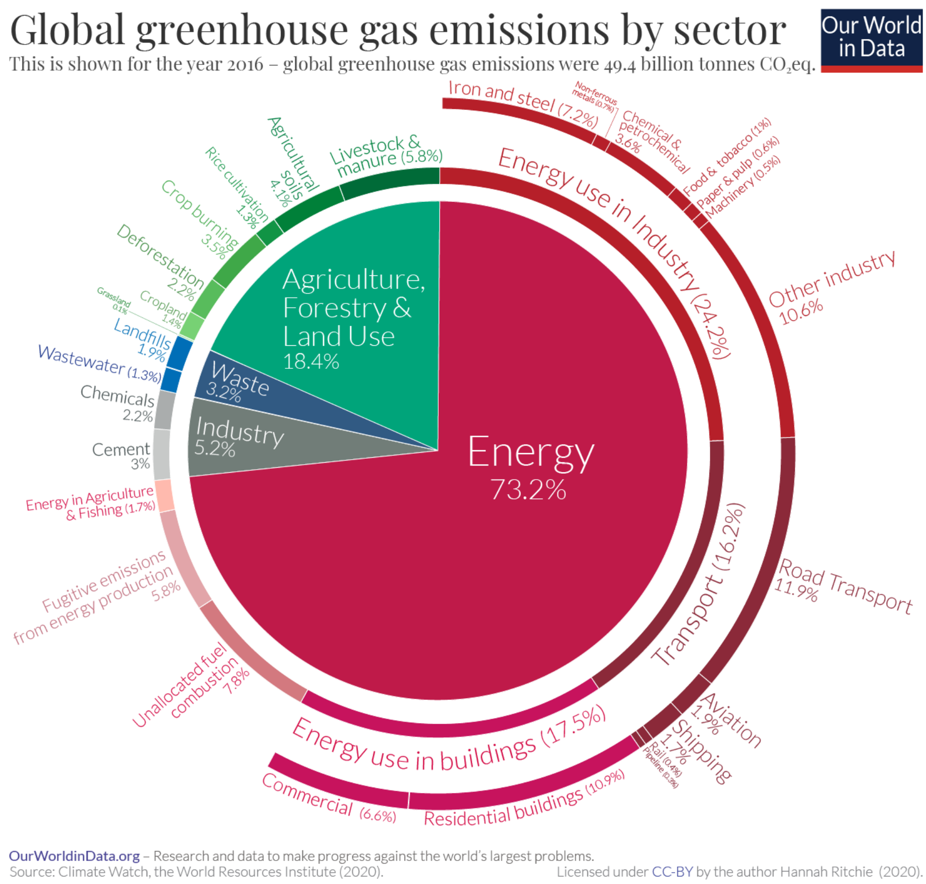


Figure 2.2: Global greenhouse gas emissions by sector (Ritchie, Roser, and Rosado, 2020)

Within road transport, in 2018 passenger vehicles were responsible for around 60% of the total emissions, while goods transport is responsible for the remaining 40% (Ritchie, 2020). Passenger vehicles have already started the transition to cleaner propulsion methods. For passenger cars, sales of battery electric vehicles have steadily increased, reaching a global market share of 8.57% in 2021 (IEA, 2022c). The trend is shown in Figure 2.3. Nordic countries in particular are where the highest shares of electric vehicle sales are found (European Environment Agency, 2022). Batteries seem like the preferred technology in this sector, with other alternative fuels lagging behind in market share. For perspective, only 15 500 hydrogen fuel cell cars were sold in 2021, compared to 6.5 million BEVs[11] (Munoz, 2022). Another alternative fuel with a notable market share is ethanol.

[11]Battery electric vehicles.

This is mainly driven by Brazil, where in 2022 ethanol-fueled cars claimed a market share of 83% of total car sales (Chapman, 2023). However, this is a unique case as Brazil introduced the "Proálcool" program in 1975, which heavily favored this fuel and in turn supported their large sugarcane industry (Rapid Transition Analysis, 2018). In the rest of the world, ethanol is mainly used as a blend-in fuel with gasoline, and rarely used on its own. Buses have also mainly adopted batteries as an alternative propulsion technology, though many also use natural gas. In Europe in 2022, diesel-powered buses accounted for 67.3% of all new bus sales, with electrically chargeable buses accounting for 12.7% of sales and other alternative fuels (mainly natural gas) accounting for 11.9% (ACEA, 2023).

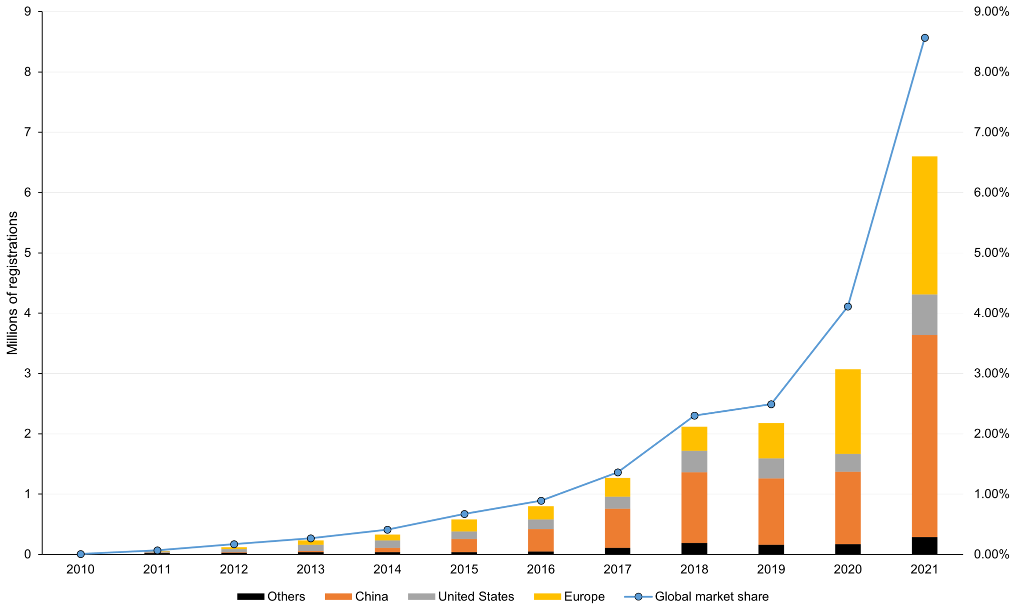


Figure 2.3: Global registrations of electric vehicles from 2010 to 2021 (IEA, 2022c)

Emissions in the HDV[12] sector have been increasing year-on-year since 2014, with the exception of 2020 due to the COVID-19 pandemic. Especially in the freight sector, emissions are increasing rapidly. This is mainly due to growing road transport demand, which is expected to keep rising in the future. In 2019, freight emissions were 44% higher than emissions from the aviation sector and 37% higher than maritime transport emissions (European Commission, 2023a). Despite this, alternative fuels have not gained as much traction as in passenger cars yet. In 2021, electric medium and heavy duty truck sales represented less than 0.3% of the total number of registrations for medium- and heavy-duty vehicles worldwide (IEA, 2022h). This stems from the more demanding use case for these vehicles, as high rates of daily utilization and large payload requirements create challenges for battery-electric powertrains. Longer driving distances mean larger battery packs, more frequent recharging stops and high-power recharging infrastructure, while

[12]Heavy duty vehicle.

heavy payloads require large amounts of power. Many trucks will not be able to return to base after each trip and thus will need accessible recharging or refueling infrastructure (Xie, Dallmann, and Muncrief, 2022). Hydrogen is being looked at as an alternative energy source for long distance operations, as it would allow for close to zero emissions operation, faster refueling and longer driving ranges (U.S. DOE, 2022a; Willmer, 2022). It could either be used in fuel cells to power an electric power train or in internal combustion engines. Both options are viable and being considered. Sources report that many manufacturers are currently working on H2ICEs, thanks to a recent revision of the definition of "zero-emissions" by the European Commission, stating that heavy duty trucks will be considered zero-emissions if their tailpipe emissions are <1 gCO2/kWh. This has created an opening for this technology, which would not be possible if the limit were 0 gCO2/kWh (DAF, 2023; MAN Truck & Bus, 2021; Verhelst, 2023). Fuel cell trucks have been in development for a few years, with major manufacturers hoping to make them commercially available shortly (DAF, 2023; MAN Truck & Bus, 2021; Scania Group, 2022; Toyota USA, 2022; Volvo Trucks, 2022). Biofuels have also been considered for long-haul trucks, due to good combustion properties and the option to work as a drop-in fuel. This makes them ideal as an aid to accelerate the decarbonization of the transport sector (Ball, 2022). However, given their limited availability due to land use change concerns, the general sentiment is that in the long term they should be reserved for sectors that are otherwise limited in options such as aviation and maritime transport (IEA, 2021; Verhelst, 2023).

2.3 Sustainable electricity generation and storage

2.3.1 Renewable energy sources

Renewable energy sources are becoming increasingly more common in the electricity grid. In recent years, their price has decreased significantly, making their economic proposition an interesting one (Roser, 2020). The most mature renewable power production technologies are hydropower, geothermal energy, photovoltaic panels, and wind turbines (Enel, 2023). While the former two are geographically limited, the latter two are more flexible and suitable for smaller-scale installations. Solar energy can also be used in solar thermal installations, but these generally perform worse than photovoltaic panels when used for electricity generation at a non grid scale size due to the added complexity, increased cost of the system, sensitivity to weather conditions, space requirements and lower potential for further cost reduction, and so are quite rare today (Lorenz, Pinner, and Seitz, 2008; Boretti and Castelletto, 2021; Gorman et al., 2021). According to Boretti and Castelletto (2021) it is unlikely that solar thermal installations can compete economically with standalone PV[13] systems, but they might be comparable to combined PV + BES installations, while offering similar dispatchability advantages. There are other power production

[13]Photovoltaic.

technologies that take advantage of renewable sources, such as tidal generators and wave converters. However, these technologies are less mature and generally not commercially available, as well as providing smaller energy yields (Enel, 2023; United Nations, 2023b).

Photovoltaics leverage the photoelectric properties of some materials, meaning that they release electrons when struck by light. This property is leveraged to produce electricity from sun rays. For further information on the functioning of photovoltaic panels, readers are referenced to Honsberg and Bowden (2023). Photovoltaic panels have seen major progress over the past decades. As can be seen in Figure 2.4, since 1976 solar capacity has increased and the price of modules has decreased. It is important to note that the graph's axes are logarithmic, meaning that the reduction in price of the technology has followed an exponential trend. In fact, the price per watt of solar modules declined by a remarkable 99.6% between 1976 and 2019, from $106 to $0.38. The reasons behind this decline, aside from economies of scale, are varied. As Roser (2020) puts it:

> The advances that made this price reduction possible span the entire production process of solar modules: larger, more efficient factories are producing the modules; R&D efforts increase; technological advances increase the efficiency of the panels; engineering advances improve the production processes of the silicon ingots and wafers; the mining and processing of the raw materials increases in scale and becomes cheaper; operational experience accumulates; the modules are more durable and live longer; market competition ensures that profits are low; and capital costs for the production decline. It is a myriad of small improvements across a large collective process that drives this continuous price decline.

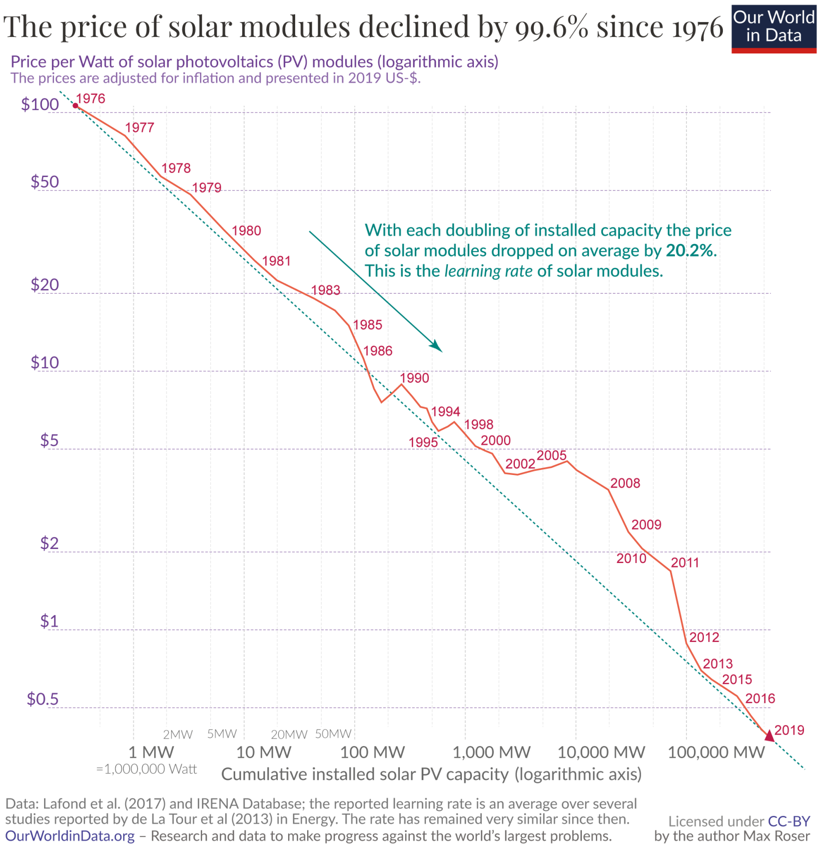


Figure 2.4: Price per Watt of solar photovoltaics vs installed capacity (Roser, 2020)

Today, photovoltaic panels are widespread, having produced 3.6% of the world's electricity in 2021. This makes it the third largest renewable electricity technology behind hydropower and wind power (IEA, 2022g). Solar power is unique among electricity generation technologies as it is increasingly used in distributed systems. In fact, in 2021 distributed systems constituted 48% of the global solar PV capacity additions, with the remaining 52% being utility scale plants (IEA, 2022g). The installation of solar PV panels often offers a great economic proposition, aided in part by the strong policy support for this technology (IEA, 2022g). One drawback of the technology is the volatility of its production: as the electricity is mostly generated when the sun is shining on the panels, it is dependent on the weather and will not generate in hours of darkness. Much research is being done on the topic with the goal of minimizing the impact of this issue through energy storage, deployment techniques, coupling with other power sources, etc. (Cevik and Ninomiya, 2022; Goldstein, Thornton, and Kerrigan, 2021; Lustfeld, 2021).

Wind energy has also seen extraordinary growth in the past decades. Figure 2.5 shows the growing share of global electricity production from wind, reaching 6.65% in 2021 (Our World in Data, 2023). As can be seen from Figure 2.6, this technology has also seen a significant reduction in cost as installed capacity increased.

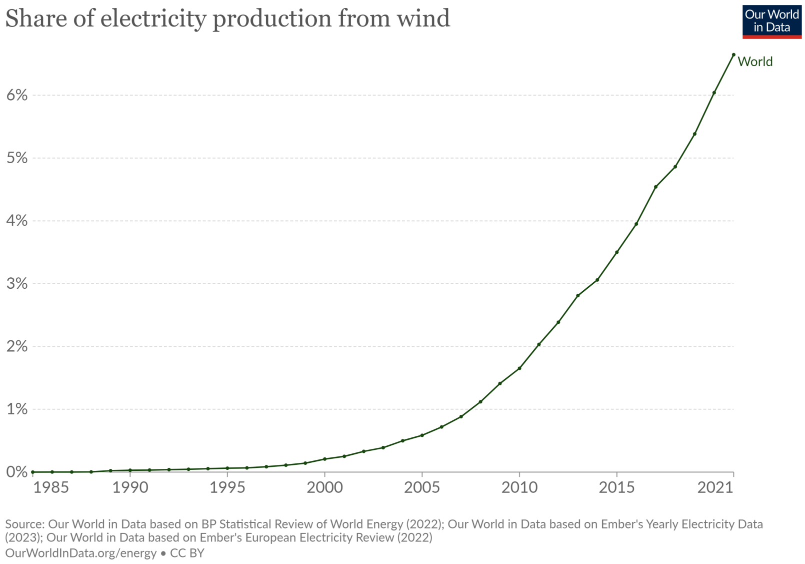


Figure 2.5: Share of global electricity production from wind

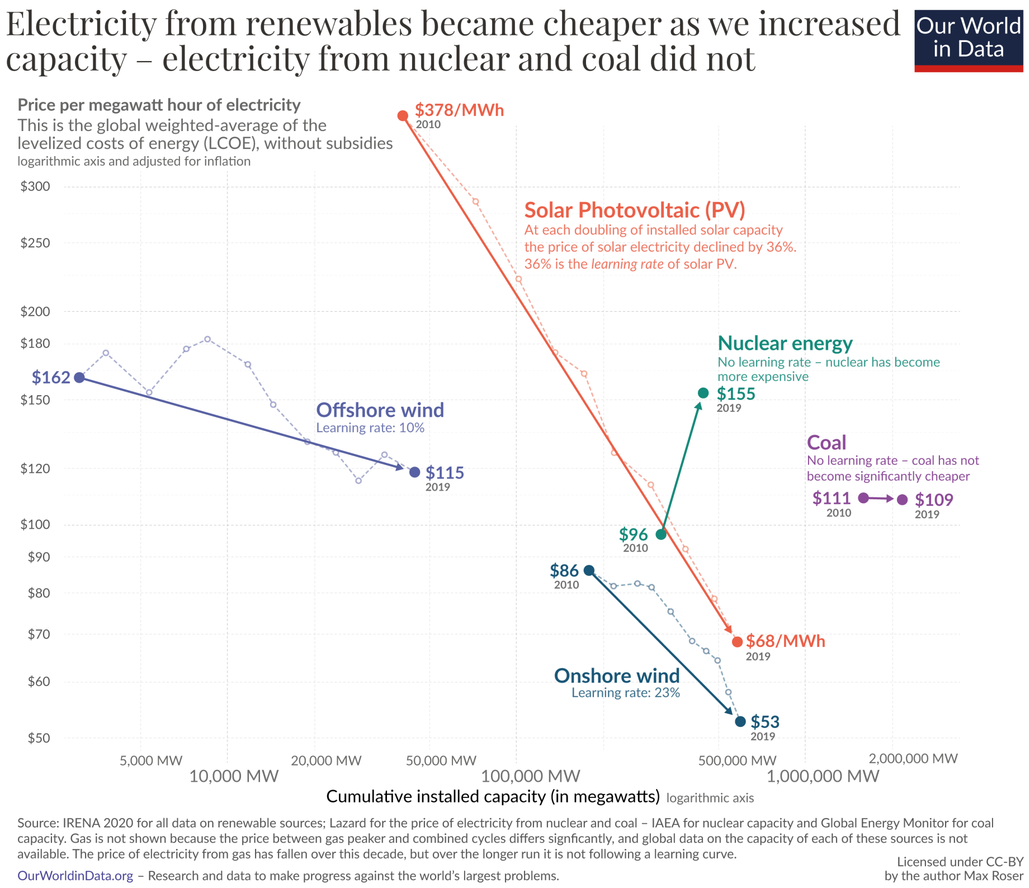


Figure 2.6: Price per Watt of different electricity generation technologies vs installed capacity (Roser, 2020)

The wind energy industry has generally settled on three bladed designs for wind turbines, as they represent a good compromise between performance and cost (Ed Rivis, 2023). However, much progress is still being made to improve the productivity and cost of turbines. Namely, turbines with increasingly larger rotor diameters and heights are being developed, as they allow for increased productivity. Unfortunately, for onshore wind installations this advancement is often limited, as size is restricted by transport, environmental and public acceptance concerns. Still, market reports from the DOE[14] show a growth in the size of installed onshore wind turbines throughout the years, as shown in Figure 2.7 (Wiser and Bolinger, 2022). In offshore installations, on the other hand, size is generally not an issue, and larger turbines are constantly being adopted (U.S. DOE, 2022b). This, together with the rapid development of floating foundations, is leading many to believe that this technology may be the key to transitioning to clean energy across the world (IEA, 2022i).

[14]U.S. Department of Energy.

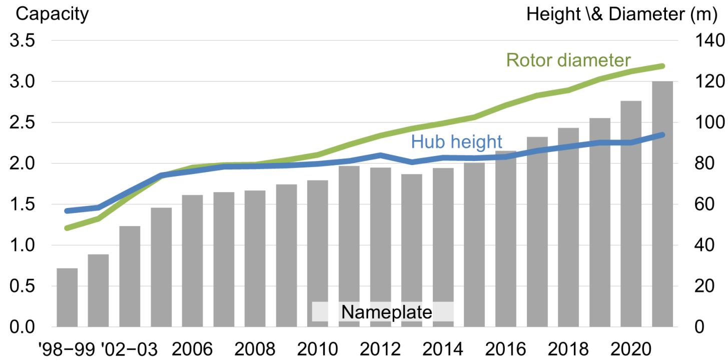


Figure 2.7: Hub height, rotor diameter and nameplate capacity trends for onshore wind turbines in the USA (Wiser and Bolinger, 2022)

Wind turbines are suitable for installations of various sizes, ranging from a singular turbine with a nameplate capacity of a few megawatts to huge wind farms with capacities in the thousands of megawatts (Frangoul, 2022).

Looking at market data, it is clear that China is investing heavily in wind power. Reports show it having the largest manufacturing capacity as well as the largest deployment of turbines both onshore and offshore. The U.S. also is a significant power in the market for onshore installations, whereas it is not investing heavily in offshore power plants (Global Wind Energy Council, 2022). Looking at investment costs, for onshore installations most of the CAPEX[15] is directly linked to the turbines themselves, with the tower, rotor, nacelle, and foundation adding up to just over 75% of the CAPEX on average. This differs significantly from offshore installations, where the turbine only represents 35% of the CAPEX, with the foundations contributing an additional 12.6% (Global Wind Energy Council, 2022).

Wave energy converters are another power generation technology that may be interesting for ports, given their geographical location. Contrary to the previously described technologies, wave energy converters are still in their infancy (Enel, 2023; United Nations, 2023b). Many different designs are being studied and developed, and few are available commercially. Wave energy is said to have huge potential, though much of it is concentrated in coastal ocean areas like Alaska, the western coast of Europe, the western tip of South America, and Australia (Gunn and Stock-Williams, 2012; Lewis et al., 2011; National Renewable Energy Laboratory, 2021). There have been plenty of studies on so called “low energy seas”, and specifically the North Sea, finding that not all sites are suitable for wave power generation (Beels et al., 2007). The southern coast of Sweden does not hold a particularly high potential according to this study. Another study has found that generally wave energy converters work better as base load generators, as more often than not, even in high energy sites, the power available in the waves is much lower than the maximum potential (Coe et al., 2021). Because of this, the study states that it might be

[15]Capital expenditure.

better to scale WEC[16] installation down to increase the capacity factor, which can reach up to 80%, and not use the WEC in high energy conditions to ensure its longevity. Usually WECs have capacity factors in the range of 25-30% (Lavidas, 2020). Other studies have shown the potential of this technology in ports, showing that its integration can be an interesting prospect for power generation in some cases (Calheiros-Cabral et al., 2020; Saheli et al., 2022). All configurations show relatively low power outputs, but with a relative ease of expandability. The solution proposed by (Calheiros-Cabral et al., 2020), in particular, is very interesting as it integrates the WEC in breakwaters, which are a structure that is almost universally needed in ports.

2.3.2 Hydrogen, fuel cells and batteries

Energy storage has become an increasingly central topic in the energy field. The intermittent nature of renewable energy sources heralds a need for energy storage to match users' demand as a larger share of electricity is produced through them (Singhvi, 2022; Iberdrola, 2021; Alexandra Zablocki, 2019; IEA, 2022b; IEA, 2022d). There are various energy storage technologies, with the most widely used being pumped-storage hydropower. Other technologies are on the rise, such as battery energy storage, which has seen strong growth in recent years (see Figure 2.8) and is considered the most scalable at a grid-scale, and hydrogen. Other technologies also exist but play a comparatively smaller role in current power systems, such as compressed air and gravity storage (IEA, 2022d). Much innovation is being seen in the sector, as highlighted by the intense patenting activity (Gregori et al., 2020). The report also highlights the dominance of batteries within the electricity storage innovation landscape, representing 88% of all patenting activity in the area and being the only technology that saw significant growth in innovation after 2012. This analysis does not however consider hydrogen and fuel cells, which have also seen significant growth in recent years (IEA, 2022e; IEA, 2019).

[16]Wave energy converter.

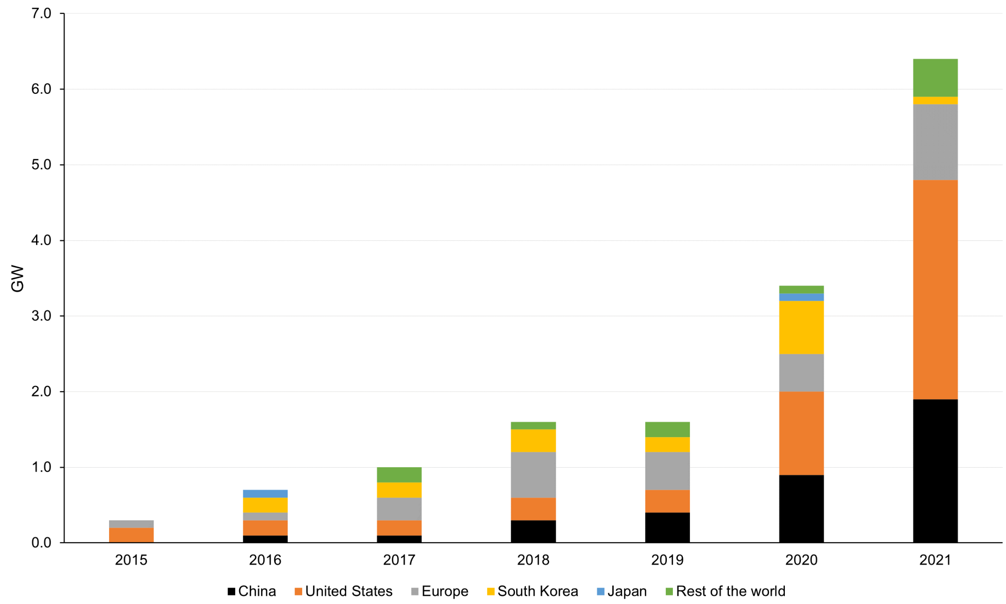


Figure 2.8: Annual grid-scale battery storage additions (IEA, 2022d)

When narrowing the scope to commercial, non-grid scale applications, pumped-storage hydropower becomes unattainable, as it is limited by geographical topology and is generally hard to deploy at a small scale (de Oliveira e Silva and Hendrick, 2016). Other forms of gravity energy storage can be interesting, as shown by pilot projects such as Gravitricity's demonstrator in the Port of Leith, Edinburgh (Gravitricity, 2022), but the technology is still in its experimental phase and not ready for commercial deployment. Furthermore, it is often limited by weather conditions for solutions such as EnergyVault's (Energy Vault, 2022) or geographical features for technologies like Gravitricity or ARES. Nevertheless, there is interest in the technology due to its many advantages such as fast power delivery, scalability, long lifetime, competitive LCOE and integration with waste materials (Energy Vault, 2022; Gonzales and Kayali, 2021).

As mentioned, batteries have seen significant growth in both development and adoption in recent years. This is reflected in their price per kWh, which has fallen by 97% since 1991 (Ritchie, 2021). When plotted against cumulative capacity (Figure 2.9), it is possible to notice that the learning rate[17] of batteries is very high, and similar to that of solar modules, the former being 18.9% and the latter being 20.2%. Batteries have many strong qualities: high energy efficiency, high energy density, fast power delivery, scalability and maturity (Olabi et al., 2022).

[17]Relationship between the price of a technology and its experience, measured as the cumulative installed capacity (Roser, 2020).

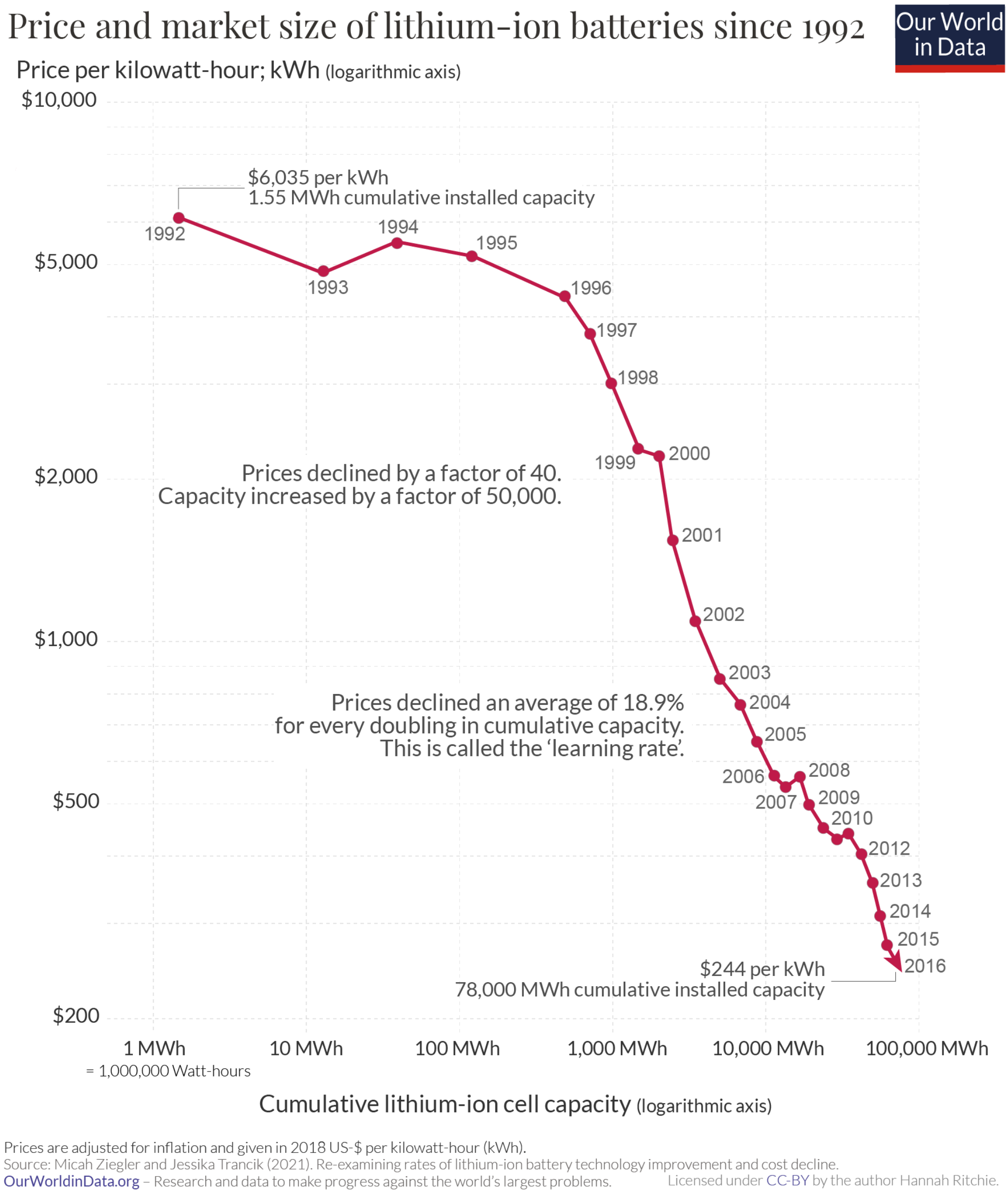


Figure 2.9: Price per kWh vs installed capacity of batteries (Ritchie, 2021)

Chapter 3

Energy flows in the port of Trelleborg

While at first glance the most notable resource moving through a commercial port on a day-to-day basis is freight, at the same time a huge quantity of energy quietly flows in and out of these areas. This energy is present in various forms. The first one is electricity: port areas have high electrical demands, as port equipment must keep up with the continuous flow of freight and vessels, and lighting for very large areas is required as the port's activities continue into the night. Additionally, port areas are increasingly being used for electricity generation, as they are well suited for the installation of renewable energy sources due to the large amount of unobstructed space present within them. Fuel for the vessels is another major component of the energy flows. Nowadays the vast majority of vessels consume mainly fossil fuels such as heavy fuel oil (HFO), which are provided at the port. However, the shipping industry is focusing on transitioning to alternative fuels to allow for cleaner operation and less emissions. Examples of such fuels are liquefied natural gas (LNG), hydrogen, liquefied petroleum gas (LPG), methanol and biofuels (DNV GL, 2018). Thus, ports may see an increased presence of these fuels within their premises in the future. The Port of Trelleborg also owns a gas station catered to trucks, which it rents to external companies. At the moment the station only provides diesel fuel to the many vehicles traversing the port, but as long-haul trucks adopt different propulsion technologies this may change, with the station providing alternative fuels like compressed hydrogen. Finally, some lesser, but still significant, energy flows are present. Examples of these include heating for the port's offices and warehouses, wastewater discharged by the vessels, gas, and other combustibles transported by the ships.

In this section an inventory of the energy flows in the Port of Trelleborg will be presented, with detailed insights into the figures obtained from the data and an energy flow chart to summarize the information in Figure 3.9. Then, an outlook on how these flows may potentially change in the coming years is proposed.

3.1 Electricity

The electricity consumption data for the port is available as far back as 2016. The data is obtained from the metering stations scattered throughout the port and is provided as hourly values. As of 2023, there are 21 metering stations in the historic part of the port, and only one metering station in the newer part of the port. Because of this distribution, it is difficult to quantitatively recognize the major consumption spots in the newer part of the port. However, qualitative analysis can give a picture of the main electricity consumers in the area.

Looking at the total yearly electricity consumption for the available data, there is no clear trend as can be seen from Figure 3.1. This is believed to be connected to the large amount of construction work taking place in the port. As different expansions and installations are worked on, temporary housing structures for workers are erected. Due to their momentary nature, these structures do not have great thermal insulation, and thus require a lot of power to be kept warm. Thus, depending on the number and size of these buildings being present in any specific year, the overall electricity consumption is heavily affected, as a large amount of energy is utilized to electrically heat the buildings.

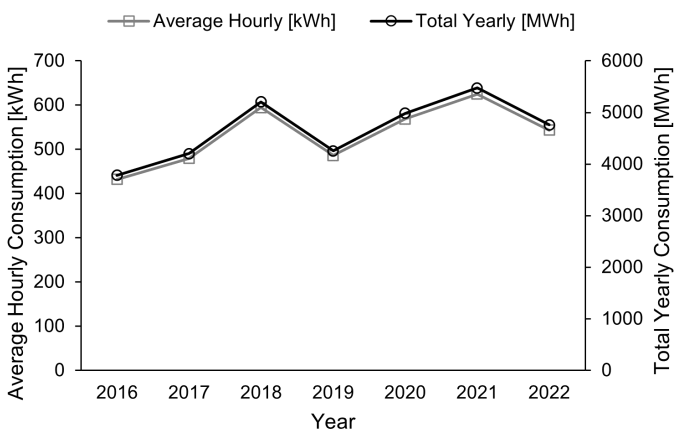


Figure 3.1: Year on year electricity consumption trends in the Port of Trelleborg

A large amount of the electricity consumed in the port is used for lighting. By law, the area of the port must always be lit up to a certain degree. Given the large footprint of the port's premises, this requires the presence of an abundance of lighting fixtures. These lamps have a fixed brightness and consumption on the older side of the port, while in the new premises the fixtures have smart control and can be dimmed locally when areas are not experiencing heavy traffic. This allows for reduced power consumption while still satisfying the legal and practical requirements for lighting performance. At present, all of the port's external lighting fixtures are active, as activities are conducted both in the old and new part. However, consumption is forecasted to decline in future years as the port's activities gradually move to the newly constructed side and the historical part of the port begins to close.

Other electricity consumers are port equipment such as ramps, which are mainly used for the train ferries. Additionally, port buildings such as offices and warehouses consume a small amount of electricity during normal operation for electrical equipment and heating. Finally, the port offers a charging service for refrigerated trailers and other power-dependent transport equipment, which also has a small influence on electricity consumption.

Looking at 2022, the electricity consumption profile remains consistent throughout the year. The average consumption curve shows a maximum at 10 pm, where the usage approaches 0.8 MW. The consumption remains consistent at around 0.7 MW until 3 am, after which it gradually decreases until 10 am. Between 10 am and 3 pm the consumption remains consistent at around 0.3 MW, before gradually increasing until reaching the nightly peak at 10 pm.

When separating the data into seasons, some interesting observations can be elicited. Predictably, during summer and spring the evening peaks are at a later hour, as the sunset is delayed, and so is the activation of the lights. Likewise, the decline in consumption is seen earlier in the morning, as the sun rises sooner. Interestingly, this decline is smoother during summer and spring, with consumption declining directly from the nighttime values to the baseline daylight values. On the other hand, in autumn and winter there is a brief escalation between 4 and 6 am before the consumption starts to drop. This pattern is also seen in the 2021 consumption. It is theorized that this might be related to increased port activity at around 5 am. This would require more lighting during the darker seasons, while in summer and spring there would be sufficient natural light. Additionally, there seems to be a baseline shift in consumption within seasons independent of the hour of the day. For example, in 2022 throughout the day there seems to be a difference in hourly consumption between summer and winter of around 300 kW. This value remains quite consistent throughout periods where both curves are flat but increases when approaching sloping areas of the curve. This can once again be explained by the fact that in wintertime lights are turned on earlier and turned off later than in summer, influencing consumption significantly. The baseline offset between the consumptions is assumed to be related to the electrical heating of buildings. In past years, this value has fluctuated as buildings for the workers constructing the facilities in the new side of the port have been raised and taken down. As mentioned previously, these buildings have poor insulation and thus have high electrical consumption for heating. Additionally, the port's office building is electrically heated in the colder months, though its consumption remains quite consistent. In winter, for example, the office's electricity consumption is consistently around 13 kW.

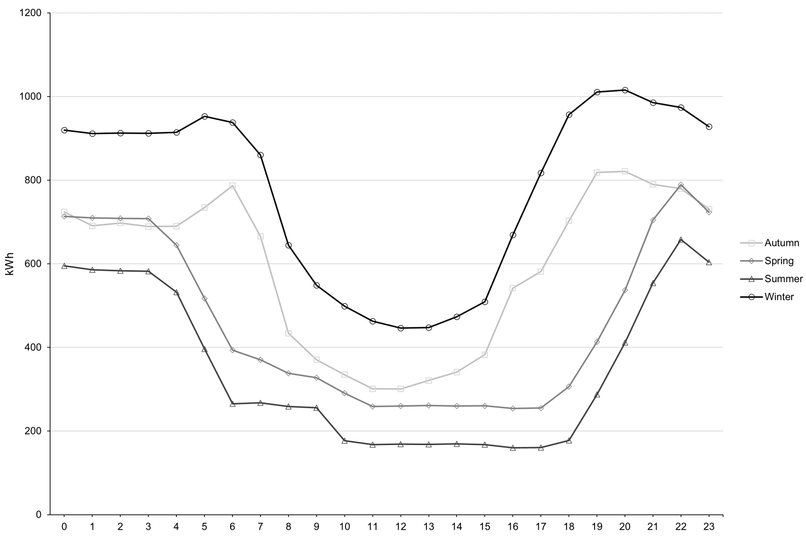


Figure 3.2: Average hourly electricity consumption for different seasons in 2022

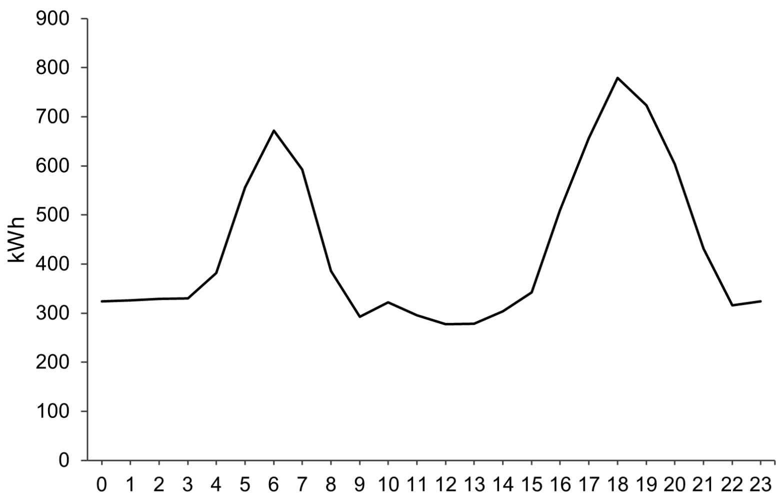


Figure 3.3: Difference in hourly electricity consumption between winter and summer

Before 2022, the port purchased electricity at a fixed price. However, in mid-2022 the port started purchasing electricity at the monthly market price. Thus, hourly fluctuations of electricity prices do not influence the port's expenditure. It is nevertheless interesting to examine hourly spot prices, as the port may benefit from switching to them depending on its load profile. In fact, if the port had used hourly spot price rather than monthly in the analyzed timeframe, their daily expenditure on electricity would have been 4% lower.

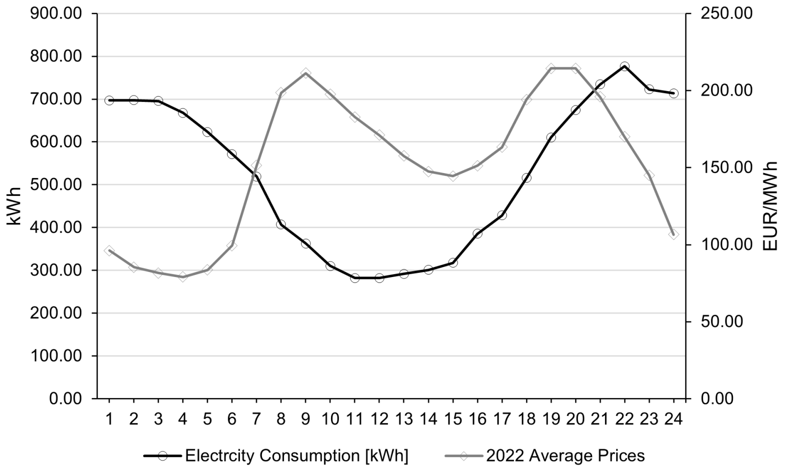


Figure 3.4: Average hourly electricity consumption and spot prices in 2022

By multiplying the average hourly spot price with the average hourly consumption, it is possible to obtain a chart showing the average hourly expenditure for the year. The chart is reported in Figure 3.5. It is evident that the biggest expenditure is had in the evening hours, when electricity consumption is peaking and the price of electricity is high. Throughout the rest of the day the expenditure remains quite consistent, with a small hump around 8 am. By multiplying the average hourly spot price with the average hourly consumption, it is possible to obtain a chart showing the average hourly expenditure for the year. The chart is reported in Figure 3.5. It is evident that the biggest expenditure is had in the evening hours, when electricity consumption is peaking and the price of electricity is high. Throughout the rest of the day the expenditure remains quite consistent, with a small hump around 8 am.

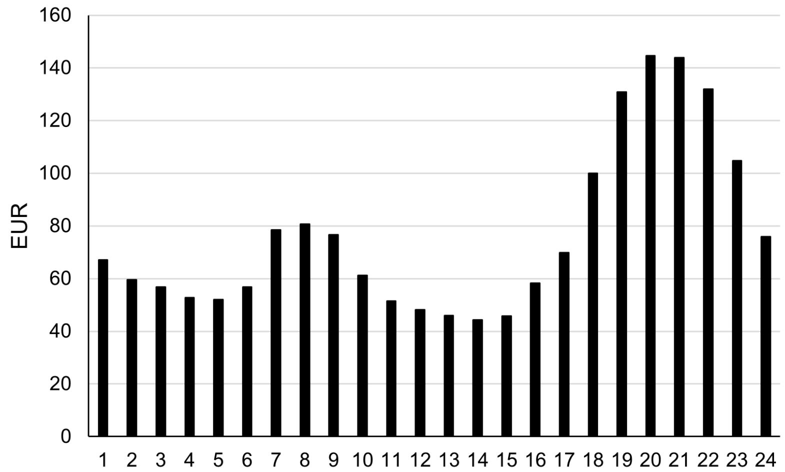


Figure 3.5: Average hourly expenditure in 2022

Having knowledge of the port's planned expansions, it is possible to draw some predictions on how the changes may influence electricity consumption. Firstly, as mentioned, consumption from the lights is forecasted to decrease as the older section of the port is decommissioned. Moreover, the planned wastewater treatment plant (WWTP) is predicted to be finished before 2024, and its operation will slightly increase the consumption in the new part of the port. As regulations on emissions get stricter, it is realistic to assume that more vessels will want to utilize shore-to-ship connection when moored. This will heavily affect the electricity consumption patterns at the port, as the power requirements of these ships are comparatively very significant. The effect of ship-to-shore connections will be studied more thoroughly in section 3.1.1.

Furthermore, as the heavy-haul transport industry seeks to reduce their emissions, it is likely that there will be an increased demand for electrical charging of battery electric vehicles. This demand may be twofold: some of it might be due to a switch to battery electric tractors for the port's internal moving operations, while some of it might be due to increased demand for charging from the heavy-duty trucks coming through the port. Both can be forecasted and accounted for in advance when knowing the extent of trucks that will use the technology. In fact, the tractors tend to follow set routes and shifts, and thus the location and timing for the charging can potentially be managed by the port with only minimal alterations in workflow. For the external trucks, the demand can be linked to the arrivals and departures of ferries, which are agreed upon on a weekly basis by the port and the ferry lines. Having said that, these schedules show more variability, and thus internally accounting for this demand might be more challenging.

The port is not only a consumer, but also a producer of electricity. In 2020, a 434 kWp photovoltaic panel installation was completed on the eastern section of the port. The panels were forecasted to produce around 450 000 kWh/year. So far, production has been in line with this prediction, with 1 179 227 kWh produced between September 2020 and March 2023. The deployment strategy for the electricity produced by the panels is straight forward: the electricity is used to cover the port's instant electrical demand, and in case of production exceeding demand the surplus electricity is sold to the grid. Like the purchased electricity, the electricity produced by the panels is also valued at the average monthly market price.

It is important to note that the metering stations used to create the load profiles measure electricity consumption independently of the source, therefore the profiles are unaffected by the photovoltaic installation and its production.

3.1.1 Cold Ironing

One important factor to consider when dealing with the port's electricity consumption is shore-to-ship connections, also known as cold ironing. As illustrated in Section 2.1, the topic of cold ironing is becoming ever more central to ports. As emissions legislation gets stricter, shore-to-ship power is one of the most immediate actions that can be taken to reduce the environmental impact of ships. The Port of Trelleborg is at the forefront of this field, as it already provides shore-to-ship power to two of its vessels. The system was introduced in January 2018. When connected to shore, each of these vessels consumes up to 1.4 MW. Additionally, if the internal elevator is used to move vehicles to and from a lower deck in the ship, the power consumption is further increased by 1.2 MW. For this reason, the port and the ships' operators have agreed to only use shore-to-ship connection when the elevator is not in use to not overload the port's electrical infrastructure. The connections are clearly visible from the historical electricity consumption data, as the ships use a significant amount of power compared to the baseline port consumption. However, looking at the ships' cold ironing data does not reveal a pattern. The chart in Figure 3.6 shows the monthly consumption of the two ferries between 2018 and 2022.

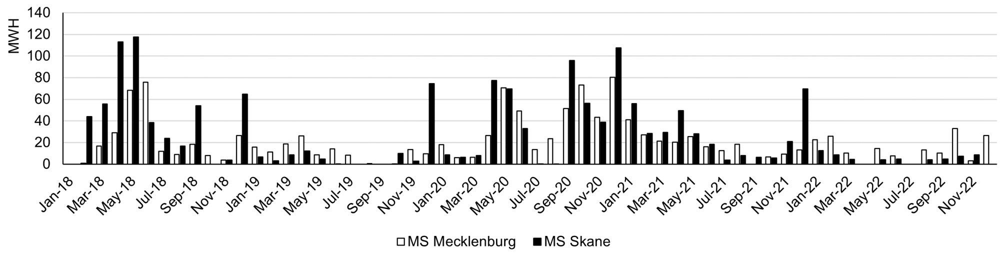


Figure 3.6: Electricity consumed for cold ironing since the installation of the system

On average, the yearly electricity consumption from cold ironing amounted to 277.8 MWh. The value has fluctuated significantly since the system's installation in 2018, however, as shown in Figure 3.7.

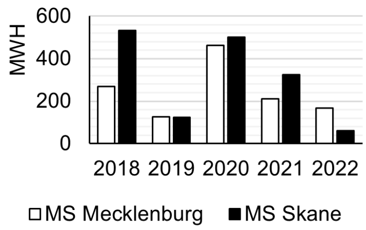


Figure 3.7: Yearly consumption of electricity for cold ironing

Based on this data, it would be hard to make predictions for the future regarding cold ironing, as demand appears inconsistent. However, due to environmental legislation it is expected that moored ships will operate their engines increasingly rarely. Therefore, shore-to-ship power demand may become more predictable as ships might have to rely on it to power all of their operations at port. For the sake of analysis, a rudimentary model was constructed based on the berth assignment schedules of the port to portray how the electricity demand for the port may change in the future.

As the berth assignments are mainly visual, the model was based on a limited dataset from 2022, as manual analysis of the schedules was the only way to gather statistics on berth occupation and thus ferry presence. Given the availability of historical berth assignment data dating back 10 years, with proper tools it would be possible to extend this analysis and potentially obtain more accurate results. Most of the numbers in this model are speculative: this is because the scope of this study did not allow for proper inquiry with ship operators to understand their potential operational patterns and cross-reference them to build the predictive model. This step would be crucial for obtaining accurate results if the port wanted to further the study of this topic in the future.

The model was built starting from the available historical data on the electrical demand of ferries at berth, and the berth assignment schedules. From these, the parameters in Table 3.1 were obtained. It is important to note that the load values are entirely based off the available data for the two vessels currently using shore-to-ship power at the port. Other vessels may require higher or lower amounts of electricity depending on their size and systems.

Then, several parameters were appointed in order to model charging behavior. These are entirely speculative and may not be representative of the real charging patterns of ferries. The first four parameters were roughly based off of the berth assignment schedules, though as mentioned a deeper analysis would be needed to gain more accurate data. The load coefficient was added to account for the fact that not all ferries may need shore-to-ship power: in a scenario where no ferries use their engines in port, then this would be 1. A value of 0.5 indicates that half the ferries present in the port daily are practicing cold ironing. The peak load coefficient is meant to compensate for the fact that the ferries will not always demand electricity at peak load: this is only achieved when the ferry is charging and its elevator is running, which only happens during loading and unloading operations. While some ferries stay at berth only for the length of time needed to complete these operations, many stay for longer, meaning that the percentage of time they spend at peak load would be very low. The proposed value of 0.3 is entirely speculative, however a more accurate value could be obtained if a study on the operational patterns of ferries at the port were to be conducted. As the potential electricity demand is tightly linked to the loading and unloading operations of the ferries, such a study could be conducted even today with low cold ironing adoption and yield useful results for the future.

Table 3.1: Base parameters for the cold ironing prediction model

Baseline Load (MW) - BL	1.2
Peak Load (MW) - PL	2.6
Peak Traffic - Number of Ferries	8
High Traffic - Number of Ferries	6
Medium Traffic - Number of Ferries	4
Low Traffic - Number of Ferries	2
Peak Traffic - % of day	0%
High Traffic - % of day	10%
Medium traffic - % of day	30%
Low Traffic - % of day	60%
Load Coefficient (% of ferries charging) - LC	0.5
Total number of hours at dock, all ferries	43
Peak Load Coefficient (% at peak load) - PLC	0.3

Based on the above parameters, a rough estimate of the potential electricity demand from ferries cold ironing was calculated according to this formula:

$$Demand = (PLC \times PL + (1 - PLC) \times BL) \times LC \times n_{hours}$$

The resulting figure for the daily electricity demand from ferries was 34.83 MWh. For comparison, the port's average daily consumption of electricity between February 2022 and February 2023 was 12.59 MWh. This shows the huge impact that widespread use of cold ironing would have on the port's operations, even in a relatively conservative scenario.

Additionally, the loads on the port's electricity infrastructure would increase significantly. Using the parameters above, at high traffic times demand from ferries could reach peaks of 7.8 MW, and even at medium traffic hit highs of 5.2 MW. Based on this, it is important that the port develops strategies to mitigate the stress on its infrastructure. These could entail coordination efforts to avoid numerous ferries being at peak load at the same time by staggering operations to lower the effective peak load, or adding electrical power sources close to the berths to distribute generation and reduce the stress on the shared parts of the electrical grid. It is important for the port to perform further studies on this issue, as it will represent a significant challenge with the increasing demand for shore-to-ship connections.

3.2 Fuels

The port's role as a transport and logistics hub means that a large amount of fuel is moved through its premises every day. The main fuel users are ferries, transiting trucks, passenger cars, and the port's rolling equipment. Ferries mainly utilize HFO, though some have recently been venturing into LNG operation. Land transport vehicles mainly use diesel fuel, except for some passenger cars running on unleaded fuel. These, however, do not have refueling options within the port, and thus do not appear in the energy flow charts. Port equipment presently runs on HVO[1] or diesel fuel, with the former being used by tractors and the latter being used by reach stackers. Transport cars are battery electric and charged within the premises. AdBlue[2], though not technically a fuel, is also used extensively in the port's vehicles, and is thus also reported.

Data was collected quantifying the fuel usage of the port's vehicles in 2022. Unfortunately, due to an issue in the vehicles' data collection system, data was only available for 13 out of the 21 tractors operated by the port. To compensate, each of the tractors with missing data was assigned a fuel consumption equal to the average fuel consumption of the tractors with available data, which totaled 21 102 liters per year per tractor. The fuel consumption in liters is shown in Figure 3.8.

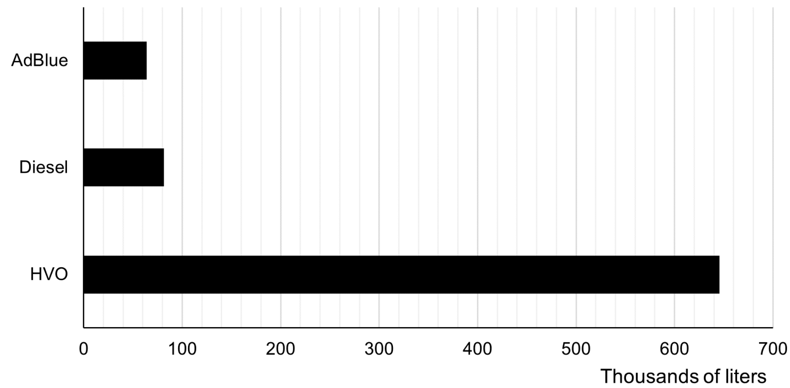


Figure 3.8: Total reported fuel consumed by the port's vehicles in 2022

The energy contents of the fuels was also calculated and appears in the Sankey diagram in Figure 3.9. The LHV[3] and density values used in the calculations were obtained from the following sources: European Commission. Joint Research Centre. Institute for Energy and Transport. (2013) and Aatola et al. (2008)

[1]Hydrotreated Vegetable Oil.

[2]AdBlue is a clear mixture of demineralised water and pure urea (32.5%) and is also referred to as Diesel Exhaust Fluid or AUS 32. It is designed to reduce harmful emissions of nitrogen oxides (NOx) from diesel vehicles to non-hazardous gases, in order to comply with more stringent emission standards (Eurol Lubricants, 2020).

[3]Lower Heating Value. Defined by the Gas Processors Suppliers Association as "the enthalpy of all combustion products, minus the enthalpy of the fuel at the reference temperature, minus the enthalpy of the stoichiometric oxygen (O2) at the reference temperature, minus the heat of vaporization of the vapour content of the combustion products." Alternatively, the American Petroleum Institute defines LHV as "the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C." In general, the LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered (chemeurope.com, 2023).

All refueling activities are handled by entities separate from the port. For trucks, there is a refueling station which is owned by the port but managed by external companies (in 2023, this is Shell). Similarly, ferries bunker through the use of trucks, and the operation is managed by the ferry lines themselves. However, the fuel used for the bunkering operations is stored within the port premises in tanks owned by the port and rented to an external company.

3.3 Gas and heating

Gas in the port is primarily used for heating of its buildings. The gas is procured through the Swedish gas network. The gas comes in the form of natural gas or biogas depending on the supply.

3.4 Lesser energy flows

A number of smaller energy flows also move through the port. Of these, wastewater from ships has been considered in this analysis despite not being presently treated by the port, as the planned wastewater treatment plant is set to be operational in the near future. The calculations on wastewater are based on the technical documents and measurements provided by the company building the plant. The measurements for incoming wastewater flow were taken for 12 vessels mooring at the port during the 2019 pandemic and were corrected to account for increased load during regular operation and for the addition of three new vessels from TT Line. The values were measured both during low and high season. A sensitivity analysis was also conducted by the company comparing their measurement and forecasts with a previously conducted analysis in the Port of Ystad, which sees similar traffic, which showed good correlation. The values are reported in Table 3.2.

Table 3.2: Measured and calculated parameters for the wastewater treatment plant

Parameter	Value	Unit
Average incoming flow	348	m3/day
Average inflow high season	387	m3/day
Average inflow low season	305	m3/day
Maximum incoming flow	621	m3/day
Minimum incoming flow	144	m3/day
BOD7[4]	339	mg/l
CODCr[5]	880	mg/l
Ntot[6]	136	mg/l
Ptot[7]	20	mg/l
SS[8]	386	mg/l
Average CODCr Daily	306.2	kg
Chemically bound Energy (Maminski)	4.9	kWh/kgCOD
Thermal Energy (Maminski)	7	kWh/m3WW
Average Energy Content	3936.5	kWh/day

The wastewater will only be treated by the plant to minimize harmful compounds before being discharged back at sea or in the municipality's sewage network. The plant will mainly remove particulate matter and reduce phosphorus and metals, as well as BOD7 and COD to some extent. The dewatered sludge produced during the process will be stored and then shipped by truck to a sludge reception facility. Consequently, the chemical and thermal energy contained within it is not recovered in any way by the port.

3.5 Ferries and external trucks

As mentioned previously, the port is not directly involved with the refueling of either ferries or trucks that are not port-owned. Because of this, data was unavailable on the volumes of fuel used in these activities. Nevertheless, they represent a large part of the energy flowing through the port, and might be of further interest in the future as the road and maritime transport industries transition to alternative fuels, requiring appropriate infrastructure to be built for their storage and distribution. Because of this, it might be useful

[4]Biochemical oxygen demand, also called biological oxygen demand. Defined as the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down the organic material present in a water sample, at a specific temperature and specified period, it is one of the most commonly used parameters to assess the environmental impact of wastewater (Yu and Brooks, 2016; Von Sperling, 2007). The BOD7 represents the milligram of oxygen per liter of sample consumed during 7 days of incubation (European Environment Agency, 2021).

[5]Chemical oxygen demand. COD is defined by Naturvårdsverket (n.d.[a]) as "a measure of the amount of oxygen needed for chemical oxidation of all organic compounds into their inorganic end products. Dichromate is used to oxidise the organic substances in the method called CODCr".

[6]Milligrams of nitrogen per liter of sample.

[7]Milligrams of phosphorus per liter of sample.

[8]Milligrams of suspended solids per liter of sample.

to visualize the magnitude of these flows by deducing them from auxiliary data, if only in a qualitative manner as the data would not be strictly empirical.

For trucks, the estimate is based off of traffic data for heavy duty vehicles transiting through the port in 2022. Assumptions were made regarding the number of trucks refueling at the station and the amount of fuel purchased. It was assumed that only 1% of the trucks coming through the port refueled at the station, with an average of 262.5 liters purchased by each[9]. This resulted in a total of 1 741 811 liters sold. Converting this figure to energy units using density and LHV data for diesel from European Commission. Joint Research Centre. Institute for Energy and Transport. (2013), the total energy content of the hypothesized fuel sold to external trucks in 2022 was 17 308 MWh. For perspective, this is 32% more than all of the other measured energy flows combined. This is visualized in Figure 3.10.

Unfortunately, it was not possible to calculate a satisfactory estimate for the bunkering of ferries because of the general lack of information coupled with the uniqueness of each vessel and the variance in itineraries and companies' refueling habits. Further study on the magnitude of this energy flow is encouraged.

3.6 Conclusions

When looking at the data collected, some conclusions can be drawn. Firstly, most of the energy in the port is used quite efficiently, and there is not a lot of waste within the premises. Energy efficiency of buildings, in particular insulation, can be a potential development for the future, but other than that not much heat or electricity is wasted. There is significant energetic potential in the wastewater stream, though it is not economically feasible to extract it as of today. In the future, this stream could be used for production of biogas and chemicals, as well as potentially for heating. The port's dependency on fuels is also clearly shown: the magnitude of this energy flow is an omen for the difficulties the port may face if it chooses to convert its equipment to electrical power.

[9]This figure is based on the size of the tank of the Volvo FH16, one of the more popular HDV models on the European market (Monteforte et al., 2023). Volvo offers sizes ranging from 150 to 900 liters (Volvo Trucks, 2023), thus a size of 525 liters was chosen for this calculation. Furthermore, it was assumed that the trucks would refuel only half of their total tank capacity on average.

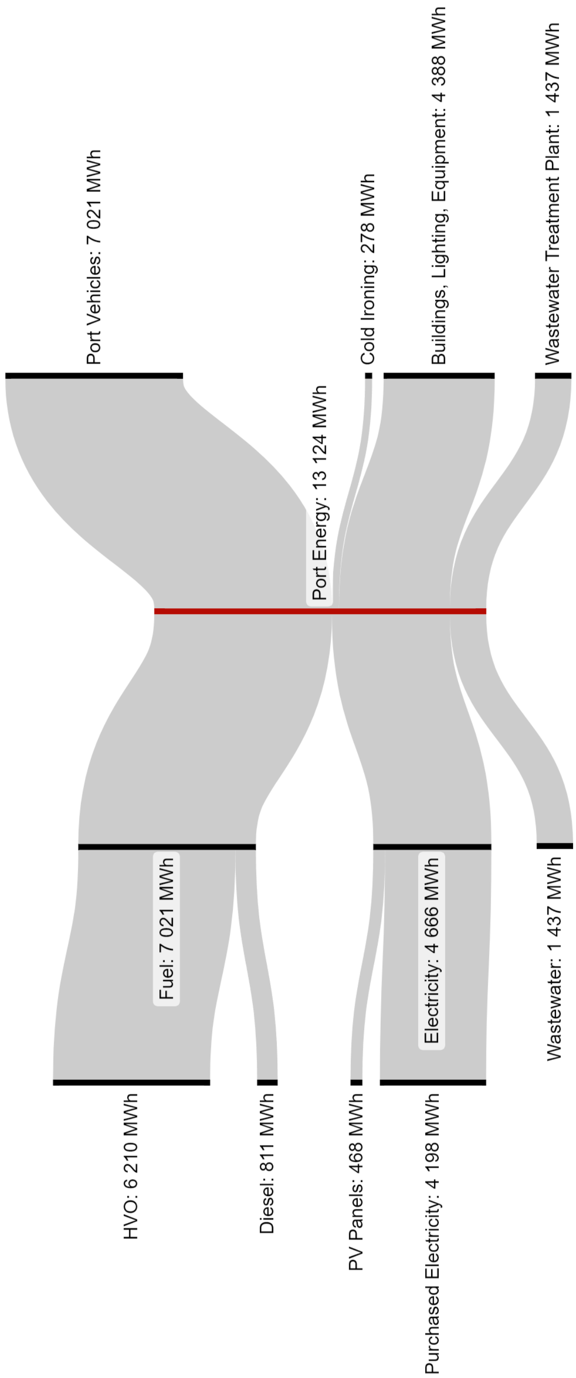


Figure 3.9: Energy flows in the port of Trelleborg in 2022

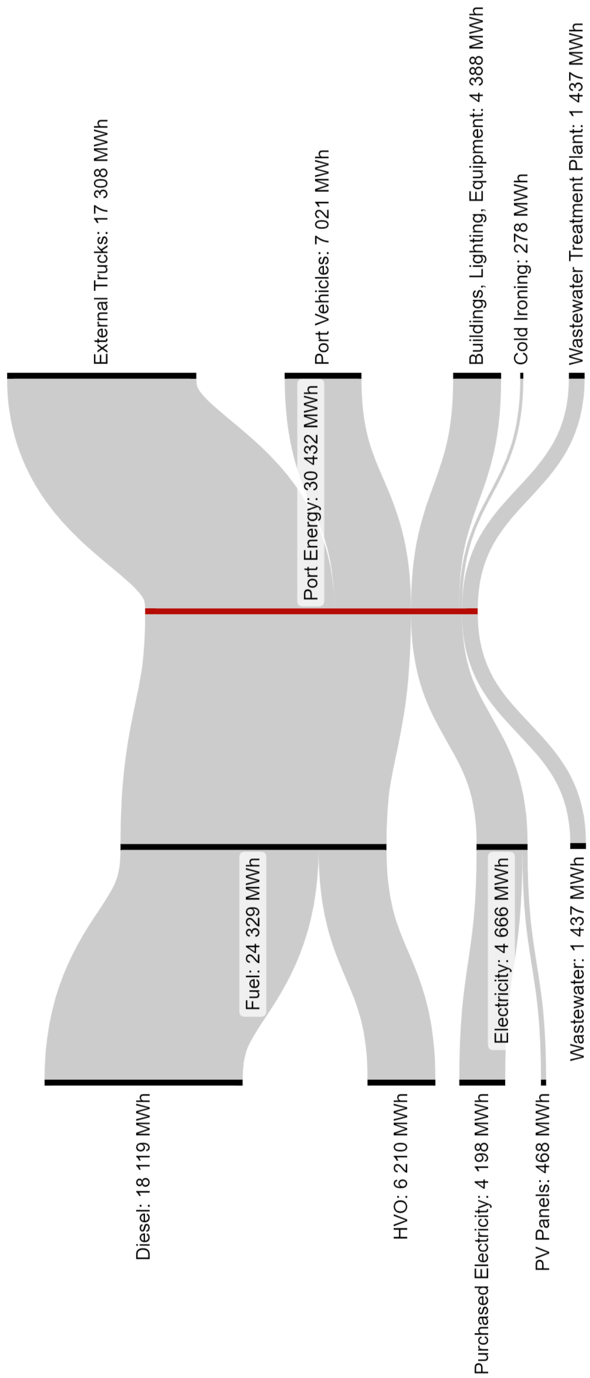


Figure 3.10: Energy flows in the port of Trelleborg in 2022, including the speculative truck refueling flow

Chapter 4

Techno-economic analysis of potential development strategies

Based on the data presented in Chapter 3, several potential development strategies for the port were studied. Inspiration for the installations was taken from a multitude of sources, including development plans of many other ports. Some of the proposed solutions are more traditional and a proven investment, while some are more innovative and may prove riskier. Either way, as this work aims to be an inspiration for future developments, they were included in this paper even if not presently economically viable.

4.1 Emissions reduction

An environmental impact analysis performed by the port in 2022 showed that the majority of the emissions within the port area were not generated by factors controllable by the port itself. In fact, 74 % of the measured emissions originated from downstream land transport. A further 6 % was emitted by the ferries calling in the port.

The main source of emissions owned by the port was its vehicles and machinery, accounting for 4 % of the overall tally in 2021. Therefore, in terms of emissions reduction this is undoubtedly the most important area for the port to focus its efforts on. Within the port's equipment, it is safe to assume that the majority of the emissions come from the yard tractors, which constitute the bulk of the port's fleet and are generally operating all throughout the day and night. Other vehicles and equipment are personnel cars for transportation within the port, which are already battery electric and thus do not amount to any direct emissions, and reach stackers, which are vehicles used for handling intermodal cargo containers[1].

The port has already looked into transitioning their yard trucks to electric propulsion. While there are some options on the market, such as the Terberg YT203-EV, the Gaussin APM or the Mafi T230e, none of these are specialized for RoRo ports. In previous trials conducted by the port, it was found that none of the currently available options were powerful enough to handle the steep slopes that can be encountered when driving onto a ferry. Additionally, since none of the options are specialized for this type of operation, they do not offer a swiveling seat, which is essential for the efficiency of the drivers. Therefore, as of today there are no options for the port to switch to tractors with electrical propulsion.

Reach stackers are the other major port vehicle. While fewer than the yard tractors, they do operate in the port on a daily basis to handle intermodal traffic, and it would be beneficial for the port's emission reduction goals to switch them to electrical propulsion. In this case, commercial options are available, and provided by the same company which currently supplies the port, Kalmar. Their ERG420-450 has similar capabilities to the models currently being operated in the port, and the transition should be rather simple. It is recommended that a more detailed study is conducted on the topic to assess the economic impact of the adoption of electric reach stackers, and which battery size and charging solution is apt for the port's needs.

It is hard to analyze the value proposition of transitioning to this equipment as no technical data on the potential tractors is available, and thus energy consumption analysis cannot be performed. Therefore, it is hoped that future studies on the subject are carried out once this information becomes available, to inform investors of the potential economic benefits and drawbacks of such a solution.

What is clear from the energy consumption data is that if the port were to fully transition to electric vehicles, a major impact would be had on its electricity consumption. In 2022, the energy content of the fuel consumed by the port vehicles was 150% of the electricity consumed by all port operations. Even discounting the lower conversion efficiency of internal combustion engines, the increased electrical demand would be substantial. As with cold ironing, this would heavily affect the port's electrical infrastructure, and may warrant some upgrades so that it could handle the increased load. Studies should also be carried out to determine the optimal charging locations for the vehicles, as different solutions may bring different benefits. For example, a distributed charging infrastructure such as electrified roads throughout the port may lengthen the operational time of the vehicles before their battery is depleted and disperse the charging load in both space and time. On the other hand, a centralized high-speed charging infrastructure could benefit from being near the port's own power generation sources, and limit upgrades to a smaller part of the port's electrical grid. The possibilities are varied, and the economic impacts of each choice are

[1]Intermodal shipping refers to moving freight by two or more modes of transportation. By loading cargo into intermodal containers, shipments can move seamlessly between trucks, trains and cargo ships (Yeager, 2020). In the Port of Trelleborg, all three modes of transportation are present and involved with intermodal shipping.

multi-faceted: the potential consequences could influence the number of vehicles needed to provide competitive operation, costs related to the electrical infrastructure, the choice of power sources to be installed in the port, etc.

Hydrogen powered vehicles would be easier to implement in comparison, as their operation closely resembles that of a traditional ICEV[2]. With fast refueling times, the infrastructure and operation for this technology could resemble that already present in the port, with a centralized refueling station that the vehicles use whenever their reserves are running low. Nevertheless, this solution is not without its drawbacks. Firstly, storage may be an issue, as port authorities have stated concerns about safety in this regard. At a basic level though, one of the biggest drawbacks of hydrogen propulsion is its energy efficiency. Even with fuel cells, which can reach efficiencies of up to 72% (Aminudin et al., 2023), the overall well-to-wheel efficiency[3] is lower than with electrical propulsion (M. Li, X. Zhang, and G. Li, 2016). This may lead to higher overall costs, even in the scenario of lower initial capital costs if less tractors need to be purchased compared to BEV due to the faster refueling rate of FCEVs[4]. Both solutions should be studied when options become available, to determine which one is better suited to the port's environment.

4.2 Power generation

Opportunities for power generation in the port are plentiful thanks to the large footprint of its premises. The port is well suited for the installation of renewable energy technologies due to the abundance of flat unshaded space, both at ground level and on the roofs of warehouses. Furthermore, its strong internal electrical infrastructure allows for seamless integration of new energy sources, with little work needed to connect them to the municipal grid. In this section, various potential solutions for power generation are presented, with a focus on renewable technologies.

4.2.1 Solar photovoltaic panels

Photovoltaic panels have grown to be an increasingly safe investment in recent years. Southern Sweden is well suited to the technology, as proven by its widespread adoption in the region. As previously discussed, the port itself has a ground-mounted photovoltaic installation within its premises of 434 kWp, which covered around 10 % of the total electrical demand of the port in 2022.

[2]Internal combustion engine vehicle.

[3]A method to evaluate efficiency and emissions of an energy source by considering its entire life cycle (Morgenstern, 2022). This includes the production of the primary fuel and its transport, the production of the road fuel and its distribution, and the conversion efficiency inside of the vehicle itself (European Commission, 2016)

[4]Fuel cell electric vehicles.

One area of the port with huge untapped potential for solar generation is the roofs of the buildings within the port. In fact, due to the storage services offered by the port, many warehouses are present within its premises, with large and mostly flat roofs. The buildings are generally not tall and quite spread out. This means that, combined with the absence of cranes for the loading and unloading of container ships, shading on the roofs is minimal.

An initial study was conducted in SAM to assess the potential of a roof mounted PV system using all the available roof area of current buildings. It is important to note that this study is only hypothetical, as the port is planning to completely move its operations to the newly constructed eastern side, while all the buildings in question are on the older western side. However, as they are central to the port's activities, new buildings with a similar footprint are planned to be built on the eastern side of the port as operations are transferred, and thus the potential of the PV installation would be similar to that presented in this study. Additionally, the new buildings can be built with features such as reinforced roofs to support the installation.

Roof areas were calculated using satellite images of the port. As can be seen in the map in Figure 4.1, seven buildings were selected for the installation. The resulting total roof area is 65 480 m2. This is only an estimation, as in reality some of the areas on the roofs may not be appropriate for the installation of panels. Additionally, one of the buildings presents a gable roof, which was considered flat in this analysis for simplicity.

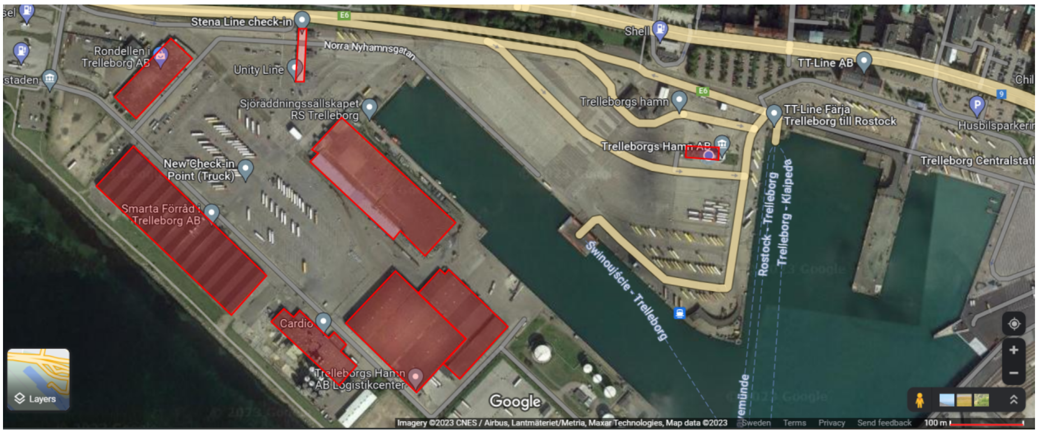


Figure 4.1: Map of the port highlighting the roofs selected for the hypothetical PV installation (Google and CNES, 2023)

Given the hypothetical nature of the study, the PVWatts model was used in SAM, which simplifies the system design phase by omitting the choice of photovoltaic module and inverter. Using a conservative ground coverage ratio (GCR) of 0.3[5], the maximum name-

[5]GCR is the ratio of the photovoltaic array area to the total ground area. For an array configured in rows of modules, the GCR is the length of the side of one row divided by the distance between the bottom of one row and the bottom of its neighboring row. An array with a low ground coverage ratio (closer to zero) has rows spaced further apart than an array with a high ground coverage ratio (closer to 1) (NREL, 2023).

plate capacity of the system would be 12 430 kWpDC. A standard DC/AC ratio of 1.1 was chosen, with a standard value for inverter efficiency of 96 %. System losses were also added, using standard conservative values for this type of PV installation. Losses such as shading may actually be lower in this application as explained above. On the other hand, snow losses are considered null in this analysis as the weather file did not contain usable information in this regard, but they would undoubtedly be present in the real installation. The losses are listed in Table 4.1.

Table 4.1: Losses considered in the PV system simulation

Loss Type	Loss %
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-induced degradation	1.5
Nameplate	1
Availability	3
Total system losses	14.08

The panels were installed facing south, as that is the most common and usually best orientation for PV systems, and the orientation of the future buildings where the systems would be installed is unknown. Later in this section it is shown that for the chosen location it is actually preferable to install the modules facing south-east, which is also one of the most likely directions for the future buildings to be facing given the geography of the port. Thus, in this regard the simulation may provide a slightly lower yield than the real installation would. Simulations with different tilts were run, which showed that the best tilt for overall production was 40 degrees. Results from the different simulations are shown in Figures 4.2 and 4.3. The weather file used was acquired from the European Commission Photovoltaic Geographical Information System (EUPVGIS). Specifically, the downloaded typical meteorological year (TMY) file came from the PVGIS-SARAH2 database, containing meteorological data spanning from 2005 to 2022. A ground albedo[6] value of 0.2 was used, as it is a good conservative estimate for roof surfaces according to Bhargava (2018), NREL (2023), and based on data from Misni (2017) and Ban-Weiss et al. (2015). Depending on the color of the buildings' roofs the real albedo value could differ from this figure.

[6]Albedo is a measure of the amount of sunlight reflected by the ground. SAM uses albedo data to calculate the ground diffuse irradiance incident on the module, and for bifacial modules, to calculate the irradiance incident on the rear side of the module. A value of zero means a completely non-reflective surface, and one means completely reflective. Thus, a lighter colored surface will have a higher albedo value, as it reflects more sunlight, while a darker colored one will have a lower albedo (NREL, 2023).

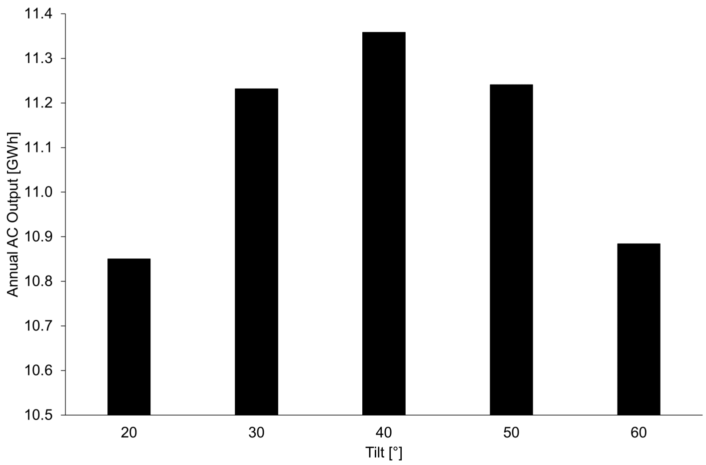


Figure 4.2: Annual production of the PV system with different tilt angles

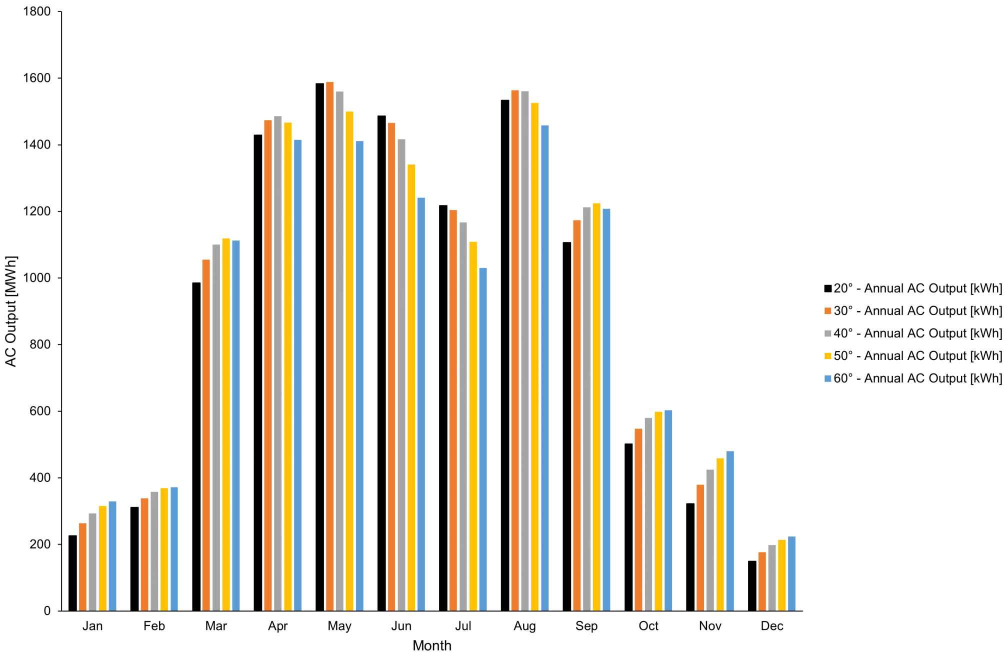
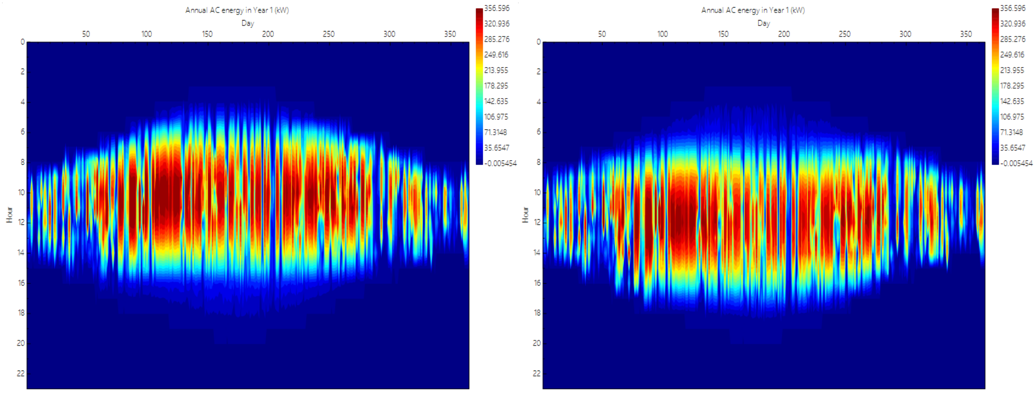


Figure 4.3: Monthly production of the PV system with different tilt angles

To verify the accuracy of the weather files and the simulation, a 1:1 model of the PV system currently installed in the port was recreated and simulated in SAM. The simulation used the Detailed PV Model – Distributed from SAM, which expands on the PVWatts model by allowing more control over the specifications of the system. Thus, the simulated system used the exact same model of panels as the real one, with matching specifications, and a very similar model of inverter, as the inverter used in the real system was not available in the software's database. The results of the simulation were compared to the production data from the real system and to the preliminary simulations run by the company who installed the panels. The results were indeed similar: the simulations by the installation company gave an annual AC production estimate of 463 747 kWh. The average yearly production for the real system was 467 674 kWh (calculated by taking the total production since installation, dividing it by the number of days passed, and multiplying that number by 365). The simulation run in SAM predicted an annual AC energy output in year 1 of 432 282 kWh. This figure is lower, but accounts for more losses than the simulation by the installation company, which might be excessive. When using the same performance ratio as the installation company (91.3% vs 81% used in the original SAM simulation) the resulting annual production is 469 890 kWh, which is aligned with the rest of the results. This would suggest that generally the SAM simulations provide conservative estimates on the system's performance, and it is likely that the system will perform better in reality.

Some further analysis was performed on this setup to better understand the influence of different parameters on the system. Firstly, a simulation was run with the panels tilted at 55°, equal to the latitude of the installation, as opposed to 20° in the original system. As expected, this resulted in a 4.5% increase in annual output compared to the original configuration, with the production being slightly better distributed throughout the year. Predictably, in this configuration the production during winter and early spring months is higher, while during the summer months it is slightly lower. When asked about the reasoning for the lower tilt, port officials cited structural concerns due to strong winds.

Additionally, a simulation was run with the panels at 55° tilt and facing directly south (as opposed to the 146° azimuth of the real system). Interestingly, this system's annual production was 2% lower than that of the previously analyzed configuration. This is surprising, as it is common practice to set modules in a south-facing direction. As it turns out, this is caused by a slightly higher average level of irradiance in the morning hours rather than the afternoon in Trelleborg, according to the PVGIS weather file. This might be caused by weather effects in the area. The panels facing the south-east can then better exploit this irradiance and thus produce more energy overall. As an added result, they produce more energy in the morning and less in the afternoon, while for the south facing panels the production is more evenly distributed. This is shown in Figures 4.4a and 4.4b . Figure 4.5 is a heat map of the irradiance in Trelleborg from the weather file, where it is possible to see the increased irradiance in the morning.



(a) 146° azimuth (SE)

(b) 180° azimuth (S)

Figure 4.4: Heatmaps showing the production of the PV systems with optimal tilt of 55° and different orientations

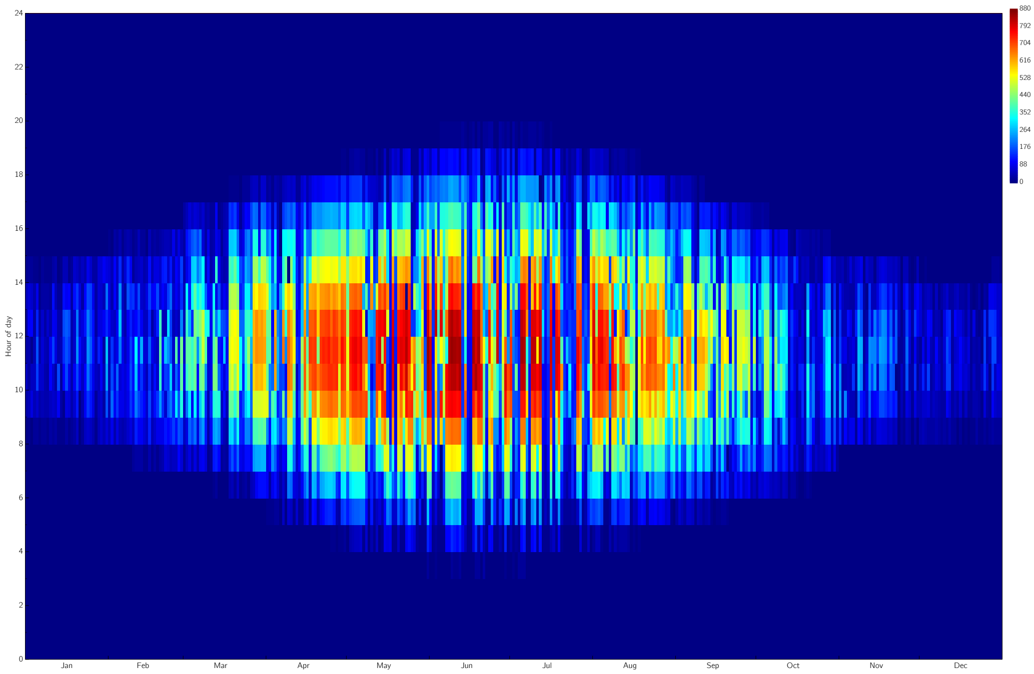


Figure 4.5: Heatmap showing the global horizontal irradiance from the weather file [W/m2]

Coming back to the planned potential PV system, economic analysis based on the results from the PVWatts simulation was performed both on SAM using hour-by-hour values and on Microsoft Excel, instead using average hourly yearly values. The simulation gave an AC electricity production in year 1 of 11 358 MWh, with a DC capacity factor of 10.4%. The system sees a gradual loss in performance throughout its lifetime, generating 11% less annual electricity by year 25. The bulk of the electricity is produced from March to

September, with the rest of the months seeing low production due to short days and bad weather (see Figure 4.6).

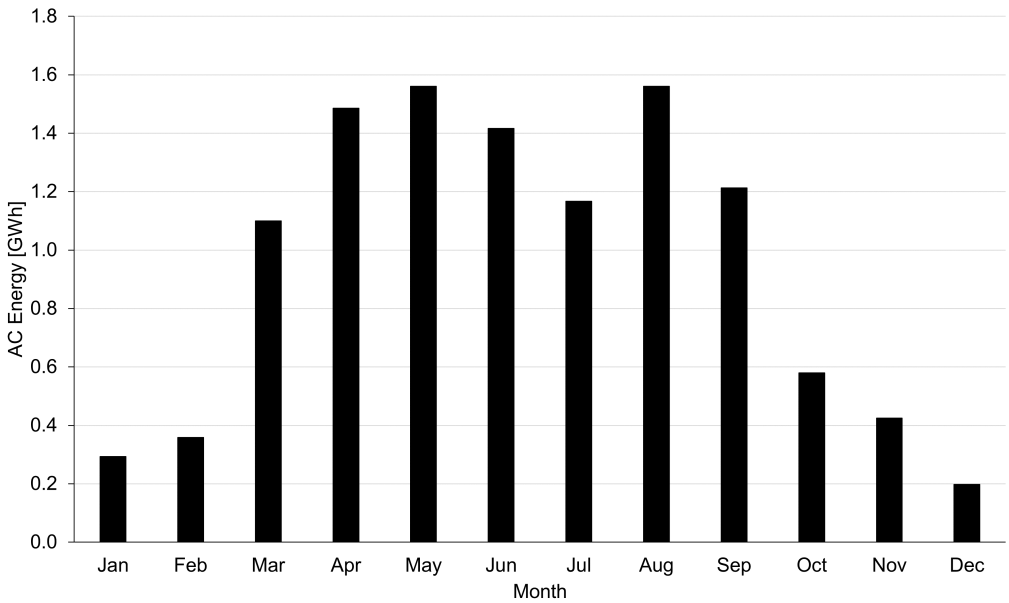


Figure 4.6: Monthly production of the PV system

To perform an initial economic analysis, the hourly production data was parsed to obtain the average hourly production of the system throughout the year. This was matched with average hourly grid prices and average hourly electricity load to obtain an estimate of the average potential savings and earnings from the system. The accuracy of the results depends on many factors, such as electricity purchase price, purchase agreement, costs of installation and maintenance and weather conditions. However, it is believed to be a good initial estimation to show the potential of such a project.

Initially, CAPEX and OPEX[7] prices were based on the 2020 survey by the IEA PVPS[8] and the Swedish Energy Agency (Lindahl et al., 2021). The survey provides prices for different applications. Firstly, prices for residential applications were used to simulate a high-cost scenario. Then, prices for large-scale, roof-mounted commercial applications were used, which should be more representative of the offer the port might receive. These amount to a CAPEX of € 18 147 800 and € 10 068 300 respectively, and an OPEX of € 98 408 per year for both cases. A discount rate of 5.5% was used when calculating

[7]Operational expenditure.
[8]International Energy Agency Photovoltaic Power Systems Programme.

NPV[9], based on the 2018 survey by Grant Thorton, specifically the section concerning the Nordics (Grant Thornton UK llp, 2019). Project life was set at 25 years based on the same survey. Potential interest costs from loans to cover the initial CAPEX were not covered in this analysis.

The results were very positive, especially when using 2022 grid prices. In this case, the system led to € 732, or 40% of the daily electricity expenditure, in savings. Furthermore, a potential € 4653 of revenue can be generated daily on average by selling surplus generation to the grid. Assuming constant cash inflow (implying no degradation of the panels and constant price of electricity) and accounting for O&M[10] costs, the NPV for the project would be € 7 916 094 (IRR[11] of 9.96%) when using residential prices, or € 15 574 387 (IRR of 20.39%) when using commercial prices. This is a staggeringly positive result and indicates that the project would be a good investment, even when taking into consideration the degradation of the panels' output. It is also important to consider that, as shown previously, the electricity output estimates from the SAM simulations are very conservative, and it is thus reasonable to expect a higher yield from the real system.

The results are predictably heavily dependent on the price of electricity. When performing the same analysis using the commercial application prices and electricity prices that reflect the average hourly values of the prices from 2011 to 2022, the results are very different. In this case the NPV is € -1 914 752, and the IRR is 3.32%. This shows that careful consideration of risks is required before an investment of this size. A power purchase agreement[12] would eliminate the risks posed by volatile electricity prices, and some are being granted for large scale PV projects in Sweden (Frii and Göransson, 2021). However, it is unclear whether a project of this size would classify for such an agreement.

Economic analyses were also performed in SAM, where both hourly and monthly purchase/sale prices were used. The same financial parameters as the Excel analyses were used. SAM performs simulations on an hour-by-hour basis, considering production, load, and grid prices. It also considers degradation and losses.

When simulating the port purchasing and selling electricity at hourly spot prices, results closely resemble those from the Excel analysis. The NPV for the project when using commercial installation prices and 2022 grid prices was € 15 418 052, which is within 1% of the result obtained in Excel. SAM also provides plenty of other useful data, such as

[9]Net present value, defined by Gallo (2014) as "the present value of the cash flows at the required rate of return of your project compared to your initial investment." It is a commonly used metric to financially assess and compare projects when making investment decisions. Financial analysts favor it as it considers the time value of money and allows for effortless comparison between projects (Gallo, 2014). It is calculated as:

$$NPV = \sum \frac{Cash\ Flow\ Year\ n}{(1 + Discount\ Rate)^n}$$

[10]Operations and maintenance.

[11]Internal rate of return, it is the discount rate for which the NPV of the project would be € 0.

[12]A long-term agreement to purchase clean energy from a specific asset at a predetermined price between a renewable developer and a consumer (Iberdrola, 2023).

the simple and discounted payback periods, capacity factors, LCOE[13] and electricity bills. These are reported in Table 4.2.

Table 4.2: Results of the SAM simulation and economic analysis using hourly purchase and sale prices of electricity

Metric	**Value**
Annual AC energy in Year 1	11,358,419 kWh
DC capacity factor in Year 1	10.4%
Energy yield in Year 1	914 kWh/kW
LCOE Levelized cost of energy nominal	7.69 ¢/kWh
LCOE Levelized cost of energy real	6.08 ¢/kWh
Electricity bill without system (year 1)	646,629
Electricity bill with system (year 1)	€ -1,295,378
Net savings with system (year 1)	€ 1,942,008
Net present value	€ 15,418,052
Simple payback period	3.9 years
Discounted payback period	5.0 years
Net capital cost	€ 10,471,032
Equity	€ 10,471,032
Debt	€ 0

The scenario using monthly sale/purchase prices yields similarly positive results, reported in Table 4.3, but with some interesting takeaways. Firstly, it is interesting to see that the electricity bill without the PV system is higher than in the previous case, proving once again that it would be more convenient for the port to purchase its electricity at hourly spot price rather than monthly, as shown previously in Section 3.1. With the system installed, the results are once again positive, but the economic parameters are appreciably worse across the board compared to the previous scenario. These results highlight the importance of switching, if possible, to hourly billing, as the loss would be significant when installing such a large system (amounting to around € 155 000 per year).

[13]Levelized cost of electricity. It is the sale price of electricity required for a project's revenue to equal its cost, including the effects of discount rate (Ghose and Franchetti, 2018; Papapetrou et al., 2017).

Table 4.3: Results of the SAM simulation and economic analysis using monthly purchase and sale prices of electricity

Metric	**Value**
Annual AC energy in Year 1	11,358,419 kWh
DC capacity factor in Year 1	10.4%
Energy yield in Year 1	914 kWh/kW
LCOE Levelized cost of energy nominal	7.69 ¢/kWh
LCOE Levelized cost of energy real	6.08 ¢/kWh
Electricity bill without system (year 1)	€ 694,814
Electricity bill with system (year 1)	€ -1,139,723
Net savings with system (year 1)	€ 1,834,536
Net present value	€ 14,074,830
Simple payback period	4.1 years
Discounted payback period	5.3 years
Net capital cost	€ 10,471,032
Equity	€ 10,471,032
Debt	€ 0

An additional economic analysis was performed, integrating this system with hydrogen production via electrolysis. This analysis is discussed in chapter 4.3.1.

4.2.2 Wind power

The windy and flat nature of the area the port is located in makes it an ideal candidate for wind power installations. In fact, the port has been considering the installation of two wind turbines on the eastern bank, a project which is currently awaiting approval from municipal authorities.

The wind resource in Trelleborg is unquestionably powerful, but has been somewhat hard to quantify precisely. In fact, only one weather station appears to exist within the city, but data from it has proven arduous to retrieve. Nevertheless, different sources have been used to gain an understanding of the potential in the area. Firstly, a report was obtained from the Swedish Meteorological and Hydrological Institute (SMHI) weather station in Falsterbo, 21 km west of the port. The report provided a wind rose and wind speed data for the years 2009 to 2018. This shows the prevalent wind direction to be west, and an average wind speed at the site of 6.78 m/s. Data was also gathered from a former SMHI weather station in Maglarp, 6 km west from the port. The data was recorded between 1986 and 1995. The wind rose obtained after processing this data looked very similar to that measured at the Falsterbo weather station. The average wind speed recorded by the Maglarp weather station was 6.54 m/s. Finally, the last set of data analyzed was obtained from the Global Wind Atlas (GWA). The GWA is a tool developed by the Technical University of Denmark and The World Bank which uses a downscaling process to provide approximate wind data for use in wind development projects. Starting from atmospheric re-analysis data gathered by the ERA5 dataset from the European Centre for Medium-Range Weather Forecasts

(ECMWF), various models and generalizations are applied to obtain a generalized wind climate which aims to capture both mesoscale and microscale effects. Consequently, the data obtained from the GWA is not directly based on measurements, but rather a larger scale model which calculates wind conditions at the specified location. The data gathered was once again very similar, with an average wind speed within the port area of 6.52 m/s and a wind rose which resembles the other two. One noticeable difference is that the GWA wind rose presents a higher frequency of south-western wind as opposed to the other two. Despite this, the correlation is still good, as the wind rose for the Maglarp station also showed a more pronounced peak in the southwestern direction compared to Falsterbo, albeit to a lesser degree.

As mentioned, a study was already conducted to assess the possibility of erecting two wind turbines on the eastern shore of the port. The study demonstrated the promise of the project, as many positives were gathered from it. Most notably, it was concluded that the turbines would cause minimal additional shading and sound pollution, as well as have a small visual impact on the area. The biggest hurdles were posed by security clearance from the Swedish military, which requires the turbines to be shorter than 120 m, and the risk of ice throw during winter months. A further study on ice throw showed that with the ice detection system equipped on the chosen turbines, and proper operational security measures and signage, the risk posed by the ice throw would be within acceptable limits. The first issue is on the other hand solved simply by choosing smaller turbines, such as the range provided by ENERCON.

Simulations were run to assess the potential production and production patterns of the planned turbines. The turbines were placed in the positions proposed by the previously mentioned study. Multiple simulations were run with different parameters, such as different turbine models (Enercon E82 E2 or E82 E4), different electricity prices and wind speeds. All simulations were run using a Rayleigh distribution for the wind resource, and thus can only provide a year-round estimate of the system's production. For more detailed, hour-by-hour numbers, more accurate wind measurements would be needed.

Firstly, a simulation was run using the same stated wind speed as was used in the external study in order to validate the results of the simulation software. This consisted in an average annual wind speed at the hub height of the turbines (78m for both models) of 7.9 m/s. The study did not state what kind of distribution was used for the wind resource, so a standard k value of 2 was used for the Weibull curve, thus making it a Rayleigh distribution. This is a common distribution used when little information is available on an area's wind resource. Wake was considered, though given the spacing and layout of the turbines its effect is negligible. Included losses are reported in Table 4.4.

Table 4.4: Losses included in the wind turbine simulations

Loss Type	Loss %
Availability	3.58
Electrical efficiency	0.5
Electrical parasitic consumption	0.1
Icing	0.21
Environmental	0.4
Degradation	1.8

The results match those of the external study, with an annual AC electricity production and capacity factor of 17 602 MWh and 33.3%, and 16 356 MWh and 39.7% for the E4 and E2 models respectively. While there is an apparent variance in the monthly energy production as shown in Figure 4.7, this is simply due to the differing lengths of months, as the simulation uses a single value for daily average production.

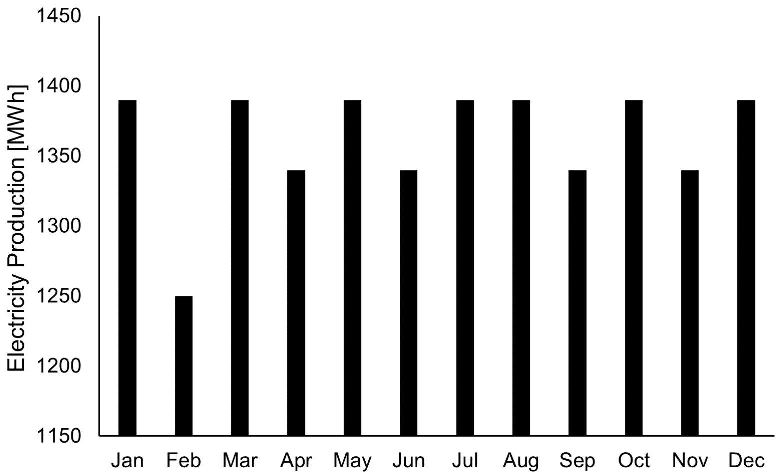


Figure 4.7: Simulated wind production throughout the year

An economic analysis was also performed for these simulations. The installation cost was set at 1200 € /kW and the operating cost at 42 €/kW-year, after parsing multiple sources (Brindley, 2022; A. Duffy et al., 2020; IRENA, 2022; Riva et al., 2018; Stehly and P. Duffy, 2022; Valpy and English, 2017; Wiser and Bolinger, 2022). Electricity rates were set to the 2022 monthly average spot prices, both for purchase and sale, to emulate the port's real agreements. Discount rate was set at 6.4% based on (Grant Thornton UK llp, 2019). Inflation rate was set at 2.5%. No incentives or depreciation were considered, as well as no debt. The load was based on the port's 2022 load.

The economic analysis gave positive results, with an NPV of € 21 937 960 and € 21 870 856 for the E4 and E2 models respectively. Given the higher capacity factor and lower capital cost of the E2 model, the LCOE was lower for that configuration: 3.98 ¢/kWh against the 4.72 ¢/kWh of the system with the E4 turbines. In reality, the NPV may be lower as it is likely that the port may take out a loan to cover the initial capital cost, as it exceeds 5 or 7 million euros depending on the configuration. Furthermore, sales tax and insurance may also affect the NPV negatively. On the other hand, incentives may facilitate the investment and thus increase the NPV, as would having a salvage value for the system at the end of life, which for the current simulation was set to € 0. Altogether, the simulation paints the wind turbines as a promising investment for the port.

The simulation was also run using the average wind speed measured by the Maglarp weather station, applied to a Raleigh distribution. As the average wind speed was higher, the annual production and capacity factors were also better, equaling 16 942 MWh and 41.2% respectively for the E2 model, and 18 316 MWh and 34.6% for the E4 model. Predictably, the NPVs were also higher, being € 22 942 710 and € 23 168 136 respectively. The LCOE were also lower across the board.

Finally, a simulation was run using the average electricity rates from 2010 to 2022 instead of using only the 2022 ones, and the wind data from Maglarp. These were much lower, as the electricity prices in the area have increased sharply in 2022. Consequently, the profitability of the investment was also lower: the resulting NPV was € 1 888 862 for the E2 model and € 407 450 for the E4 model. While significantly lower than in the previous cases, the NPVs were still strikingly positive, demonstrating the long-term safety of the investment even in the scenario of electricity prices returning to pre-2022 levels.

The results of the different simulations are summarized in Table 4.5.

Table 4.5: Results of the different wind simulations

Metric	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Wind data	External study	External study	Maglarp	Maglarp	Maglarp	Maglarp
Wind distribution	Raleigh	Raleigh	Raleigh	Raleigh	Raleigh	Raleigh
Wind turbine model	Enercon E82 E2	Enercon E82 E4	Enercon E82 E2	Enercon E82 E4	Enercon E82 E2	Enercon E82 E4
Electricity rates	2022	2022	2022	2022	2010-2022	2010-2022
Annual AC energy in Year 1	16,355,607 kWh	17,602,756 kWh	16,942,278 kWh	18,315,790 kWh	16,942,278 kWh	18,315,790 kWh
Capacity	4,700 kW	6,040 kW	4,700 kW	6,040 kW	4,700 kW	6,040 kW
Capacity factor in Year 1	39.70%	33.30%	41.20%	34.60%	41.20%	34.60%
LCOE nominal	5.01 ¢/kWh	5.94 ¢/kWh	4.84 ¢/kWh	5.75 ¢/kWh	4.84 ¢/kWh	5.75 ¢/kWh
LCOE real	3.98 ¢/kWh	4.72 ¢/kWh	3.84 ¢/kWh	4.57 ¢/kWh	3.84 ¢/kWh	4.57 ¢/kWh
Electricity bill without system (year 1)	€ 694,952.00	€ 694,952.00	€ 694,952.00	€ 694,952.00	€ 231,936.00	€ 231,936.00
Electricity bill with system (year 1)	-€ 1,792,865.00	-€ 1,982,566.00	-€ 1,882,102.00	-€ 2,091,024.00	-€ 592,278.00	-€ 659,097.00
Net savings with system (year 1)	€ 2,487,817.00	€ 2,677,518.00	€ 2,577,054.00	€ 2,785,976.00	€ 824,214.00	€ 891,033.00
Net present value	€ 21,870,856.00	€ 21,937,960.00	€ 22,942,710.00	€ 23,168,136.00	€ 1,888,862.00	€ 407,450.00
Simple payback period	2.4 years	2.9 years	2.3 years	2.8 years	8.2 years	10.1 years
Discounted payback period	2.8 years	3.5 years	2.7 years	3.4 years	14.4 years	22.1 years
Net capital cost	€ 5,640,000.00	€ 7,248,000.00	€ 5,640,000.00	€ 7,248,000.00	€ 5,640,000.00	€ 7,248,000.00

Unfortunately, the risk of ice throw highlighted by the previously mentioned study prevents the installation of additional wind turbines in other busier parts of the port. Therefore, this study did not venture further into possible installations, as they would pose too high a risk to the personnel and customers of the port. One potential solution to this problem would be to prevent the operation of the turbines during days when the risk of ice throw is particularly pronounced. However, another thorough risk analysis would have to be carried out to determine the viability of this solution. Another alternative to capitalize on the wind resource in the area would be to install near-shore turbines. However, this project would be of larger scope, and would need to be carried forward in close collaboration with the municipality, as the land would not be directly owned by the port. Furthermore, the visual impact would potentially be more significant, as the turbines would not blend into the industrial background as they do on the port premises. For this reason, no further research on such an installation was performed.

4.2.3 Tri-generation fuel cell

One interesting novel solution that has been considered for the Port of Trelleborg is a tri-generation fuel cell. This is a particular type of fuel cell which produces electricity, heat and hydrogen using natural gas or biogas as an input. The technology is still in its infancy, though there are instances of its successful adoption: examples are the Port of Long Beach in California ("FuelCell Energy Trigen System for Toyota at Long Beach" 2017) and the Fountain Valley energy station, also in California (U.S. Department of Energy, 2016).

Originally, the idea was to capitalize on the presence of the wastewater treatment plant within the premises of the port to produce biogas, which in turn could be used in the fuel cell to produce electricity for the port, heat for its buildings and hydrogen to be sold to trucks or used as fuel by the port's yard tractors. Such a solution would make full use of the resources generated by the port, and provide it with heightened energy independence.

Running a preliminary study on the feasibility of this solution, however, revealed that the size of the wastewater treatment plant would not be able to support this type of operation. In fact, based on the measurements taken by the company installing the plant, the average incoming flow of wastewater is 348 m3 per day, which when considering its composition corresponds to 1874 pe/day [14]. According to Bachmann (2015), expected biogas production rates from anaerobic digestion are between 18-26 l/pe. Using a value of 22 lbiogas/pe yields a daily biogas production of 41 278 l/day. Both Bachmann (2015) and Swedish Gas Technology Centre Ltd (2012) indicate a methane content in biogas produced from anaerobic digestion in the range of 60 – 70 %. A biogas with a methane content of 65 % would have an energy content of 6.5 kWh/m3 (Swedish Gas Technology Centre Ltd, 2012), and thus the daily energy output in the form of biogas of the port's WWTP would be of around 268 kWh/day. While this is not a small amount of energy, even with a 100 % conversion efficiency it would only cover 2 % of the port's daily electricity needs. This is too little to justify the large investment needed to add an anaerobic digestion step to the treatment plant. As a reference, according to the numbers provided by Leo and Fuel Cell Energy (2023), the company behind the tri-generation fuel cell system in Long Beach, to

[14] Population equivalent, a parameter quantifying the pollution potential of a wastewater flow by quantifying the population size that would produce the equivalent polluting load. It is calculated as:
$PE = \frac{BOD\,load\,in\,flow\,(kg/d)}{per\,capita\,BOD\,load\,(kg/inhab.d)}$ (Von Sperling, 2007).
In Sweden, the pe is calculated using a per capita BOD7 load of 70 gr/inhabitant-day (Naturvårdsverket, n.d.[b]).

produce 1 MW of electricity a fuel input of 2.61 MW would be needed. This is order of magnitude larger than what would be produced by the WWTP. Bachmann (2015) provides an example of a large scale WWTP (100 000 pe, 50 times larger than the planned installation in the port) equipped with anaerobic digestion. Even such a large plant would produce 5 694 MWh/year, which if distributed equally would equate to an average biogas output of 0.65 MW, not enough to fulfil the port's electricity needs.

Given the results of this study, it was clear that the only feasible way to run a tri-generation fuel cell in the port would be with gas purchased from the grid. This would remove the energy independence virtue of the solution. Nonetheless, such a fuel cell remains interesting as its outputs and their proportions align with the interests of the port. For this reason, another study was conducted analyzing the economic feasibility of such a system when ran on gas purchased from the gas grid. This is how the system in Long Beach is run, where the port establishes sources of renewable biogas throughout the state which inject the biogas in the grid, and they extract the same amount of gas from the grid to run their fuel cell (Elinstallatoren SE, 2019). In Trelleborg, a similar arrangement could be set up by, for example, purchasing gas from e.on, who guarantees a supply of 100 % renewable biogas (E.ON Energy Solutions, 2021).

An initial economic analysis was performed on this last setup. It was assumed that the fuel cell system would have an AC output of 1 MW, to cover the current electricity needs of the port fully as well as prepare for increased demand in the future. The input and production values were based off of the white paper by Leo and Fuel Cell Energy (2023). CAPEX and OPEX prices for the fuel cell were based on Papadias et al. (2015) and are shown in Table 4.6. Total project lifetime was set at 20 years, and replacement of components with shorter lifetimes was considered in the relevant annuities. These were the stack, replaced every five years, and the compressor and dispenser, replaced every ten years (Papadias et al., 2015). Availability losses due to replacement are assumed to be included in the O&M costs. A relatively high discount rate of 8% was used. It was assumed that the fuel cell runs 24/7, and that all surplus electricity and hydrogen is sold. Hydrogen price was set at € 10/kgH2, based on Hydrogen Fuel Cell Partnership (n.d.) and Alpman (2021). The prices for gas were sourced from E.ON Energilösningar (2023) and ApportGas AB (2023). The electricity prices were sourced from Nordpool and separated into average annual hourly value in the same way as in chapter 4.2.1. Water produced by the fuel cell is considered as a saved expense, while heat is not considered in the financial analysis as no data on expenditure on heat in the port was available. The fuel cell is assumed to produce 0.07 MW of usable heat per day, according to Leo and Fuel Cell Energy (2023).

Table 4.6: Parameters for the techno-economic analysis of the tri-generation fuel cell system

Parameter	**Value**
Fuel Cell Size (kW)	1000
Specific Price of Fuel Cell (€/kWe)	1320
Fuel Cell Price (€)	1320000
FC[15] Stack Price %	28%
FC BOP[16] Price %	42%
FC Remaining Price %	30%
FC Stack Price (€)	369600
Compression, Storage, Dispensing (CSD) (€/kWe)	1658
CSD + PSA[17] (€/kWe)	1932
Storage Price %	13%
Dispenser Price %	10%
Compressor Price %	34%
Refrigeration Price %	10%
Control, Electrical, Piping Price %	17%
PSA Price %	16%
CSD + PSA Total Price (€)	1931633
Compression, Refrigeration, PSA, Control Price (€)	1487357
Discount Rate	8%
O&M Cost (% of Capital Cost)	6.50%

Firstly, an analysis was attempted using 2022 prices for gas and electricity. This immediately showed negative results, as the installation did not generate any daily profit due to the inflated price of gas. For reference, the 2019 prices were 13% and 29% of the 2022 prices for natural gas and biogas, respectively. NPV and IRR considerations were not attempted in this scenario, as the system shows net losses across the board.

However, when performing the analysis using 2019 prices for both gas and electricity, the results are quite the opposite. Given the significantly lower price of gas in this scenario, the value proposition for the project soars. Due to the much lower price of electricity in 2019 compared to 2022 (the average daily price in 2019 was 42% of the average daily price in 2022) the savings and earnings related to electricity are much lower. Nevertheless, this configuration leads to a daily profit of € 5 292 when using natural gas, or € 3 381 when using biogas. The main revenue source is the sale of hydrogen, which generates € 5 521 daily. The fuel cell would save the port € 500 in electricity, as well as earn an additional € 463 through surplus electricity production every day. Performing a discounted cash flow analysis, a NPV of € 11 830 529 and IRR of 52% were obtained for natural gas, and an NPV of € 5 485 730 and an IRR of 30% for biogas. This would indicate that the fuel cell would be a promising investment for the port. However, this relies heavily on all the hydrogen being sold at €10/kgH2, which might not be attainable in reality as the demand

[15]Fuel cell.

[16]Balance of plant. Includes compressors and pumps, heat exchangers, reactors and the DC/AC inverter. The latter is one of the major contributors to the cost, alongside the raffinate compressor, shift reactor and desulfurizer.

[17]Pressure swing adsorption, the system use to purify the H2.

from the transport sector is not yet there. Furthermore, this assumes that the price of gas is stable at 2019 levels; while this may have been a fair assumption seeing the historical trends before the last few years, the market is more complicated and harder to predict at present, and thus makes the investment in this technology much riskier.

4.3 Energy storage and fuel production

4.3.1 On-site hydrogen production through electrolysis

Hydrogen is a hotly debated topic in the municipality of Trelleborg. In fact, the municipality wants hydrogen to become an important part of its economy in the coming years, with abundant production and storage within its territory. Given the port's significance to the area and its potential for electricity generation, integrating hydrogen production might be an excellent strategy to satisfy both the municipality and the port's interests. Because of the commitment to lowering emissions, the most appropriate production technology would be electrolysis. Electrolysis is defined as "the use of electric current to stimulate a non-spontaneous reaction" (Kimberly Song, 2020) and is used in this case to decompose water into hydrogen and oxygen, according to the reaction (CK12, 2023):

$$2H_2O(l) + electrical\,energy \rightarrow 2H_2(g) + O_2(g) \tag{4.1}$$

The reaction is performed in electrolytic cells consisting in their most basic form of platinum electrodes immersed in water mixed with a small amount of electrolyte like H2SO4 to facilitate the carrying of charge (CK12, 2023). Multiple cells are combined to obtain an electrolyser. Different technologies for electrolysis exist today, with the most widespread being alkaline electrolysis, proton exchange membrane electrolysis and solid oxide electrolysis. The differences between them mainly concern temperature and pH of the reaction, which in turn affect the designs of the cells and the materials used for cathode, anode and electrolyte (Amores et al., 2021). Additionally, complementary systems must be added to ensure the proper functioning of the electrolyser stack. These include:

- Gas-liquid separation subsystem.
- Deionized water subsystem.
- Pressure control subsystem.
- Thermal management subsystem.
- Drying subsystem.
- Purification subsystem.
- Gas analysis subsystem.

- Power supply subsystem.
- Monitoring and control subsystem.

Regardless, the port's main concern would be that of supplying the resources needed to complete the reaction. These are electricity and fresh water. The former could be provided by the renewable energy sources that have been proposed in the previous chapter. Depending on the sensitivity of the electrolyser to the volatility of the power supply, it could only be operated when there is a surplus of electricity, or it could be in constant operation, using grid electricity to supplement the internal energy supply when needed. Fresh water can be purchased directly from the municipality, as the infrastructure for its supply is already present in the port. The fresh water would be later purified within the electrolysis system to be suitable for use in the electrolyser stack. Research is ongoing to allow for seawater to be used directly for hydrogen electrolysis, which might be an interesting prospect for the port, but the technology is still far from commercial adoption and has thus not been considered for this study (Savage, 2023).

There are numerous suppliers of hydrogen electrolysers, with global electrolyser manufacturing capacity reaching 8 GW per year in 2021 (IEA, 2022a). For this reason, it is hard to get an accurate estimation of the cost and efficiency of a system without requesting a quote from local manufacturers. Nonetheless, plenty of market information on these parameters is available from different sources. For this study, numbers were mainly retrieved from Potsdam Institute for Climate Impact Research (2023), U.K. Department of Business, Energy & Industrial Strategy (2021) and Amores et al. (2021).

An economic analysis of a possible integration between the PV system described in Section 4.2.1 and a hydrogen electrolyser was performed. The prices for the PV system were obtained from Lindahl et al. (2021) and referred to the commercial roof-mounted application. Electricity prices refer to 2022 hourly averages. For more details refer to section 4.2.1. CAPEX prices for the electrolyser were sourced from the Bloomberg 2022 data found in Potsdam Institute for Climate Impact Research (2023) or the data in the assumptions annex of IEA (2019). OPEX was set at 1.5% of capital cost, based on IEA (2019). Lifetime of the stack was assumed to be 10 years (IEA, 2019), and replacement was assumed to be included in the OPEX. It was assumed that all of the produced hydrogen is sold at € 12.3/kgH2 or € 8.17/kgH2, based on Hydrogen Fuel Cell Partnership (n.d.) and Alpman (2021) respectively. A project lifetime of 25 years and a discount rate of 5.5% were considered for comparison with the scenarios in chapter 4.2.1. An electrolyser size of 3 MWH_2 was chosen to guarantee that all the surplus electricity from the PV modules is utilized. It was assumed that the electrolyser produced hydrogen only using surplus electricity from the PV modules and was thus not in constant operation. The effects of such operating conditions are not yet fully understood, but it is suspected that it may lead to accelerated degradation and lower performance (Kojima et al., 2023). Compression and distribution were not considered in this analysis as clear figures for this application could not be obtained; these would nevertheless add further costs for both installation and maintenance.

The results of the discounted cash flow analysis described are reported in Table 4.7:

Table 4.7: Results of the discounted cash flow analysis for the Pv system with hydrogen electrolysis

Parameter	Bloomberg CAPEX, HFCP Purchase Price	IEA CAPEX, HFCP Purchase Price	Bloomberg CAPEX, Alpman Purchase Price	IEA CAPEX, Alpman Purchase Price
NPV	€ 19 608 186	€ 17 972 098	€ 9 766 162	€ 8 130 074
IRR	21%	18%	13%	11%

The figures show that, with the assumptions above, a PV and electrolyser system could be a worthwhile investment for the port. As mentioned, this scenario ignores various added expenses such as compression and distribution, and assumes that all the hydrogen is sold at the set purchase price, which might be unlikely. When comparing these results to the equivalent configuration with direct sale of surplus electricity to the grid at spot price described in chapter 4.2.1, the results are quite similar: that configuration had an NPV of € 21 851 832 and an IRR of 20.39%. However, given the added complexity of the system and the numerous assumptions made for the electrolyser-integrated system, it is hard to justify choosing it over the simpler and safer grid-selling solution. Nevertheless, if significant incentives were to be provided to produce hydrogen, such as a guaranteed, fixed sale price, this solution may be of interest to the port as it does provide a good economic value.

4.3.2 Battery energy storage

Battery energy storage may be beneficial for the port as a tool for load shifting and to support the potential charging of ferries without overloading the grid connection. Large scale batteries are becoming increasingly more common and cheaper, and thus may be a viable investment for the port. As it stands, since the port purchases and sells electricity at the average monthly price, installing a battery would not bring any evident benefit. If, however, the port was to switch to an hourly electricity contract, then a battery may prove a valuable investment.

The value proposition of batteries has soared in 2022, as prices for electricity have risen, and fluctuations have been larger than ever. Moreover, with the port's plans for added electricity generation, and the forecasted increase in electricity demand due to the increased cold ironing of ferries and the electrification of internal trucks, the presence of a battery would allow the port to shift its spending and earning at times when it is more economically convenient, potentially having a large economic impact. For example, if the port were to install a large photovoltaic panel system, the electricity generated could be sold in the evenings when the market spot price is high, rather than in the middle of the day when the electricity is produced and the selling prices are lower. Or else, the electricity generated could be stored in the battery in order to cover the cold ironing needs of a specific vessel which is planned to moor at times when the spot price for electricity is high and the port is not generating enough to sustain the load.

What a battery offers is increased flexibility and control over one's electricity signature, but this comes at a hefty cost. Hence, a thorough economic analysis has to be performed to assess whether or not the investment is a good one, and how risky the investment may be.

A techno-economic analysis of a battery storage system combined with the PV system described in chapter 4.2.1 was performed. The study was based on the port's current load, as it is difficult to predict with certainty how cold ironing may affect the electricity demand, as explained in chapter 3.1.1. To simulate the battery, the REopt tool included with SAM was used. The tool automatically generates the optimal size, power and dispatch strategy for the battery based on the system design, costs, electricity rates and load.

The chosen battery technology was lithium-ion, as it has become the primary chemistry for stationary storage starting in 2021 (National Renewable Energy Laboratory, 2023). The battery costs were based on National Renewable Energy Laboratory (2023), using the figures referring to the 2023 market offerings for the "Moderate" scenario. For the battery, these amounted to 1 433.4 €/kW installation costs and 35.84 €/kW-yr operating costs (exchange rate adjusted as of 24-04-2023). The O&M costs also include battery replacement based on measured battery degradation rates. For more information about the components of the cost estimates view the source. The REopt algorithm selected a 4-hour battery with a capacity of 7725 kWhac and 1864 kWac. The discount rate remained unchanged from the analysis in chapter 4.2.1 for ease of comparison, amounting to 5.5% before adjusting for inflation, itself set at 2.5%.

Unfortunately, the results from the simulation were unsatisfactory. It was noticed that the cash flows in the simulation of the system with batteries were smaller than in the system without batteries, completely erasing the value proposition of the battery system. After thorough examination, this was attributed to the dispatch strategy generated by REopt, which was seemingly not the optimal one. As such strategies are results of complicated multi-variable optimization problems, it was not possible to develop an alternative strategy manually, and the results from the simulation had to be scrapped.

Nonetheless, previous studies have shown that as of 2023, the capital cost of batteries is still too high to be worth installing from a purely financial perspective (Braeuer et al., 2019; Komorowska et al., 2022; Zhao et al., 2023). That said, the price of batteries is falling rapidly, and the benefits of the technology are numerous, so it is a field worth monitoring for the future.

Chapter 5

Discussion

The results from the studies presented can be analyzed from a more general perspective to make some considerations on strategies that may be effective in RoRo ports across the world.

Firstly, it seems likely that electricity will play an increasingly important role in ports worldwide. With environmentally conscious measures becoming increasingly necessary to combat climate change, and many in the transport industry seeing electricity as the key to transitioning to zero-emissions operation, the electrical demand seen in ports has the potential to skyrocket. Ports should prepare for this increased demand by strengthening their existing electrical infrastructure, as well as integrating it with on-site electricity generation, smart load management strategies and potentially on-site energy storage. Furthermore, depending on the direction taken by the maritime and road transport industries, demand for alternative fuels may rise significantly, and so will the need to accommodate them within the port's infrastructure. However, it may be unwise to commit on investing fuel-related projects before the direction taken by these industries is clearer.

It is evident that RoRo ports are perfectly suited for solar PV generation. Even in Trelleborg, whose weather conditions are not necessarily ideal for this technology, the investment proved to be profitable in almost any scenario. The vast open areas available in such ports, combined with minimal shading and relative freedom of design for the photovoltaic installations, means that it is possible to maximize the electricity production potential of the installed modules. This means that, considering the falling prices for modules and inverters, the long operational life of the systems, and the relative reliability of production, large scale photovoltaic installations would be a great investment for most RoRo ports, and one that would provide great value both to the port and to the region surrounding it.

On-site wind power generation is also another area where RoRo ports have great potential. The layout of these ports, with large open areas both on the seaside and on land, means that the wind will be undisturbed by the terrain's roughness and thus be stronger. Ports' position on coasts is not only advantageous for wind speed, which is often higher than inland, but also for the ease of supply and construction of wind turbines. Direct access to the sea means that the turbines can be raised without the need for land transport, lowering costs and enabling the construction of larger turbines without incurring road transport size limits. Furthermore, the industrial nature of port areas minimizes concerns about shading and aesthetic impact, as the wind turbines tend to blend into the environment, and residential buildings are rarely close enough to be impacted by the turbine's shadow. Sound is believed to be a minor issue, as ports' noise levels are generally quite high to begin with. Nonetheless, large installations may close in to noise limits, and thus studies should be done to ensure that these are respected. The biggest limitation for the deployment of more wind turbines in the Port of Trelleborg was the risk of ice throw, which could pose a security risk to the port's personnel. While this issue may arise in other ports in colder climates, ports that are located in more temperate environments will not have to face it. For these ports, on-site wind turbines may be a great investment to increase their energy independence and facilitate their regions' transition to clean energy without any major impact on the land. As wind energy is generally more consistent in its production compared to solar energy, a large enough installation could realistically cover the port's energy needs year-round, with plenty of surplus which could be sold to the grid or used internally to produce fuels or other energy-intensive products.

Tri-generation fuel cells may offer an interesting value proposition to ports. While it seems unsustainable for most ports to feed the fuel cells with locally produced biogas, external supply from the gas grid is a potentially profitable option. The fuel cell offers more flexibility in electricity generation compared to solar or wind power and has the added advantage of the auxiliary flows of hydrogen, which could be sold to heavy duty trucks, and heat, which can be used for the port's buildings. Moreover, if supplied by port owned sources or supplemented with sizeable fuel storage, the fuel cell can provide temporary independence from the grid in emergency situation, increasing the port's energy resilience. The distribution of the electricity and heat flows generally matches the demands of ports, which require a large amount of electricity and a comparatively small amount of heat. The hydrogen may be sold to heavy duty trucks and passenger cars if the industry moves towards that direction, or alternatively sold to the numerous other markets which make use of it. The profitability of this solution is heavily dependent on the demand for hydrogen, and consequently its sale price, and the costs of gas. In 2022, gas prices skyrocketed, making this proposal impractical. Nevertheless, tri-generations fuel cells should still be considered as an option by ports in regions where gas prices are relatively stable and are not predicted to increase, as well as for regions where prices are forecasted to eventually drop back in line with the trends seen pre-2021. It may be wise to wait and see how the long-haul road transport industry develops before investing in such a technology, to ensure the sale of hydrogen at a competitive price. However, if ports are in a region with strong interest in hydrogen and can guarantee that the hydrogen they produce is purchased consistently at a good price, then this technology may be worth investing in forthwith.

The value proposition of on-site hydrogen production through electrolysis will depend entirely on the relative price of electricity and hydrogen. As an electrolyser system entails a significant investment cost, and electrolysis inevitably leads to the loss of some of the energy inputted, the sale price of hydrogen would have to be significantly higher than that of electricity to justify the investment. Furthermore, the added complexity in the system may discourage the investment further, as it would increase operational costs and require significantly more involvement. On the other hand, if the road transport industry shifts to hydrogen as its main fuel in its process of decarbonization, then investing in an electrolyser may be a very good idea to have a steady supply and not be subject to market prices. This would allow ports to sell hydrogen to trucks at a competitive price and with potentially significant margins, as well as supply their own internal equipment with the fuel if needed. In conclusion, electrolysers should be kept in mind as a potential future investment for ports, especially if interest for hydrogen in the region is high.

Given the low potential for wave generation in the Port of Trelleborg and the uncertainty on commercial availability of generators, no study was done on a potential installation in the port. Other ports, especially those in areas with high wave energy potential, should consider performing preliminary studies to integrate this technology in their premises, as it could be an interesting addition to their electrical grids given its good base load generation potential.

In terms of emissions reduction, RoRo ports do not have many options outside of the port handling equipment, specifically the yard tractors. At the moment, this action is limited by the lack of suitable offerings by manufacturers. However, it is likely that in the future such offerings will become available, as electric vehicles for similar applications are already commercially available. A transition to electric or hydrogen powered vehicles would entail a significant reduction in emissions generated by ports themselves, bringing them closer to zero-emission operation. It could also mean a reduction in operational costs, especially if paired with on-site RES for power generation. On the other hand, the switch from fossil fuels would warrant a significant investment in infrastructure to support the charging or refueling of the tractors. There are also concerns about the range of vehicles, especially battery powered, which might force ports to expand their fleet in order to maintain current operational efficiency. Clearer conclusions on this solution will be reached once electric or fuel cell powered RoRo tractors become commercially available, and a proper techno-economic analysis can be performed.

Chapter 6

Conclusion

This thesis had two main objectives: to inventory and analyze the energy flows in the port of Trelleborg, and to propose energy-related development strategies based on the collected data. Throughout the text, both of these objectives were accomplished.

Data was collected from a number of internal and external sources to quantify the energy flows in the port. The results showed a heavy presence of both fuel and electricity, the former being currently used by the port's rolling equipment and the latter being used to power most of the other equipment and facilities in the port. A smaller energy flow was found in the wastewater flow from the ferries unloading in the port; however, it is not currently economically viable to extract any of the energy it contains. Wastewater aside, the port is quite efficient with its energy usage, having adopted several energy-saving measures such as dimmable lights. The port has also started to generate its own electricity in 2020, with the installation of a first photovoltaic system, which covered around 10% of the port's electricity needs in 2022. There were also flows tangentially related to the port, such as the fuel sold to non port-owned trucks and the fuel used to refuel the ferries mooring at the port. These flows are not owned or processed by the port itself, so data for them was not available. However, estimations extrapolated from auxiliary data revealed that the magnitude of these flows is significant, and their quantification would contribute to obtaining a fuller picture of the port's complete energy ecosystem.

Throughout the duration of this study, it was made apparent that the energy flows in the port are due to change drastically in the near future. A thorough literature review and discussions with port officials revealed that as environmental measures get stricter, the demand for electricity in the port has the potential to skyrocket. The first driver for this increased demand is no doubt shore-to-ship power, with its widespread adoption being seen as one of the most immediate measures to reduce the emissions from the maritime shipping sector. By analyzing the data on the two ships currently practicing cold ironing in the port, it was possible to get an idea of how this may impact the port's electrical demand in the future. The resulting estimation saw the port's daily consumption of electricity potentially increase threefold, with a single ship's baseline load surpassing the port's peak daily loads. Furthermore, the port's emission reports revealed that the port's rolling equipment is the most likely candidate for modifications in order to lower the port's climate impact further. This may mean a conversion of the equipment to electrical propulsion, which could increase the electrical demand in the port by a significant margin, given that the energy contained by the fuels currently used by these vehicles is 1.5 times larger than the amount of electricity used in the port on a yearly basis. This, coupled with a potential increased electrical demand from non port-owned road vehicles, foretells a need for a strengthening of the port's electrical infrastructure in the near future.

Of the development strategies analyzed, the two most presently viable were the installation of wind turbines and the installation of photovoltaic panels on the roofs of the port's buildings. The former has already been planned by the port, and is awaiting approval from authorities. The planned installation of two 3 MW turbines is forecasted to produce upwards of 16 000 MWh of electricity annually, with excellent economic return. More and larger wind turbines could be beneficial for the port, but expansion was deemed unattainable due to safety concerns related to ice throw. The presence of multiple large, flat, and unshaded roofs within the port is ideal for the installation of a large photovoltaic system. The proposed system would produced upwards of 11 000 MWh per year, and showed very promising financial parameters within the current economic landscape. As with most energy projects, these installations' value proved to be susceptible to electricity grid prices, though this issue could potentially be eliminated with agreements such as a PPA.

An analysis of a potential integration of the photovoltaic system with a electrolyser-based on-site hydrogen production facility was also performed. The solution showed promise, though its success is dependent on interest in hydrogen as a fuel. Using current market prices and assuming all of the produced hydrogen was sold, the NPVs for this system were very close to those of the system selling its electricity to the grid. Depending on the direction taken by the land and maritime transport industries, this solution may be worth considering in the future, as it could provide more stability compared to selling the large amounts of surplus electricity from the previously proposed installations to the grid. Battery energy storage was also briefly analyzed. The study showed that with the current prices of the technology and the scale required to effectively support an operation of this size, batteries are not currently a good investment for the port. Nevertheless, given the rapid decline in battery prices and the increased flexibility offered by battery energy storage systems, it is worth monitoring the technology for the future.

A tri-generation fuel cell solution was also studied as it could potentially provide value to the wastewater energy stream by producing electricity, hydrogen and heat from biogas. Unfortunately, the study showed that the port's wastewater flows are much too small to support such an installation, and thus gas would need to be purchased from the grid in order to support it. This may still be a viable solution, as it could provide the port with increased energy resilience and potential temporary independence from the grid, while simultaneously producing a good amount of hydrogen to potentially be sold to vehicles and vessels. However, the profitability of this installation is highly dependent on gas prices, which means that as of 2023 it would not be a good investment. Having said that, the study showed that the solution has the potential to be profitable if gas prices return to pre-2022 levels, bearing in mind that its economic value also hinges on the market interest for hydrogen and the prices for electricity. It is nevertheless a solution worth monitoring, as its outputs may align well with the future interests of the port.

All in all, this study revealed that RoRo ports will face big challenges in the future, but that these are also great opportunities for ports to develop and flourish further. Ports should be prepared to make big changes to their energy infrastructure, with a particular focus on electricity in the short-term and alternative fuels in the long-term. Many of the proposed investments show great promise, some already in the present, and some potentially in the future. As the shipping industry continues to grow, so will the importance of ports, and a good strategy for energy development will be the key to their continued success.

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