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Electrification of the Port of Gothenburg

How will it affect the Gothenburg energy system?

Master's thesis in Sustainable Energy Systems

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Cover: Image of the Port of Gothenburg[1].

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Abstract

The purpose of this thesis is to investigate an electrification of the Port of Gothenburg and how it will impact the energy system of Gothenburg in a carbon neutral future scenario. The vehicles investigated are trucks that transport goods from and to the port, on-site machinery used for logistics inside the port and ships arriving and departing from the port. All of these will be electrified by one of three electrification options, direct electrification with batteries, hydrogen or electrofuel. Together with the literature study about these electrification options and an investigation of how the vehicles operates, each vehicle type could be paired with the most suitable electrification option/options. This data could then be transformed into load profiles that was implemented into an energy system model of the city of Gothenburg. The model is a linear optimisation model used to minimise the cost of the energy system. Because of the great uncertainty in the continued development of electrification, a number of scenarios were constructed to analyse some different paths of possible electrification. The result shows that the largest loads occur during the day and that an electrification of the port will increase the need for local electricity production and import. The import is limited to present-day capacity but will import during more hours of the year. The major part of the locally produced electricity is produced by photovoltaic solar power(PV). Since this thesis investigate the area of Gothenburg, an argument can be made that the invested capacity for PV will occupy an area not feasible for the city of Gothenburg. An upper limit on PV is therefore investigated and results in a significantly more expensive energy system.

Keywords: electrification, port, Gothenburg, trucks, ships, electricity demand, electrofuel, batteries, hydrogen.

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Simon Hansson & Martin Wall, Gothenburg, June 2022

Abbreviations

BET - Battery electric truck
CHP - Combined heat and power
EB - Electric boiler
FCT - Fuel cell truck
GT - Gas turbine
H2 - Hydrogen gas
HOB - Heat only boiler
HP - Heat pump
HVO - Hydrogenated vegetable oil
ICE - Internal combustion engine
TES - Thermal energy storage
Opt - Optimal charging scenario
OSM - On-site machinery
OSP - Onshore power
PV - Photovoltaic solar power
RoRo - Roll on/Roll off
RoPax - Roll on/Roll off passenger vessel
BEC - Battery electric cars

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1
Introduction

The thesis investigates an electrification of the Port of Gothenburg and the impact it might have on the Gothenburg energy system. The work is carried out in cooperation with the port to understand which type of loads are relevant in a future scenario where current fossil energy sources are replaced with zero emission technologies. This section presents a background to provide a context and relevance for the performed work. The section also presents the main aim of the thesis and the limitations which are set in order to present the specific questions of investigation which the thesis is based on.

1.1 Background

In recent years the impact that we humans have on the climate have gained more and more attention. Because of this, the whole world agreed that something had to be done. This realisation resulted in the Paris agreement which states that the global temperature increase should be limited to well below 2, preferably to 1.5°C, compared to pre-industrial levels[2]. But the Paris agreement had no road map or defined plan to achieve this goal. This responsibility was outsourced to each country and continent to solve themselves, which the European Union and many countries now have defined. The European Union made the European Green Deal which states that the green house gas emissions should be lowered by at least 55% by 2030 compared to 1990 levels and be completely climate neutral by 2050[3]. The slightly stricter targets set in Sweden states that Sweden should reduce green house gas emissions with 63% by 2030 compared to 1990 and be completely climate neutral in 2045[4]. In background of these goals, many companies have decided to act and try to reduce their climate impact, amongst them, Port of Gothenburg.

The main climate impact in and around the port comes from transportation and about 600 000 trucks enter the port each year. In Europe, transportation stands for about 25% of the green house gas emissions and of those emissions, about 25% are represented by heavy duty vehicles[5][6]. There are several ways of reducing these emissions but the most efficient way is perhaps to change the energy source to something that removes the tailpipe emissions entirely. HVO (Hydrogenated vegetable oil) is a biomass based diesel fuel which could replace the fossil content from the vehicles[7]. Another option, which is opted for in this thesis, is some kind of electrification which could mean the use of batteries, hydrogen or electrofuel to power the trucks instead of the regular fossil based fuels. The use of these electrification options is covered further later in the thesis. Besides heavy duty vehicles, a significant share of the European transport emissions comes from ship transport and the emissions from ships represent about 13% of the greenhouse gas emissions from the continent[8]. To reduce these emissions for both heavy duty vehicles and ships there is need for work and infrastructure which allows new technologies and ports might be a good place for this[9].

One port aiming to reduce its greenhouse gas emissions is the Port of Gothenburg. In cooperation with Volvo group, Scania and Stena Line the aim is to reduce the emissions linked to the port with 70% by 2030 in an initiative called the ”Tranzero iniative”[10]. The companies involved in the project have agreed to supply customers with fossil free technologies to ensure that the goal is met.

1.2 Aim

The aim for this thesis is to investigate the future electrification of the Port of Gothenburg and how this might affect the city energy system. The future loads will be assessed both in terms of total energy as well as how the energy is distributed over time. The aim is also to analyse the impact of these loads on the energy system of Gothenburg. This leads to two main research questions which are presented below.

- What change in electricity demand can be expected after an electrification of the port? In terms of total energy needed and how it is distributed in time.
- What is the impact of an electrification of the port on the city energy system?

1.3 Limitations

In this section the different limitations for this thesis work will be presented.

- Only consider electrification of trucks, ships and on-site machinery.
- A maximum of three electrification options per vehicle will be considered. Direct electrification, hydrogen and electrofuels.
- If hydrogen or electrofuel is opted for, all production will occur within the city energy system.
- The energy model will only include the area of Gothenburg and not consider limitations that might occur outside of this area.
- The future need of transport in Port of Gothenburg will be estimated from current levels, no advanced projections of future need will be done.

2 Literature study

This literature study will present the three vehicles categories that is investigated in this project, trucks, ships and on-site machinery. Each vehicle category was investigated in terms of what fuel that is used today and which of the three electrification options, direct electrification, hydrogen and electrofuels that might fit that vehicle in the future. Furthermore will the last section present the existing energy system model of Gothenburg that will be used in this project.

2.1 Trucks

Trucks are normally a very flexible mode of transport, they can run many short distances or long haul transportation. This wide range of flexibility is also used by the trucks visiting the port since some have deliveries in nearby areas while others may even deliver to other countries. However, when the trucks are electrified the flexibility changes. The distance the truck can run on one charge is about 300km for a battery electric truck with 540kWh battery[11] and 800km for a fuel cell truck (FCT) with 70kg hydrogen[12]. The range of an electrofuel truck will depend on what type of electrofuel that is opted for, since different electrofuels will have different properties. Two different carbon neutral fuels that can be used for trucks are HVO and methanol. HVO is however mainly produced from biomass instead of electricity and therefore, the focus in this study will be on methanol [13]. Methanol have an energy density of about half of regular diesel[14]. Half the energy density should give about half the range of a regular diesel truck, which based on a tank size of 900 liters and a fuel consumption of 30 liters/100km would have a range of 3000km[15][16].

Looking at the total efficiency for the different truck electrification options, it is clear that BETs are the most efficient. The BETs have a charging efficiency of about 95% and consumes 1,8kWh$_{el}$/km which would mean a total of 1,9kWh$_{el}$/km from the grid[11][17]. The FCT will instead have a 75% efficiency in the process of producing hydrogen through electrolysis and will consume 87,5g$_{H2}$/km[12][13]. Given the gravametric energy density of hydrogen of 120MJ/kg is 87,5g$_{H2}$/km equal to 2,9kWh$_{H2}$/km which in turn is equal to 3,9kWh$_{el}$/km if the electrolyser is operating at an efficiency of 75%[18]. A truck using methanol as fuel can have the same or even higher efficiency than a regular diesel truck[19]. If a regular diesel truck consumes 30L/100km and diesel have a volumetric energy density of 38,6MJ/L, it would mean that the regular diesel truck will consume 3,2kWh$_{diesel}$/km[20]. Given that methanol trucks should be able to have the same efficiency it would mean that the consumption for a diesel truck also would be 3,2kWh$_{M}$/km. The methanol production have a power to methanol efficiency of 65%, which would give the methanol truck a need of 4,9kWh$_{el}$/km[13].

Another important factor when observing BETs is the charging time. The BET will take 2,5 hours to fully charge the battery with fast charging technology that exist today[11]. There are however many projects in progress today that aims to build chargers, faster than the ones existing today. One example is the CHARIN association who aims to construct a megawatt charging system that will have a maximum charging capacity of 3,75MW[21]. If this system could be adapted to the current batteries it would mean a charging time of less than ten minutes. The charging time will not be a problem for FCTs since the existing system for refilling an FCT takes about 15 minutes[12] which is marginally longer than what it takes to refuel a diesel truck. This should not be a problem for trucks using methanol either since methanol is liquid at atmospheric conditions and have similar properties to regular diesel and therefore simple to handle[14].

2.2 Ships

According to Jivèn et al.[22], the demand on fuel for shipping in Sweden is divided between three main categories which can be seen in table 2.1. The table also shows the energy density for each of these fuels, which can be used to calculate the total energy needed to replace these fuels with one of the three options for electrification observed in this project[23]. The ECA oil is an oil with higher restrictions of local emissions such as sulphur oxides and nitrogen oxides[24]. The oil can be based on different kinds of shipping oil and the value in the table are therefore based on the mean value from HFO and MGO.

Table 2.1: Energy density of shipping fuel

Fuel type	Market share (%)	MJ/L	MJ/kg
Heavy fuel oil (HFO)	20	38,3	40,4
Marine gas oil (MGO)	50	34,5	43
Emission control area oil (ECA-oil)	30	36,4	41,7

When it comes to ships, it actually do not exist any large scale that uses batteries but many companies are now making big investments to make it happen in the coming years [25][26]. There are however one battery electric ship that is planned to be in use in Gothenburg in 2030, the Stena Elektra[27]. This ferry will go the relatively short route between Gothenburg and Fredrikshamn but even with that short trip it will need about 40MWh for a one way trip. A bit longer routes might be possible in the future but the energy density of batteries need to be dramatically increased if long distance shipping is going to use batteries as the only energy source[28][29].

The energy density becomes more important when observing ships compared to trucks since they are so much larger and will therefore require much more energy. A lower energy density will therefore make a big impact on the amount of goods that can be transported and cost money in terms of loss of transportation capacity[30]. But energy density can be divided into gravametric energy density and volumetric energy density which will be an important distinction when observing hydrogen for shipping. This distinction has to be made since hydrogen has a gravametric energy density of 120MJ/kg, which can be compared to regular diesel that has 45,6MJ/kg[20]. But the volumetric energy density of hydrogen will depend on which state it has, hydrogen gas at 1 atm has 0,01MJ/L while liquid hydrogen has 8,5MJ/L compared to regular diesel which has 38,6MJ/L[18][20]. Hydrogen gas will therefore require a lot of space and will therefore not be suitable to be used as a shipping fuel. Furthermore is hydrogen gas difficult to handle and make the refuelling process too time consuming[31]. Liquid hydrogen is therefore generally the option discussed when hydrogen is considered. The liquidification of hydrogen is however an energy intense process and will require about 30-40% of the energy content of hydrogen, assuming the gas is at atmospheric pressure going in to the process[32]. This means that liquid hydrogen has a total efficiency of about 45-53%, if the electrolyser have an efficiency of 75%. Liquid hydrogen also means that the storage system has to be more complex, since it needs a storage that can sustain a cryogenic temperature. This added complexity will increase the amount of space and weight required compared to the conventional tanks that are used on ships today[31]. This added complexity and in extent space and weight will not be the case for fuels similar to conventional marine fuels, such as methanol.

When it comes to electrofuel for the shipping industry most of the focus is on ammonia and methanol. These two have similar cost and total efficiencies[30]. Since this project focus on how the electrification affect the grid of Gothenburg either one can be used but since it only adds complexity using both, methanol was chosen as the electrofuel for ships in this project. Methanol have a total efficiency (η_M) from power to methanol of 65% and will require 0,75 units hydrogen per unit methanol, later referred to as $H2_{in}$[33]. From the production of both hydrogen and methanol, it is also possible to make use of waste heat which for example can be used for district heating. The heat which can be used is about 8,3% of the input energy from the hydrogen production and about 25% from the methanol production[13].

2.3 On-site machinery

The Port of Gothenburg has several types of machinery in the port. As of today all except the cranes use HVO as fuel. The cranes are directly connected to the grid and are therefore already electrified. The machinery left are terminal tractors, reachstackers, straddle carrier and forklifts. All of these have electric alternatives on the market today. For example is the Kalmar ERG420-450 an fully electric reachstacker with the alternative to have a battery size from 245-587kWh[34]. Kalmar also offers a fully electric terminal tractor, the Kalmar Ottawa T2E+, which have a battery size of 152-184kWh[35]. An even larger battery can be found in the Terberg terminal tractor YT203-EV, who has a battery pack of 222kWh[36]. An electric forklift is also available to buy and can have a variety of capacities depending on size[37]. There are also fully electric straddle carriers on the market today, one example being the Ciamolai Technology Spa MST 160[38].

2.4 Existing model

The existing model that this project used was an energy system model developed by Heinich et al.[39]. This is an investment optimisation model that connects the electricity and heating sector in Gothenburg. The basic idea together with inputs and outputs are presented in figure 2.1, where blue represents existing model and green the added loads presented in this project.

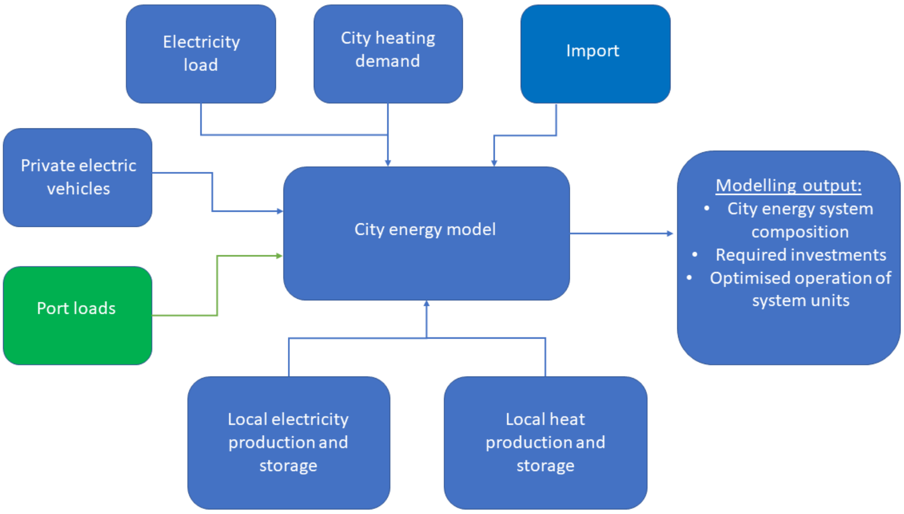

Figure 2.1: The existing city energy model with the new port loads included. Figure adapted from [39].

The objective function of this model is the minimisation of annualised investment and running cost over one year, as equation 2.1 describes. The model contains many constraints and balance equations but the two major ones are the electricity and heat balance described in equation 2.2 and 2.3. These two restrict the hourly demand to be met either by local production or import. Equations 2.1, 2.2 and 2.3 and table 2.2 along with a full description of the existing model can be found in [39].

$$MIN : C^{tot} = \sum_{i \in I}(C_i^{inv} s_i + \sum_{t \in T}(C_i^{run} p_{i,t} + C_i^{run} q_{i,t})) + \sum_{t \in T} C_t^{el} w_t, \forall t \in T \quad (2.1)$$

$$D_t^{el} + \sum_{i \in I_{EISt}} \frac{p_{i,t}^{ch}}{\eta_i} + \sum_{i \in I_{PtHt}} \frac{q_{i,t}}{\eta_i} \leq \sum_{i \in I \setminus I_{EISt}} p_{i,t} + w_t + \sum_{i \in I_{EISt}} p_{i,t}^{dch}, \forall t \in T \tag{2.2}$$

$$D_t^{h} + \sum_{i \in I_{HSt}} \frac{q_{i,t}^{ch}}{\eta_i} \leq \sum_{i \in I \setminus I_{HSt}} q_{i,t} + \sum_{i \in I_{HSt}} q_{i,t}^{dch} + X_t, \forall t \in T \tag{2.3}$$

where

Table 2.2: List of acronyms for equation 2.1 - 2.3

T	is the set of all time steps
I	is the set of all technologies in the city energy system
$\mathrm{I_{PtH}}$	is the subset to I for all power-to-heat technologies, i.e., heat pumps and electric boilers
$\mathrm{I_{EISt}}$	is the subset to I for all electricity storage technologies
$\mathrm{I_{HSt}}$	is the subset to I for all thermal storage technologies
$\mathrm{C^{tot}}$	is the total system cost to be minimised
$\mathrm{C_i^{inv}}$	is the investment cost (annualised) including the fixed O&M cost for each technology i
$\mathrm{C_i^{run}}$	is the running cost for each technology i (including fuel cost)
$\mathrm{C_t^{el}}$	is the cost to import electricity to the city from the national grid
$\mathrm{s_i}$	is the capacity of technology i invested in
$\mathrm{p_{i,t}}$	is the electricity generation by technology i at time step t
$\mathrm{w_t}$	is the electricity imported to the city at time step t
$\mathrm{D_t^{el}}$	is the electricity demand per time step t
$\mathrm{D_t^{h}}$	is the heat demand per time step t
$\mathrm{p_{i,t}^{ch}}$	is the electricity charged to electricity storage units per time step t
$\mathrm{p_{i,t}^{dch}}$	is the electricity discharged from electricity storage units per time step t
$\mathrm{q_{i,t}^{ch}}$	is the heat charged to thermal storage units per time step t
$\mathrm{q_{i,t}^{dch}}$	is the heat discharged from thermal storage units per time step t
$\mathrm{X_t}$	is the heat production profile for industrial excess heat per time step t
η_i	is the efficiency (or COP) for each technology i

Since it is a model to estimate the future, the investments in future production technology will differ depending on what restrictions that are set. Some of the technologies that exist in Gothenburg today will however be used in all future scenarios since they are already invested in and are climate neutral. These climate neutral technologies are showed in figure 2.2 below. The CHP and HOB count as carbon neutral since they are biomass fuelled. Some waste heat is also included in the existing model, but since no oil refineries are included in 2050 scenarios, only waste heat from the burning of waste are included but not the waste heat from oil refineries. The included waste heat is therefore about 1500GWh per year[40].

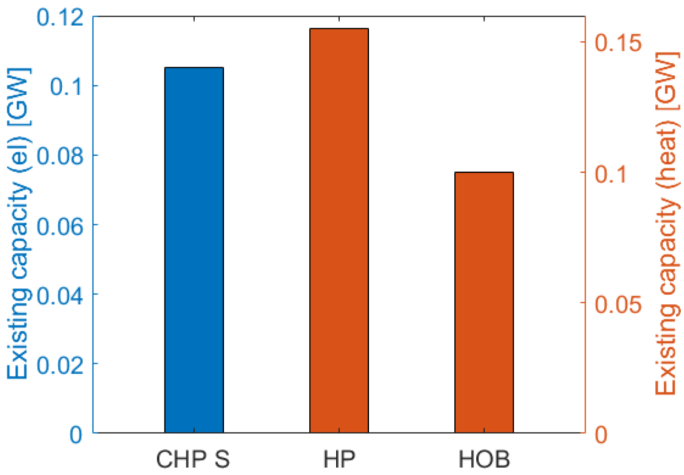

Figure 2.2: Climate neutral production technologies already existing in Gothenburg and used in all scenarios observed in this study

For the model to be realistic, the production technologies needs to account for possible limitations in the production. One such limitation is the use of biomass for the technologies mentioned above. Biomass is a natural product and has restrictions in the amounts which can be produced for power production purposes on a yearly basis. Also important to differentiate between biomass and bio gas. The biomass potential in Sweden is large because of the well established forest industry and a potential increased use of 82TWh is possible in the near term and 147TWh in the long term[41]. All of this can of course not be imported to Gothenburg for electricity and heat production but it is an upper limit that can be discussed further when the size of biomass investments are known in a later stage of the project. As for the bio gas, it also has a large potential since it is produced with biomass. It can however be interesting to know that the production of bio gas in Gothenburg 2019 was 80GWh[42].

Another production technology which could be limited is the solar PV which is limited by the area on which the solar panels can be installed. The area is directly correlated to the yearly production which is estimated to 350GWh per year on suitable roofs in the city [43]. In addition to this production there is also a potential of 300GWh per year if a solar park would be built on the closed airfields of Säve airport[43].

Later on, a battery electric car part has also been added to the model[44]. This part of the model will also be used to simulate the additional load that the development of the electric car fleet in Gothenburg will represent. The number of electric cars in Gothenburg 2050 was estimated by assuming that all cars are electric since Sweden are supposed to be carbon neutral by 2045. To estimate how many cars that exist in Gothenburg in 2050 the relation between cars and residents was observed. This relation has been steady around 0,33-0,35cars/inhabitant since 1999 and is therefore assumed to be about the same in 2050[45][46][47]. Based on 0,34cars/inhabitant and the future number of inhabitants estimate made by the city of Gothenburg in [48], the number of electric cars will be about 240 thousand.

There are currently plans for two different hydrogen production sites within the port area. Both of these are expected to be operational in the coming years and is therefore added as existing technologies in the model. The first hydrogen production site is planned by Cirkel K at Vädermotet and will have a daily hydrogen production of 720kg H2 which is estimated to equal 15 full truck tanks of hydrogen [49]. This amount equals 24MWh of hydrogen per day and with an electrolyser efficiency of 75% it equals 32MWh of electricity per day. The second site is planned by the Port of Gothenburg and is expected to produce 2000kg H2 per day [50] which, with the same calculation, would equal 89MWh of electricity per day.

3
Method

The method part of this study is divided into four parts. The first one will describe the investigation of loads in the port, which mostly consisted of an investigation of the number and types of vehicles used in the port and how they are used differently during the day, week, month and year. The second step was to convert the transport patterns, vehicle types and number of vehicles from the first step into data that can be implemented in the energy system model. This was done by combining the findings from the first step with the most suitable electrification option based on the literature study. Since many different electrification pathways are possible the following section presents some scenarios for the different vehicle types and some combined scenarios that the model can run. The final section in the method chapter presents the implementation in the energy system model. Starting with the presentation of the reference model used to describe Gothenburg in 2050 without the electrification of the Port of Gothenburg. After the reference model is presented, the additions this project have had on the model will be presented.

3.1 Investigation of loads in the port

In order to create load profiles for the different loads in the port, the literature study needed to be complemented with information about the actual loads in the port. In order to be able to create hourly load profiles there was a need for information of both the amount of different vehicles in the port as well as information about the variation of loads over different sets of time. This information was acquired in collaboration with representatives from the Port of Gothenburg. The following sections present the information provided by the port which will be considered as input data for the project. The input data are here divided into three different categories which are trucks, ships and on-site machinery.

3.1.1 Trucks

The amount of trucks in the port is estimated to be 600 000 per year and most of these are expected during weekdays which mean that approximately 2300 trucks enter the port each weekday. The traffic in the port contain a share of trucks which return to the port several times a day which mean that they are included several times in the total amount of 2300 shipments. The amount of individual trucks representing these 2300 shipments will be calculated later. All traffic in the port is assumed to be classed as heavy traffic which means that all trucks within the same electrification option are expected to have the same energy consumption per kilometre.

The information from the collaboration with the port was also complemented with a previously performed survey from CTK (Chalmers Teknologkonsulter AB)[51]. The survey focused on the truck transport in the port which answered questions of patterns from the truck drivers. These patterns also reflects on the patterns in the port and will be the base for the daily patterns in the port. Table 3.1 presents answers of the number of times each truck driver enter the port each day. This information can be used to understand the relation between the number of individual trucks and total amount of shipments in the port each day.

Table 3.1: How many times each individual truck is in port per day and the total amount of shipments they represent

Number of times in port	Individual Trucks	Amount of shipments
1	439	439
2	127	254
3	81	243
>3	236	944
Total	**883**	**1880**

Table 3.1 shows that the 883 individual trucks which answered the survey represent 1880 shipments each day. To find the total amount of individual trucks representing the estimated 2300 shipments the values were scaled according to equation 3.1.

$$883 * \frac{2300}{1880} = 1084 \; individual \; trucks \tag{3.1}$$

From the survey, the distance driven per day could be retrieved as well. The driven distance was answered in steps of 100km. The number of trucks in each category is presented in table 3.2 where table 3.2a present the number of trucks in each span of 100km. Table 3.2b present the same data but is categorised to show the share of trucks which drive up to a certain distance during one day. This information was later used to divide trucks between electrification options depending on the range possible for each technology.

Table 3.2: Number of trucks in the port divided by driving range

(a) Trucks per driving range

Distance driven per day	Number of Trucks
<100	163
100-200	195
200-300	170
300-400	154
400-500	116
>500	97
Total	**895**

(b) Share of trucks by maximum range

Distance driven per day	Number of Trucks	Share of Total
0-200	358	0,400
0-300	528	0,590
0-400	682	0,762
0-500	798	0,892
>500	97	0,108
Total	**895**	-

From the distances presented in table 3.2a it was possible to calculate the total distance which the trucks drive during a day. This distance was later used to calculate the energy demand, depending on the electrification option, for the trucks to cover the total distance. The equation calculating the total distance is presented in equation 3.2.

$$\begin{aligned} 163 * 100km + 195 * 200km + 170 * 300km + 154 * 400km+ \\ +116 * 500km + 97 * 600km = 284100km \end{aligned} \tag{3.2}$$

The total distance calculated in equation 3.2 represent the 895 individual trucks in the survey. To calculate the total distance representing all daily trucks in the port, the distance needs to be scaled with the scaling factor from equation 3.1. This calculation is presented in equation 3.3.

$$284100 * \frac{1084}{895} = 344056km \tag{3.3}$$

3.1.2 Ships

The port receive 6500 ships each year and include several different categories of ships which are presented later. The number of ships is not directly related to the shipments presented in the earlier section. The energy consumption from these ships can be divided into three main categories. The first one is the fuel bunkering in the port which is estimated to 1,5 Mton fuel each year. This amount can vary between years and is also dependent on the amount of fuel which the port offers to the ships. The value will however be used as a base case for the amount of bunkering fuel. The fuels bunkered by the ships mainly consist of HFO, MGO and ECA-oil and information of the fuels can be seen in table 2.1. The future fuels are of course more difficult to estimate but the port expects hydrogen, methanol and ammonia to be the main shipping fuels in the future.

The second category for ships in the port consists of the electrification of ferries between Gothenburg and Fredrikshavn. The current ferries will be replaced by

Stena Elektra which is a battery-electric ferry with an energy need of 40MWh to cover the distance. The ferry is expected to leave Gothenburg six times a day and will need to be fully charged each time.

The last category for ships in the port is the onshore power distribution for ships at berth which is required to maintain necessary utilities on board such as heating and lighting in living areas. These utilities are today mostly powered by keeping the motor running at berth which contributes to a large amount of emissions in the port which is why onshore power is preferred. In this thesis all ships at berth are expected to have onshore power. The power needed for ships vary between 1 and 1,5MW with the exception of the largest ships which require 5MW of power. This power is required by the ships at all hours at berth.

To understand the amount of energy needed for onshore power, an investigation of the number of ships and the hours at berth was performed. This investigation was based on data of arrivals and departures from the website of the Port of Gothenburg. The ships were divided into four categories which are roll on/roll off (RoRo), Container, roll on/roll off passenger vessel (RoPax) and Tanker. RoRo and RoPax refers to ships transporting road vehicles where RoPax contain even larger passenger areas for people travelling both with and without a personal vehicle onboard. Container refers to ships transporting goods and tankers refers to ships transporting fuels (mainly oil). Each category was then provided with information of the average number of hours in port and the number of ships in port each day. It was also estimated that RoRo and RoPax would have larger onshore power (1,5MW), compared to the other categories, since these ships contain larger passenger areas. The onshore power for the Container category is calculated as an average since it contains a combination of ”smaller” cargo ships (1 MW) and the largest container ship (5MW) which enters the port less frequently. The information was used to calculate the daily energy needed for each category. The results from the investigation are presented in table 3.3. The ferries between Gothenburg and Fredrikshavn are not included in the table.

Table 3.3: Ships in port

	RoRo	Container	Ropax	Tanker
Hours in port (h)	15	22	9	24
Onshore power (MW)	1,5	1,3	1,5	1
Ships per day (-)	3,5	2	1	5,5
Energy per day (MWh)	78,8	56,6	13,5	132

3.1.3 On-site machinery

The on-site machinery in the port consist of cranes, terminal tractors, reachstackers, straddle carrier and forklifts. The cranes are stationary and already powered directly from the grid. The other machinery currently use HVO in ICEs which mean a significant reduction of global emissions compared to fossil diesel. It is however assumed that the machinery are to be electrified with batteries. The reason for this is that the conditions for the machinery in the port are well suited for batteries since they only move shorter distances and therefore are always close to charging stations. The total energy is also lower considering the losses of HVO-production and efficiencies of ICEs compared to batteries. The amount of on-site machinery consists of about 100 vehicles which are estimated to consume a yearly amount of 3,8 million litres of HVO.

The vehicles in the port are used throughout the day and the workers are divided into two shifts over the day. It is therefore assumed that the on-site machinery can be stationary once during a break for the first shift and once during a break for the second shift of the day. The vehicles are expected to be stationary during the night. The on-site machinery is also expected to be used more on weekdays than on the weekends. The usage of the vehicles are estimated to be at half capacity during weekends which is similar to the estimation of the arrival of ships during weekends compared to weekdays.

3.2 Data structuring and assumptions

Once all information was acquired, the structuring of data to create load profiles was started. The data is later used in an energy system model. The structuring of the data was based on information from the literature study of the different electrification alternatives and the information gathered in collaboration with the port. Additionally, there was a need for interpretations and assumptions to acquire the load curves. The section also presents arguments for which electrification option that was opted for and prioritised.

3.2.1 Trucks

The total distance calculated in equation 3.3 represents the daily distance covered by trucks entering the port each day. The estimation of the amount of trucks per technology were therefore based on the share of trucks driving certain distances presented in table 3.2b. Because of the high efficiency of BETs compared to FCTs and methanol trucks, BETs was prioritised. However, because of the current range limitations it is not possible to cover all of the truck transportation with BETs. For the ranges where the BET is insufficient, hydrogen was opted for. Because of the range of up to 800km for FCTs and the quick refilling technology that exist, it was estimated that there would not be any need for methanol trucks in the future. Based on this, it was also possible to calculate the daily distance driven per electrification option using the number of trucks per driving range in table 3.2a. The calculation was performed similar to equation 3.2 and 3.3. The calculated distances provided the possibility to calculate the daily energy needed for each electrification option.

In addition to the amount of energy, an estimation of the variation of the energy over time was needed. This was especially important for the BETs since they affect the grid directly while charged. The BETs were divided into two main groups based on the amount of times each truck entered the port each day presented in table 3.1.

The two groups were divided between trucks entering the port once and recurring trucks (entering the port more than once per day). The number of trucks entering the port once presented in table 3.1 could also be divided into short and long range to see the number of trucks opting for batteries and hydrogen respectively. This could also be used to calculate the distance for recurring trucks and trucks entering the port once to separate the amount of energy required for each category.

The pattern for trucks entering the port once and recurring trucks were estimated to be different. The trucks entering the port once were expected to arrive evenly throughout the day during all hours that does not count as night-hours. It was assumed that all trucks arriving in the port during hours which could be considered to be in the middle of a shift would stop for 45 minute break and charge during that time. These hours include all hours between 11.30 and 19.30 and are based on the 4.5 hours which is allowed to drive without a break [52]. These trucks are expected to have an aggregated demand resembling the curve presented in figure 3.1. Trucks arriving between 20.00 and 00.00 are instead expected to stay for night charging and are also expected to stay for the 11 hours required by law[52]. Figure 3.2 presents an aggregated profile for when these trucks are connected to the grid. The trucks are expected to have flexible charging during the night with the requirement that the battery is fully charged in the morning.

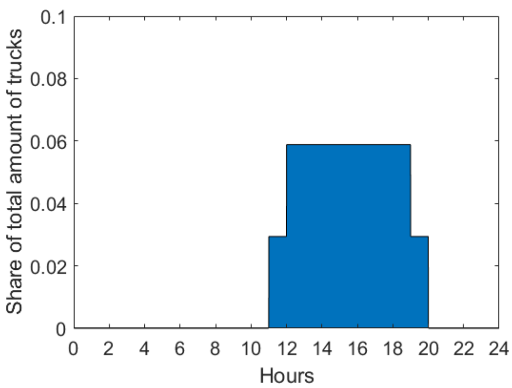

Figure 3.1: Daily load profile for trucks entering the port once

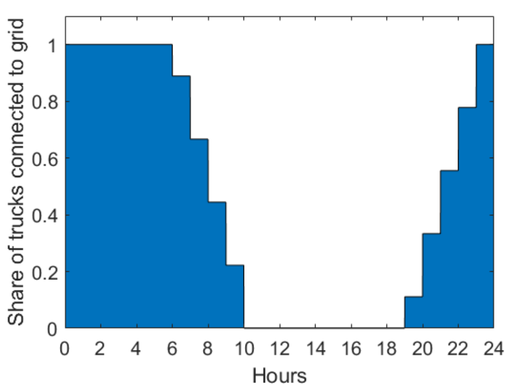

Figure 3.2: Profile for trucks connected to the grid during night in port

The recurring trucks are expected to drive during daytime (start in the morning and end in the afternoon) and are therefore expected to take their break in the middle of the shift. It is also assumed that all of these take their break while in the port area. The time for this break is expected to occur between 11 and 14 with half of the capacity at 10-11 and 14-15. The charging profile can be seen in figure 3.3. None of the recurring trucks are expected to charge in the port during the night since they are all expected to have a home station which they return to at the end of the day. These trucks are however expected to affect the city anyway since the home stations are expected to be within the Gothenburg city area. All of the recurring trucks are expected to be connected to a charger at the end of the shift and be able to have flexible charging during night (17-07) as long as they are fully charged in the morning.

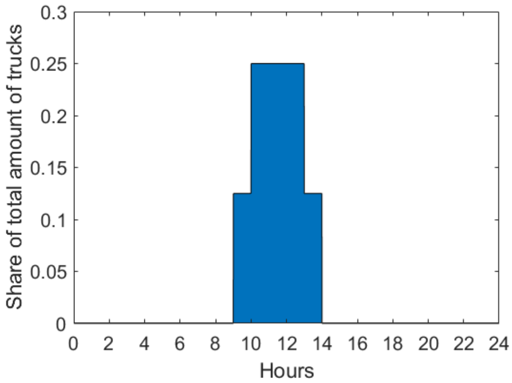

Figure 3.3: Daily load profile for recurring trucks

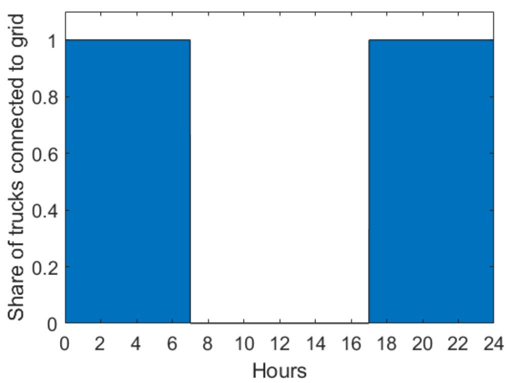

Figure 3.4: Profile for recurring trucks connected to the grid during night

The FCTs were just like the BETs divided between trucks entering the port once and recurring trucks. Because of the short refuelling time of FCTs, the need to charge on lunch breaks and nighttime was however not a demand for FCTs. This means that the FCTs will refuel when it is needed and not be concentrated at specific hours. It was therefore assumed that the demand for hydrogen for trucks would be evenly distributed throughout the workday. Given that the recurring trucks operate between 07-17 and the trucks delivering goods once a day work between 07-24, the recurring trucks hydrogen demand will be evenly distributed between 07-17 and the once a day trucks between 07-24. The combined distribution of hydrogen demand for trucks will therefore follow the profile shown in figure 3.5, where the y-axis shows the share of trucks charging each hour of the day.

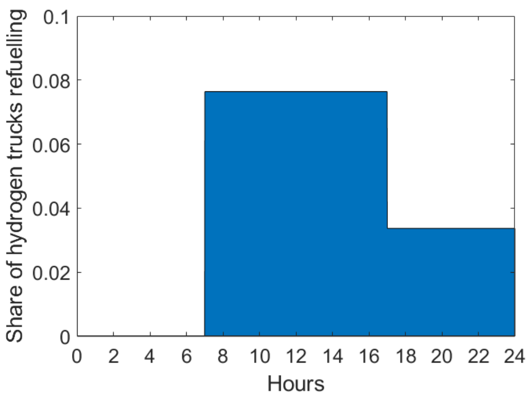

Figure 3.5: Load profile for FCTs

3.2.2 Ships

Except for Stena Elektra (the ferry between Gothenburg and Fredrikshavn), only methanol was considered as fuel for the ships. The reason for this is the low total efficiency, complex storage need and a low volumetric energy density of liquid hydrogen compared to methanol which is described in the literature study. For batteries, the low energy density compared to methanol makes it difficult to handle longer trips and was therefore only considered for the already planned ferry. The charging profile for the ferry is presented in figure 3.6 and shows the charging pattern of the ferry over 24 hours.

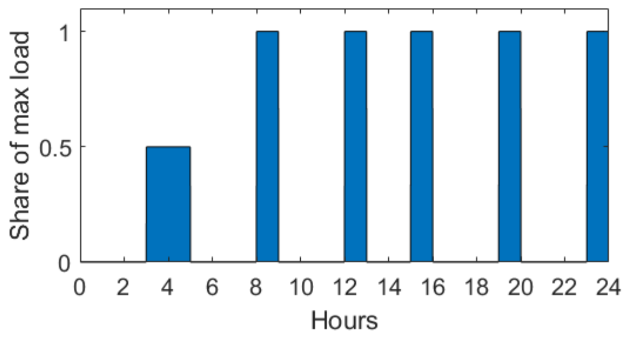

Figure 3.6: Charging pattern for Stena Elektra

To calculate the energy needed to power all ships in the port, the yearly amount of fuel was used to calculate the energy needed to replace all current fuel (1,5Mt) with electrofuels. Equation 3.4 calculates the amount of electricity needed to replace all current fuel with electrofuel. In the equation, x and E_d represents the market share and energy density respectively which are presented in table 2.1, m_{tot} represents the total amount of fuel, η is the efficiency from electricity to electrofuel and E is the the total amount of electricity.

$$E_{electricity} = \frac{m_{tot} \cdot (x_{HFO} \cdot E_{d,HFO} + x_{MGO} \cdot E_{d,MGO} + x_{ECA} \cdot E_{d,ECA})}{\eta_{methanol}} \tag{3.4}$$

The investigation of ships at berth presented in table 3.3 was used to create a load profile for onshore power. The aggregated electricity required by the ships was assumed to be evenly distributed over the day. The reason for this is that the investigation showed no clear pattern of when the ships were at berth. The daily amount of ships in the port from table 3.3 indicates an average of 12 ships in the port each day. This sum is however a combination of weekdays and weekends and in general the weekdays have a higher share of ships in the port. This led to an assumption of 14 ships per weekday and 7 per Saturday and Sunday which represent the same amount of ships per week as 12 ships all days a week. Together with Stena Elektras 6 daily departures it can be estimated that an average of 20 ships is at port each weekday and 13 each Saturday and Sunday. On a yearly basis this leads to a yearly amount of 6552 ships which can be compared to the 6500 ships the port estimates each year. Figure 3.7 presents the weekly profile for the onshore power which shows the relation between the energy required during the days of the week. The "energy per day" presented in table 3.3 could also be used to calculate the actual load from the onshore power which is presented later.

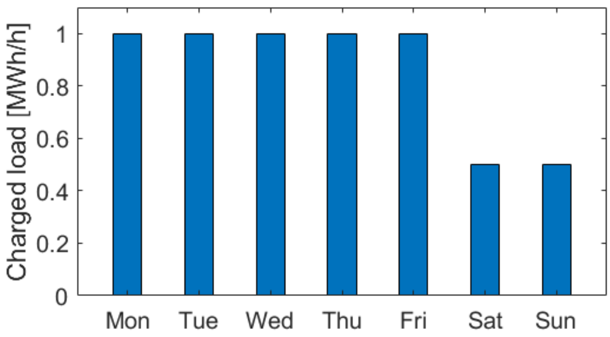

Figure 3.7: Profile for onshore power over the days of the week

3.2.3 On-site machinery

The energy needed for the on-site machinery is based on the yearly amount of fuel presented in section 3.1.3 (3,8 million litres). This amount can, together with the volumetric energy density of diesel (E_d) and the efficiency of an internal combustion engine (η_{ICE}) and a battery ($\eta_{battery}$) respectively, calculate the weekly amount of energy needed to be charged to batteries (E_{week}) according to equation 3.5. In the equation, V_{tot} represents the total amount of fuel.

$$E_{week} = \frac{V_{tot} \cdot E_d \cdot \eta_{ICE}}{\eta_{battery} \cdot w} \tag{3.5}$$

The vehicles are assumed to require charging during the day to avoid that the battery "runs out". Since the working hours in the port allows for two breaks during the day it is assumed that the machines can be charged during this time. The break during the first shift is assumed to be at lunch hours (11-12 and 12-13) where half of the on-site machinery could be charged the first hour and the second half during the second hour. A similar assumption was made during the second shift where the break was between (17-18 and 18-19). All machinery could then also be charged during the night. It was assumed that all of the batteries could be fully charged during all three of these occasions during the day. The charging profile for the on-site machinery is presented in figure 3.8 and shows the two breaks during the day as well as the charging during night which is divided by the hours of which the vehicles are parked.

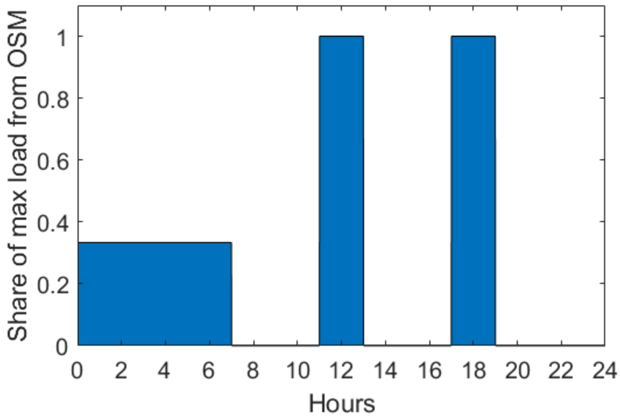

Figure 3.8: Daily profile for on-site machinery

The weekly amount of energy presented in equation 3.5 was divided between the days of the week (with half capacity on the weekend) and could then be divided by three (represented by b in the equation) to know the amount of energy which needed to be charged each break (and night). Equation 3.6 presents this calculation and also divides the energy per break with the estimated number of machines ($n_{machines}$) to see the average size of battery ($\overline{Q}_{bat}$) needed for a vehicle. The battery capacity can then be compared to the batteries presented in the literature study.

$$\overline{Q}_{bat} = \frac{E_{week}}{(\text{week} + \text{weekend} \cdot \frac{1}{2}) \cdot b \cdot n_{machines}} \tag{3.6}$$

The charging during the breaks are assumed to be static. The reason for this is that the vehicles are assumed to only be connected for an hour and they need to be fully charged. During the night all machines are also expected to be fully charged but since they are connected during a longer time they can have flexible charging.

3.3 Scenarios

To handle the uncertainties in some of the data, multiple scenarios were produced to be able to analyse the effect of the different choices made in the project. These scenarios are based on the largest uncertainties and the section presents the scenarios divided by the different vehicle types. The section is concluded with a part where the scenarios are combined to show the basis for the simulations.

3.3.1 Vehicle scenarios

The three scenarios for trucks were mainly based on the limitations of range for BETs and the number of individual trucks driving certain distances presented in table 3.2b. Truck scenario 1 was based on the current range of BETs which mean that the trucks can drive 300 km on a full battery and can charge an extra 100 km during the 45 minute break. This means that 25% of the energy used during a day can be charged at "lunch" and the other 75% during night. All trucks driving longer than 400 km per day are, in this scenario, expected to use FCTs.

Truck scenario 2 was based on a development of fast battery chargers which would mean that it would be possible to fully charge the battery during the 45 minute break. This was assumed to lead to the possibility to electrify all trucks which drive less than 500km per day with batteries. The fast charging means that it is possible to charge 50% of the daily energy during the break and the other 50% during the night. The remaining trucks were also here expected to be covered by FCTs.

Truck scenario 3 considers a larger development of fuel cells compared to batteries which would increase the share of FCTs. In the scenario, all trucks driving longer than 200 km per day is expected to use fuel cells. The trucks driving shorter than 200 km is still expected to use batteries which are able to charge 50% of the energy during the day and 50% during the night.

The scenarios for ships mainly consists of the production of methanol. It was assumed that the impact from the fuel production would be too large if all fuel were opted for. Therefore, the methanol production was tested in steps of 5 percentage points meaning that 5,10 and 15 percent of the total fuel were tested. Another aspect for the ships was the inclusion of onshore power. The scenarios were here made without consideration of the oil-tankers in the port. The reason for this was that the work expects zero emissions and it could therefore be unreasonable to expect a large share of ships transporting fossil fuels. The onshore power for tankers presented in table 3.3 is therefore not included in any scenario. The assumption also affects the amount of total fuel which needs to be bunkered but since a maximum of 15% of the fuel will be produced will this not impact the scenarios presented in the next section. The final addition from the ships was the loads from Stena Elektra. The on-site machinery(OSM) were not expected to have any large uncertainties and are together with the onshore power(OSP) and Stena Elektra included in all scenarios containing loads from the port which are presented in the following section.

3.3.2 Combined scenarios

To analyse the total impact from the loads in the port, a combination of the scenarios needed to be constructed. The combination of scenarios also needed to be compared to a reference scenario without any of the new loads in the port but included direct charging for battery electric cars(BECs). The Reference scenario was based on the existing model presented in section 2.4 and was used as a reference to see how the different combination of scenarios affected the system.

All scenarios that this project will investigate are presented in the left column in table 3.4. The Base scenario was constructed to act as a reference point for the other port scenarios. The flex EV scenario are actually two scenarios. The original "Direct" charging that is used in all other scenarios charge the cars to a full battery as soon as the car comes home. The optimal charging scenario (Opt) on the other hand will charge the car at times when it is suitable to the system. The vehicle to grid(V2G) scenario also charge when it is suitable to the system but also have the option to discharge the car battery to balance the grid if the car is not being used for driving. As with the Flex Ev will the Truck and Methanol scenarios in table 3.4 actually consist of multiple scenarios. These different scenarios were described in section 3.3.1.

Table 3.4: Simulated scenarios and what they include

Scenario	Flex EV's	Trucks Scenario	Methanol production	OSM, OSP & Stena	M&H2 heat	PV Lim
Ref	Direct	-	0%	No	No	No
Base	Direct	1	0%	Yes	No	No
Flex EV	Opt. & V2G	1	0%	Yes	No	No
Truck	Direct	2,3	0%	Yes	No	No
Methanol	Direct	1	5,10,15%	Yes	No	No
M&H2 heat	Direct	1	0%	Yes	Yes	No
Ref-PV065	Direct	-	0%	No	No	Yes
Base-PV065	Direct	1	0%	Yes	No	Yes

The $M\&H2_{heat}$ scenario will utilise the waste heat from the electrolyser and methanol production. To see the impact from the M&H2 heat option, 5% methanol production was combined with the option to include M&H2 heat. This will be further explained in section 3.4.6. The last column called PV Lim represents an option to limit the solar capacity to 0,65GW because of the estimated maximum limit that exist in the city of Gothenburg. This is only used for the PV065 scenarios.

3.4 Implementation of Energy system model

This section describes the implementation process and added equations into the existing energy system model of Gothenburg described in 2.4. The section describes the assumptions and restrictions needed to simulate the Reference scenario. The section also presents equations for the new loads in the port which are divided between the fixed and flexible loads (presented for each vehicle category). Finally, the equations for heat production from the hydrogen and the methanol process are presented.

3.4.1 Reference Model

Since the model is made to simulate Gothenburg in the year 2050 some assumptions and limits are set to best represent this. To represent the overall expansion of Gothenburg an increase of 50% of the 2012 demand was estimated[39]. Since Sweden has the goal of being climate neutral in 2045, the carbon dioxide limit is zero. No carbon capture technologies are included in the model which means that new investments that might be needed in electricity or heat production will be limited to carbon neutral technologies. Also, since only the Gothenburg area is observed, no wind or hydro power can be invested in for electricity production. This leaves the model left with solar panels, bio combined heat and power (CHP), bio-gas turbine (GT) and storage to handle the increased electricity demand that will occur in Gothenburg. The amount of electricity that can be imported is assumed to be the same as it is today, which is 895MW. To handle the increased heat demand, the model can invest in bio-CHP, bio heat only boiler (HOB), electric boiler (EB) and heat pump (HP) along with thermal energy storage technologies (TES).

3.4.2 Fixed loads

All of the daytime electrical loads that is added through the electrification of the Port of Gothenburg are fixed and can therefore be implemented by simply adding them to the existing Gothenburg demand. The fixed daytime electrical loads is the on-site machinery, BETs, Stena Elektra and the onshore power supply. The Stena Elektra and onshore power supply are in contrast to on-site machinery and BETs, fixed during the night as well. These four new demands and the old Gothenburg demand can therefore be expressed as the new Gothenburg demand as can be seen in equation 3.7.

$$D_{new} = D_{old} + D_{machinery_{day}} + D_{BET_{day}} + D_{Stena} + D_{onshore} \tag{3.7}$$

3.4.3 Trucks

The flexible load for trucks will consist of the hydrogen production needed for the FCTs and the night time charging for the BETs. The electricity needed for hydrogen production($G_{H2,t}$) for each time step t is described in equation 3.8. Since equation 3.8 is calculated in H2 and not electricity the efficiency for the electrolyser, η_{H2} is needed. $D_{H2,t}$ is the fixed hydrogen demand and the possibility to store hydrogen is represented by the charge and discharge terms, $C_{H2,t}$ and $DC_{H2,t}$ respectively. The last term in equation 3.8 represents the hydrogen needed to produce methanol for shipping but since the unit for $G_{M,t}$ is in electricity, μ_M is used to convert it to methanol. This is then multiplied with the amount of hydrogen needed per unit methanol, $H2_{in}$. The calculation of μ_M will be further explained in 3.4.4.

$$G_{H2,t} \cdot \eta_{H2} \geq D_{H2,t} + C_{H2,t} - DC_{H2,t} + G_{M,t} \cdot \mu_M \cdot H2_{in} \tag{3.8}$$

The hydrogen production can be flexible although the demand of hydrogen is fixed during the day because of the hydrogen storage that the model is able to invest in. The storage level in the hydrogen tank, $SL_{H2,t}$ is calculated for every time step according to equation 3.9.

$$SL_{H2,t+1} \leq SL_{H2,t} + C_{H2,t} - DC_{H2,t} \tag{3.9}$$

The flexible night charging for the BETs will be restricted by three equations. Equation 3.10 restricts the amount of charging during one night, $C_{BET,d}$ to be larger or equal to the aggregated amount of energy that needs to be charged by the trucks during the night, $CN_{BET,d}$. The time step d represent a full day. To clarify is one time step d equal to 24 hours or 24 t time steps.

$$C_{BET,d} \geq CN_{BET,d} \tag{3.10}$$

Important to note in equation 3.10 above, is that $CN_{BET,d}$ is a parameter while $C_{BET,d}$ is the variable. This is important for equation 3.11 where the value of $CN_{BET,d}$ will be set for all hours of that day, meaning that all 24 values of $CN_{BET,t}$ will be set to the value of $CN_{BET,d}$. $CN_{BET,t}$ will then be used in equation 3.11 together with $CP_{BET,t}$ which is a profile of the number of trucks available for charging to restrict the charging, $C_{BET,t}$, every hour during the night charging. The profile of trucks, $CP_{BET,t}$ can be seen in figure 3.2.

$$CN_{BET,t} \cdot CP_{BET,t} \geq C_{BET,t} \tag{3.11}$$

The third and last equation for the BETs night charging is to make sure that the electricity production for the truck night charging is greater or equal to the electricity needed. This can be seen in equation 3.12.

$$G_{BET,t} \geq C_{BET,t} \tag{3.12}$$

3.4.4 Ships

As mentioned above, the most of the energy in methanol is originated from the hydrogen input. The rest of the energy is needed in the conversion from hydrogen to methanol which use a smaller share of electricity in the fuel production. Equation 3.13 presents the amount of methanol which can be produced per unit of electricity used in the fuel production (μ_M). This electricity does not account for the electricity used in the hydrogen production which means that the amount of produced methanol presented in equation 3.13 is actually larger than the amount of electricity used in the production and the conversion factor is thereby larger than 1. The equation can be described as the unit electricity needed per unit methanol which is calculated as the electricity consumption from hydrogen production subtracted from the total electricity consumption of methanol production. This difference is then inversed to achieve the right unit for equation 3.14. The $H2_{in}$ is the amount of hydrogen needed per unit methanol, η_M is the total efficiency of the methanol production from electricity to methanol and η_{H2} is the efficiency of the electrolyser.

$$\mu_M = \frac{1}{\frac{1}{\eta_M} - \frac{H2_{in}}{\eta_{H2}}} = \frac{1}{\frac{1}{0{,}65} - \frac{0{,}75}{0{,}75}} = 1{,}857\frac{MWh_M}{MWh_{el}} \tag{3.13}$$

Because of μ_M calculated above, the production of methanol can be expressed as the electricity needed for methanol production, $G_{M,t}$ times μ_M. The left hand side of equation 3.14 can then represent the production of methanol per hour. This production per hour is then required to be greater or equal to the yearly demand, D_M times a fixed charging profile, $CP_{M,t}$ plus charging and discharging of the methanol storage, $C_{M,t}$ and $DC_{M,t}$ respectively.

$$G_{M,t} \cdot \mu_M \geq D_M \cdot CP_{M,t} + C_{M,t} - DC_{M,t} \tag{3.14}$$

The storage level for methanol is regulated in exactly the same way as the hydrogen, i.e. equation 3.9.

3.4.5 On-site machinery

Since the on-site machinery, in the equations referred to as OSM, all use batteries as electrification option the equations 3.15, 3.16 and 3.17 will be used similar to the equations used for night time charging for BETs, i.e. equations 3.10, 3.11 and 3.12. With the key difference being that on-site machinery have a different charging need($CN_{OSM,d}$) and charging profile($CP_{OSM,t}$). The charging profile will, as described in 3.2.3, depend on the working times of the workers in the port. All of the on-site machinery will therefore be available for night charging between 24:00 and 06:00.

$$C_{OSM,d} \geq CN_{OSM,d} \tag{3.15}$$

$$CN_{OSM,t} \cdot CP_{OSM,t} \geq C_{OSM,t} \tag{3.16}$$

$$G_{OSM,t} \geq C_{OSM,t} \tag{3.17}$$

3.4.6 Waste heat from H2 and methanol production

Because of the relatively large electrolyser and methanol production that might be invested in, depending on what scenario that is investigated, two equations to utilise the otherwise wasted heat from these processes were added. The heat, $H_{n,t}$ is limited by the production of hydrogen and methanol multiplied with a heat factor ϵ_n.

$$H_{n,t} \leq G_{n,t} \cdot \epsilon_n \qquad n = \{H2, M\} \tag{3.18}$$

The heat factor for the electrolyser is 8,3% but the heat factor for the methanol production is given for the whole process, from electricity to methanol which means that the heat from the electrolyser is included. Calculating the heat factor for the methanol production from hydrogen to methanol is done in equation 3.19 by subtracting the heat from the electrolyser used in the methanol production from the total heat of the methanol process.

$$\epsilon_M = \epsilon_{tot} - \frac{\eta_M \cdot H2_{in}}{\eta_{H2}} \cdot \epsilon_{H2} = 0,25 - \frac{0,65 \cdot 0,75}{0,75} \cdot 0,083 = 0,054 \frac{MWh_{heat}}{MWh_{el}} \quad (3.19)$$

4
Results

The results are presented as a basis to answer the questions formulated in section 1.2. The results are divided into two main parts where the first part aims to show the results of the investigation of the future loads in the port. The second part presents the results after the simulations have been made in the model of the city of Gothenburg. The second part includes results of both the actual loads in the port as well as the energy production required to meet the demand.

4.1 Port load profiles

The following section shows the load profiles which are the results of the investigation of the loads in the port. The section presents load profiles for trucks, ships and on-site machinery as separate parts and are concluded with a final part which presents the aggregated profiles from the port as well as a table over the total energy for all loads.

4.1.1 Trucks

The aggregated load profiles for all truck scenarios are presented in figure 4.1-4.3 and shows the loads for truck charging during day and night as well as the demand for hydrogen. All loads are presented in terms of the amount of electricity that is used from the grid, meaning that the hydrogen is presented as the amount of electricity used by the electrolyser. The loads which are assumed to be flexible are presented as striped areas to show that the loads have the possibility to adapt to the electricity price to avoid large peaks. For the night charging of trucks this means that the trucks can be charged during the time which they are connected to the grid. For the hydrogen demand it means that a hydrogen tank can be used to shift the load. Figure 4.4 presents the total load profile from all three scenarios.

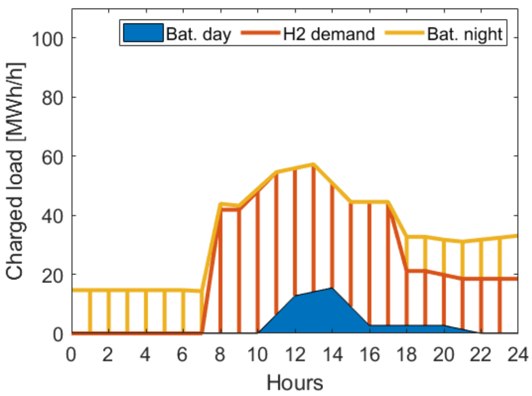

Figure 4.1: Aggregated load profile: Truck scenario 1

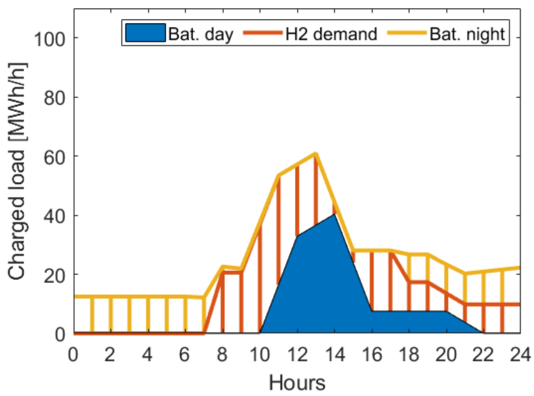

Figure 4.2: Aggregated load profile: Truck scenario 2

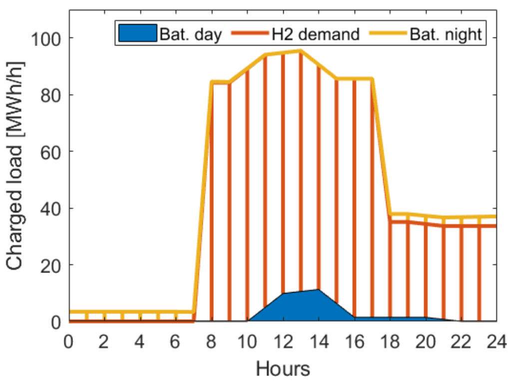

Figure 4.3: Aggregated load profile: Truck scenario 3

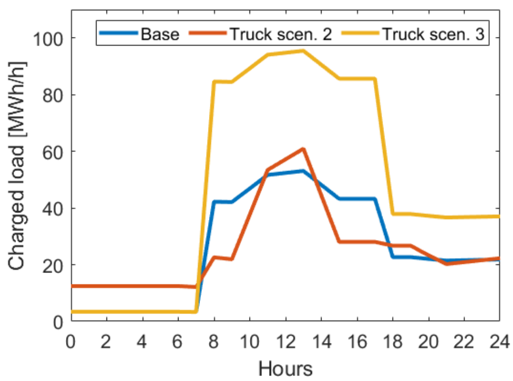

Figure 4.4: Aggregated load profile for truck scenario 1 - 3

Figure 4.1-4.4 shows the different impacts depending on which electrification option is expected. A large share of BETs, as presented in figure 4.2, requires the smallest amount of energy from the grid but instead shows a large peak in the middle of the day which can not be shifted. Figure 4.3 presents the truck scenario with a large amount of FCTs and shows the smallest fixed peak of the scenarios. The scenario does however show the largest amount energy required from the grid to meet the demand.

4.1.2 Ships

The profile for Stena Elektra is presented in figure 4.5 and shows the clear peaks when the ferry is charged. The total amount of energy needed is fairly limited but the power peaks could still have a significant impact on the grid.

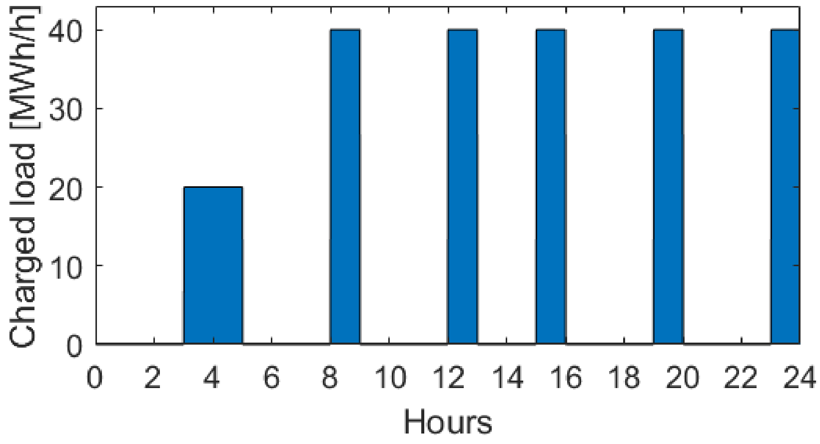

Figure 4.5: Load profile for Stena Elektra

Figure 4.6 presents the hourly energy needed for onshore power during each day of the week. The figure presents the energy for the two scenarios, which is with and without oil tankers. As mentioned earlier, the number ships in the port is lower during the weekends which means that the energy needed for onshore power is less which can be seen in the figure.

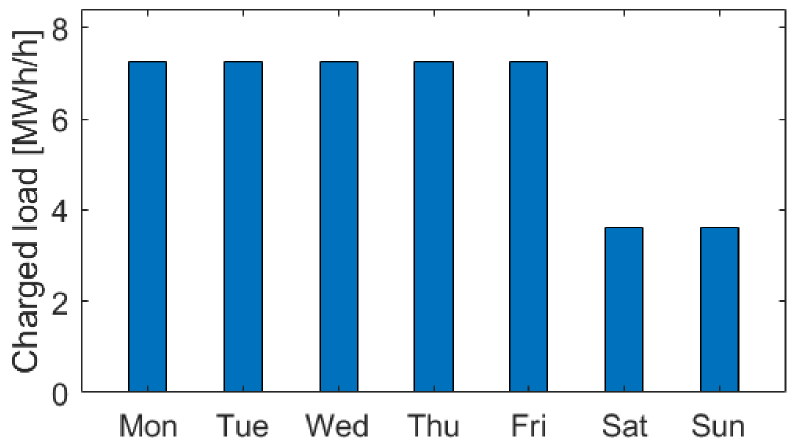

Figure 4.6: Load per hour for onshore power presented per day

4.1.3 On-site machinery

The aggregated load profile for the on-site machinery is presented in figure 4.7 and shows the two peaks that occur during the breaks over the day as well as the charging of the vehicles during the night. The night charging of the on-site machinery is expected to be flexible and is therefore presented as a striped area to show that the load can be shifted during the hours of the night to compliment other loads in the city.

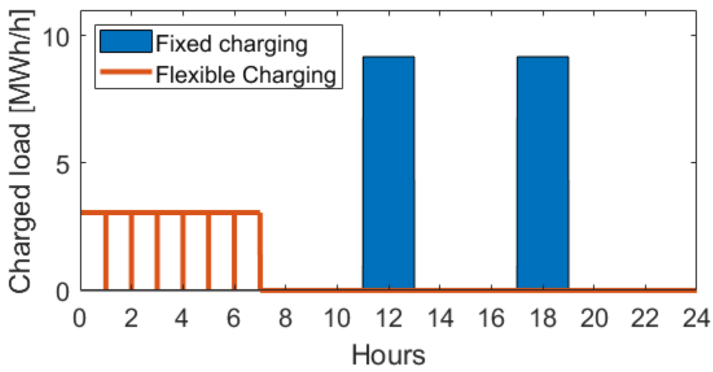

Figure 4.7: Aggregated load profile for the on-site machinery

4.1.4 Total load

To analyse the total effect of the new loads in the port, the total profile for the Base scenario is presented in figure 4.8. The fixed load are presented as fully coloured areas while the flexible loads are presented as striped areas to show which loads could be shifted. However, it is not possible to evaluate how the flexible loads are shifted until after the simulations are made which means that they here are presented according to the demand. Figure 4.8 shows that the maximum peak occurs at 13 with a power of approximately 115MW which can be compared to the average power in the city at this time which is about 700MW during summer and about 870MW during winter. At this time, the trucks, the on-site machinery and Stena elektra are charged at the same time. The peak also occurs during the day when the demand for hydrogen is high. The demand during night is lower compared to the day but still adds a minimum load of 25MW during night.

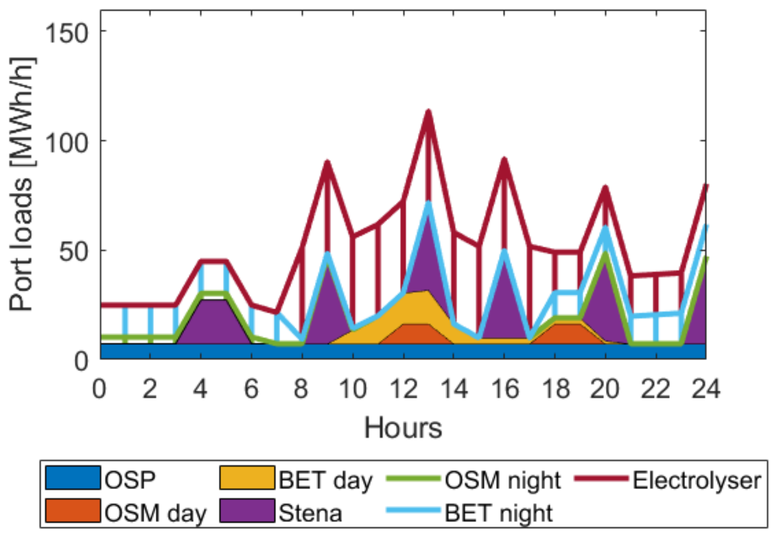

Figure 4.8: Total load for Base scenario

Figure 4.9 and 4.10 present the total load for the scenarios including Truck scenario 2 and 3 respectively. The scenario containing Truck scenario 2 in figure 4.9 have a slightly higher peak than the Base scenario but are in general at a lower level. The amount of hydrogen is also less which means that the system is less flexible than the Base scenario. The scenario with Truck scenario 3 presented in figure 4.10 have both a higher peak and a higher level of energy needed during the day. The large amount of hydrogen does however contribute to large flexibility.

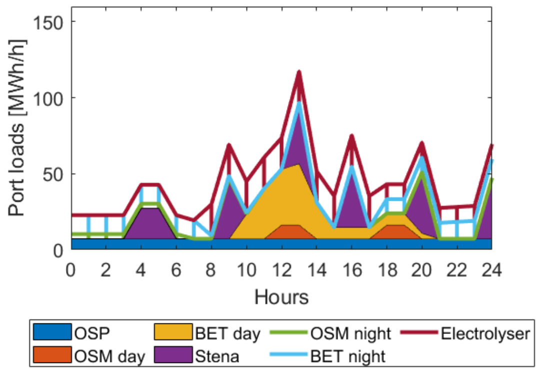

Figure 4.9: Total load for scenario containing Truck scenario 2

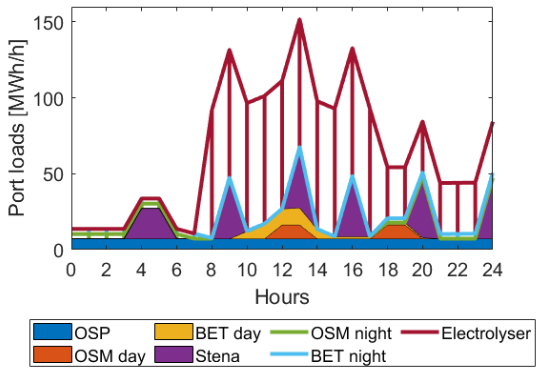

Figure 4.10: Total load for scenario containing Truck scenario 3

Figure 4.11 present the scenarios with production of ship fuel and are presented for 5,10 and 15% of the total fuel respectively.

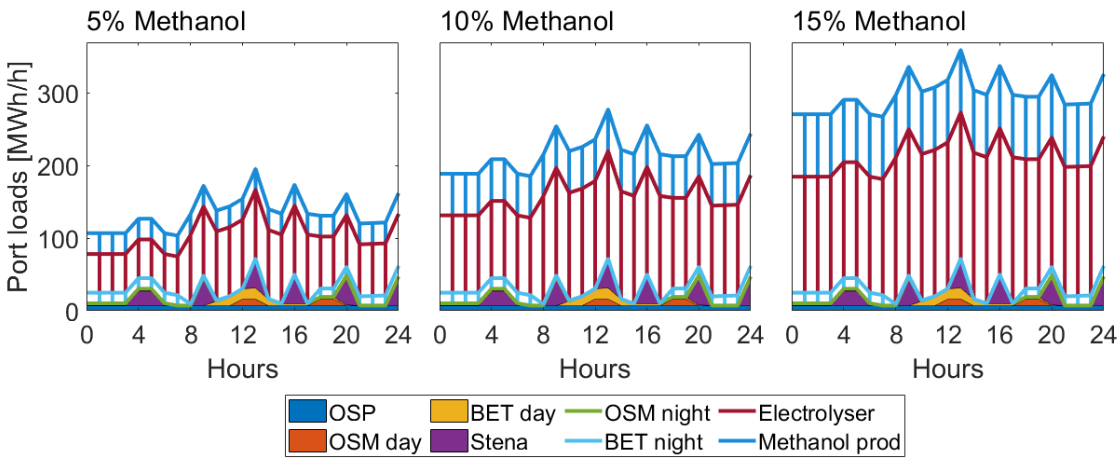

Figure 4.11: Total load presented with 5,10 and 15% production of shipping fuel used in the port

The total fuel does not include the fuel bunkered by tankers since they are not included in the base scenario. The production is presented as the total amount of energy divided between all hours of the year which mean a constant fuel production all year around. However, the production is assumed to be flexible and is therefore presented as a striped area. The figure shows that the fuel production would be a large share of the loads in the port already at 5% production. At 10%, the production of fuel requires a similar amount of energy as the peak hours from the rest of the port and at 15%, the main part of the total energy comes from the fuel production. To compare, 15% production equals 1,4TWh which could be compared to the yearly electricity demand from the city which is about 7TWh when port is added(not including the methanol production) which can be seen later in this section.

4.2 Optimization results

The following section will present the results when the new load profiles from the previous section is implemented in the energy system model. Besides the new load profiles some other scenarios will be presented which only add flexibility into the system. The focus will be on how and why the system changes in terms of new investments in production and storage capacity, for both electricity and heat. The section also presents how the electricity, heat and total system cost change between the scenarios. The main results does not contain the limit on PV but instead these results are presented on its own in the final part.

4.2.1 Flexible total loads

This section will present the total loads from section 4.1.4 but not with the flexible loads distributed according to demand but how they actually are met. Since all days are different in some way and a plot for the whole year is hard to interpret, the average profiles are plotted in figures 4.12 - 4.16. The profiles were calculated as the average of all days of the year. All of which follow the same pattern, large use during the night with a small decrease in the morning and then an increase again at lunch and finally a large decrease in the afternoon. This pattern is clearly shown in figure 4.13 where only the flexible loads for the Base scenario is plotted. Since the yearly average is plotted, it can be noted that there are some difference between summer and winter which mean that the slight peak during the day is larger during the summer and that the profile for the winter is more spread out. This can be seen in appendix B.2 together with plots over the yearly average for Truck scenario 2 and 3.

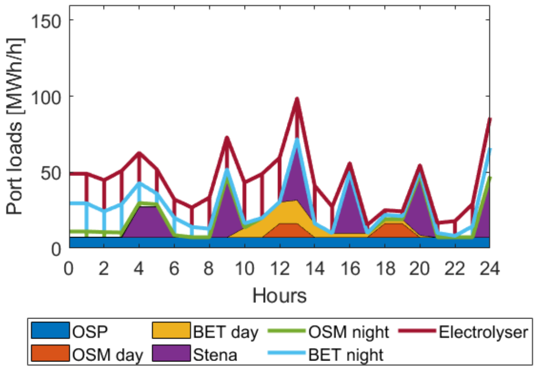

Figure 4.12: Total load for the Base scenario with flexible loads

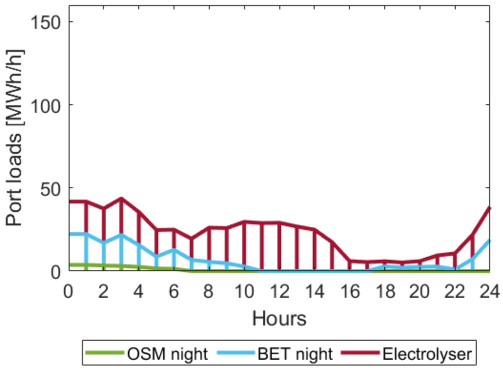

Figure 4.13: Base scenario with flexible port loads only

Although the distribution of the loads is different in the Base and Truck 2 scenario, the peak is about the same. The peak for the Truck 3 scenario is however lower when the flexible loads are used compared to when they where plotted according to demand.

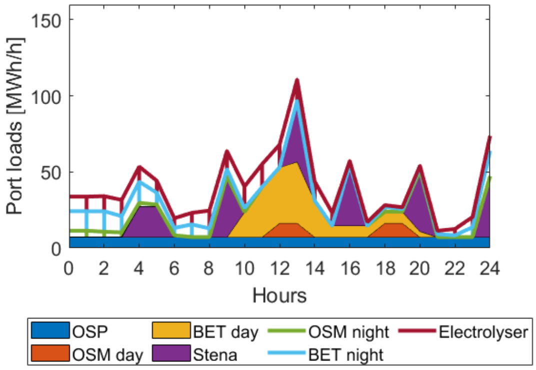

Figure 4.14: Total load for the Truck 2 scenario with flexible loads

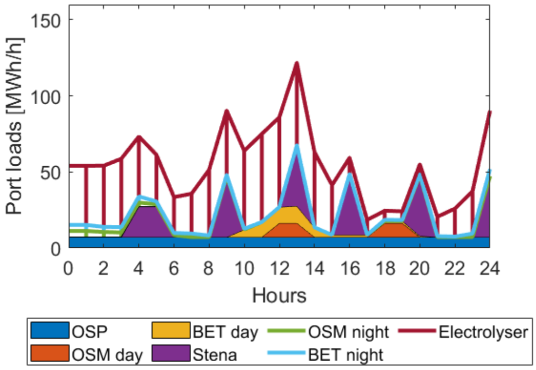

Figure 4.15: Total load for the Truck 3 scenario with flexible loads

The methanol scenarios change similar to the truck scenarios. Interesting to notice is the flexible H2 production compared to the constant methanol production considering that the demand for both are largely dependent on the methanol demand. It might look like the methanol production decrease when the electrolyser decrease after noon but it actually have a constant production during the whole day. This is because of the high investment cost of the methanol production unit which makes it expensive to invest in a larger capacity and only produce during low electricity price hours.

In contrast to the truck scenarios, the methanol scenarios actually increase the peak when the flexible loads are used. Observe that the y-axis for figure 4.11 stops at about 350MWh/h while figure 4.16 have a y-axis that is about 100MWh/h higher.

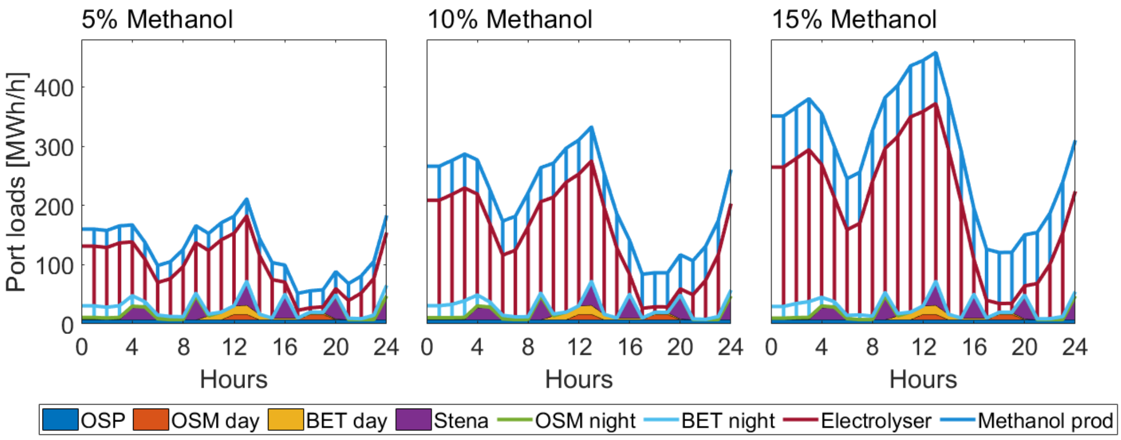

Figure 4.16: Total load for the methanol scenarios with flexible loads

4.2.2 Electricity production

Figure 4.17 presents a dispatch plot for a typical summer week as well as a typical winter week for the Reference scenario and shows the distribution of how the technologies are used. The Reference scenario is presented in this figure to describe how the system generally operates, there will be differences between the scenarios but that will be further investigated later in this section. The figure clearly shows the diurnal pattern of the production from solar PV and how the batteries are used as complement to the PV during the evening to spread the energy from the daily production. The CHP's are used as a constant base load, producing both electricity and heat which is presented later. However, during the summer week the production from solar PV is large meaning that one of the CHP's is turned off while the other one is used as complement during night. The figure also shows that the production from the new technologies in the city are also complemented with electricity imported from outside the city limits.

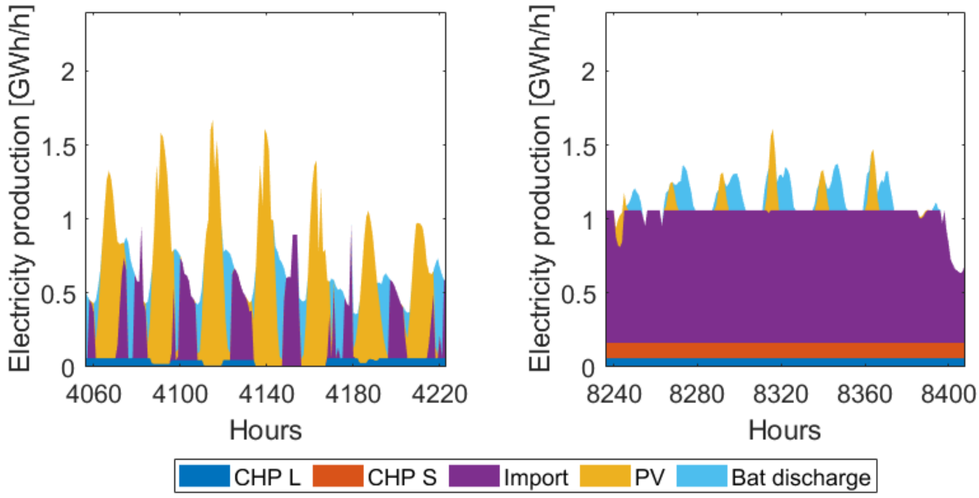

Figure 4.17: Dispatch plot for a summer week and a winter week

Figure 4.18 below presents the yearly electricity production for the Reference scenario to the left. To the right figure 4.18 shows how the electricity production changes relative the Reference scenario for all the different scenarios, i.e., how the electricity system is affected by the added loads from the port. A technology small or not showing on the right side therefore only means that it is generating a similar amount of energy throughout the year compared to the Reference scenario and not that it has stopped producing electricity. The electricity production is presented for all electricity production technologies in Gothenburg, including imported electricity. Values below zero indicate that a technology is used less compared to the Reference scenario.

The Reference scenario having a total of about 7TWh compared to present-day of about 4TWh is because of the assumptions of electric cars in the future and that the city demand will increase with about 50% excluding the port. From this it is clear that the major electricity contributors in the future are imported electricity and PV generated electricity with CHP technologies generating most of the remaining electricity. This is the case even though the import capacity remains at present-day levels, as is assumed for all scenarios.

Figure 4.8 shows the added loads in the Base scenario. These added loads resulted in the increased electricity production as can be seen figure 4.18 below. It resulted in an increase of electricity production of about 500GWh or 7% compared to the Reference scenario. The distribution of technologies are similar, mostly increase in import, PV and CHP L but also a small decrease in use of CHP S. Of the CHP technologies the CHP S is the one with the lowest alpha, meaning that it is mainly built for heat production. CHP S is also the CHP technology that exist in Gothenburg today which is described in section 2.4. This decrease in CHP S will occur for most of the observed scenarios and is probably because of the heat demand. The heat demand is never changed but the heat production will increase because of the investments in CHP technologies. When other CHP technologies are invested in because of the increased electricity need they will always produce some heat and therefore reduce the need for a CHP built for heat, i.e., CHP S.

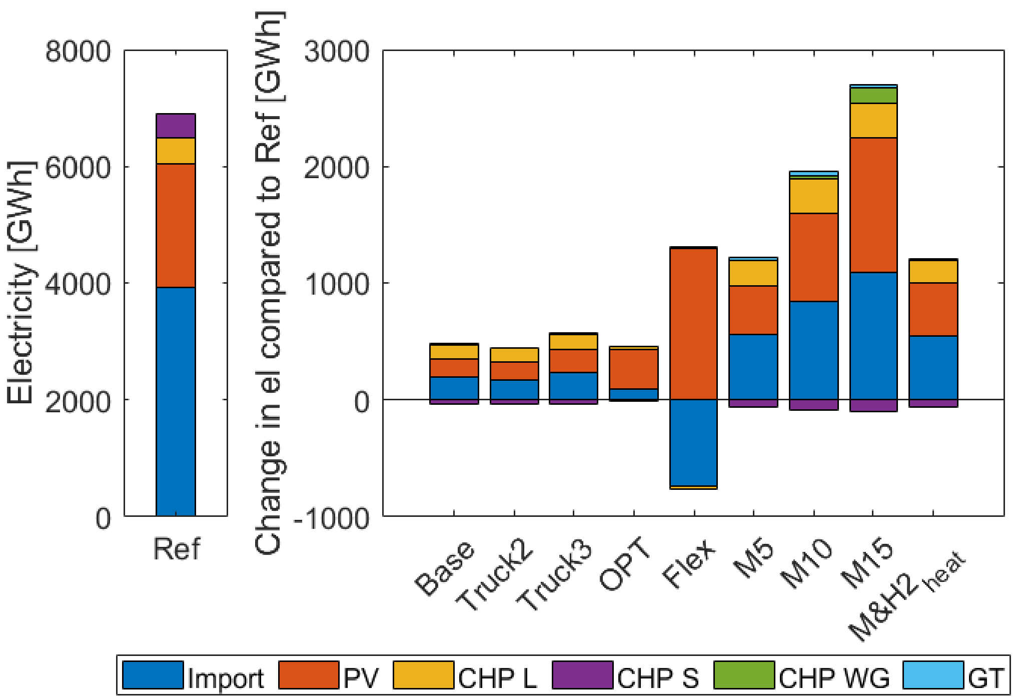

Figure 4.18: Electricity production for each technology per year for the Reference scenario and all other scenarios compared to the Reference scenario

The Truck 2 and 3 scenario in figure 4.18 refers to the to the added loads that is showed in figure 4.9 and 4.10, respectively. As figure 4.9 and 4.10 show, the demand is higher for the Truck 3 scenario and is why the production for Truck 3 in figure

4.18 is higher as well. Further more is the production for the base scenario in the middle of Truck scenario 2 and Truck scenario 3, which is expected, since Base is using the Truck scenario 1 which can be seen as a mix of the two as described in 4.1.1. The OPT and Flex scenario do not have any added load but rather use the Base scenario and give the system more flexibility through the use of more or less flexible charging of EV as described in 3.3.2. These scenarios are clearly suitable for an increased PV production. This effect is because of the good combination of using PV and batteries in an energy system, where the car is used as the battery.

M5, M10 and M15 are the scenarios including methanol production with 5, 10 and 15%, respectively which are presented in figure 4.11. These are big loads for the system which can be seen in the large increase of production in figure 4.18. Most of the increase is in import and PV but it is also interesting to notice the increased electricity from the CHP L with a larger methanol production and the CHP S that have the opposite reaction. This supports the theory that more investments in new CHP decrease the need for the old CHP S that is focused on heat production. In M10 and M15 there are however an additional CHP, the CHP WG. This CHP have a higher alpha value and is therefore invested in almost purely to produce electricity and will therefore not reduce the need of the CHP S as much as the CHP L. CHP WG use biogas as fuel which is a more expensive fuel compared to the other CHP technologies which use biomass. The methanol scenarios also have an increased production from GT but it is still a small part of the total electricity supplied to the system.

The scenario called M&H2$_{heat}$ utilise the waste heat from electrolyser and methanol production. The M&H2$_{heat}$ scenario is similar to the M5 scenario since it have the same demand inputs but with additional heat production from the utilisation of waste heat from the electrolyser and methanol production. The M&H2$_{heat}$ scenario does however have a larger energy production from PV and lower CHP L compared to M5. This is reasonable since less heat is needed in the M&H2$_{heat}$ scenario. Another effect of this is the increased need of battery capacity compared to M5 as can be seen in figure 4.19.

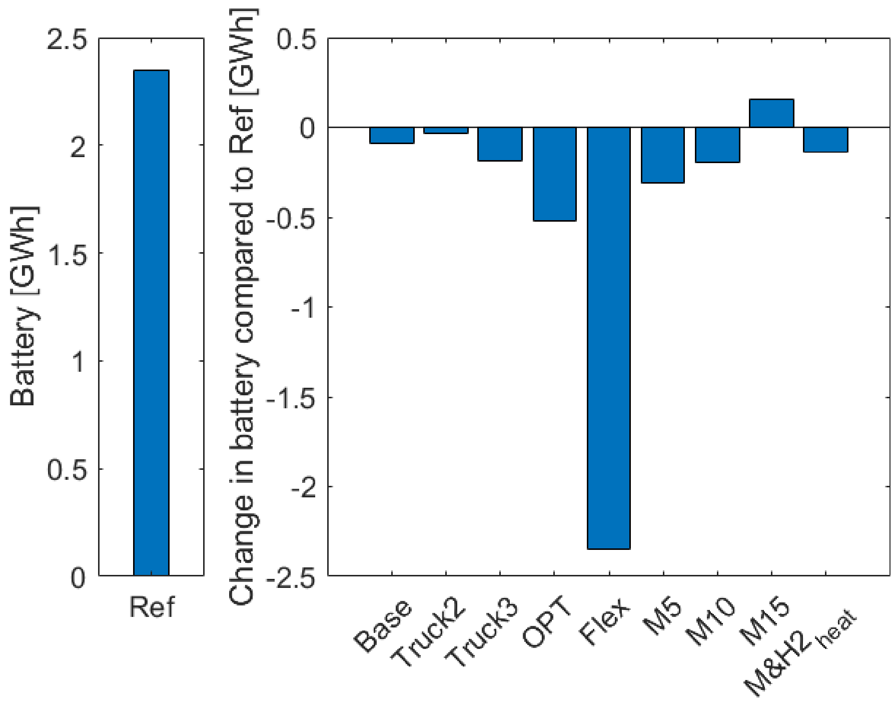

Figure 4.19: Battery capacity for each scenario compared to the Reference scenario

With the large investments in PV, the system will need batteries to utilise the electricity as can be seen on the left side in figure 4.19. What is interesting is the decreased investments in batteries for most of the scenarios, as can be seen on the right side of figure 4.19, even though the investments for PV increase for all scenarios as presented in figure 4.18. This is possible due to that the loads of the port which are added in all scenarios have a peak at 13:00. This coincides with the PV production which means that much of the added PV production can be directly used for port loads instead of charging the battery which then leads to a decreased need for battery investments. Furthermore is it clear that scenarios with more flexible loads, such as hydrogen production, have lower demand for batteries. The extreme case of this would be the Flex scenario where no stationary battery is needed since all BECs in the city are already acting as one. The only scenario needing an increased size battery is the M15 scenario. This is due to the large demand that is evenly spread out over all hours, meaning that the PV production can not be used as efficiently as for loads focused on midday.

4.2.3 Heat production

The model is also required to match the heat demand with heat production. The heat production for the Reference scenario is presented in figure 4.20 which shows the distribution of the heat production technologies within the city. The figure shows that the CHPs and the waste heat have the highest amount of full load hours (FLH) and have the most constant production over the year. The HOBs are mainly used as peak production during winter hours when the heat demand is large. The HP is also mainly used as peak production but since the HP is run on electricity it is also used during hours when the electricity price is low. For example, during the summer when the production from solar PV is large or when the import electricity price is low, the import electricity price can be seen in appendix A.1. The EB is also used during hours with low electricity prices. The model also invests in a PTES which is used to help with the large heat demand peaks but also as a way to make use of the cheap electricity during the summer.

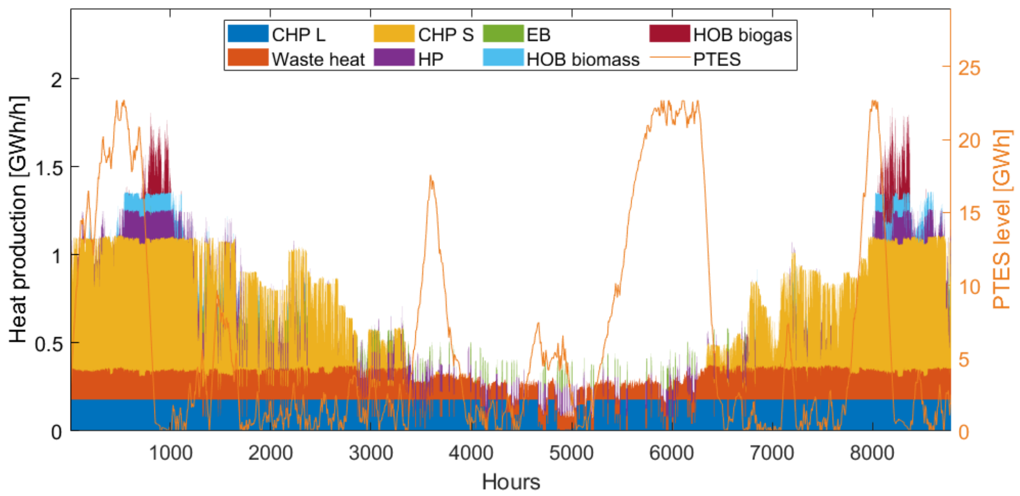

Figure 4.20: Heat production dispatch plot over a year for Reference scenario

Figure 4.21 below presents the yearly heat production for the Reference scenario to the left. To the right figure 4.21 shows how the heat production changes relative the Reference scenario, as a results of the added port loads, for all the different scenarios. The Reference scenario mostly consists of waste heat, CHP L and CHP S. The waste heat is used evenly in all scenarios and is therefore not shown in any of the scenarios. Interesting to note is that CHP L and CHP S is a relative small part of the Reference when observing the electricity production in figure 4.18 but a major part when it comes to the heat production. This large difference is because of the low alpha values which means that the CHP have a high share of heat production.

Observing the right part of figure 4.21 it is clear that the heat demand is not increased since the positive and negative part of the bar is equal. This means that all new investments that produce heat(mostly the CHP L) allows less investments in other heat production technologies or alternatively, that it is possible to reduce the production from the existing technologies to compensate for the new heat production. The technology that decrease its production will follow a pattern throughout all scenarios, with some exceptions. The pattern is usually that CHP S decrease most followed by HP, HOB WG and HOB Bio, in that order. The CHP S is a production technology that operates with high FLH and since the system invests in CHP L, which also have a similar pattern, they will for the most part replace each other. Due to the possibility to invest in TES and that CHP S is an already existing technology, some of the peak and intermediate technologies such as HP, HOB WG and HOB Bio can be replaced as well. The raised level of constantly produced heat makes TES a good investment since it can fill up during periods of low heat demand when the CHP technologies still operate to cover the electricity demand. The TES can then discharge at peak heat demand and in that way decrease the need for peak heat technologies. This would mean that an increased TES investment would be needed, which is true for all except OPT and Flex as can be seen in figure 4.22.

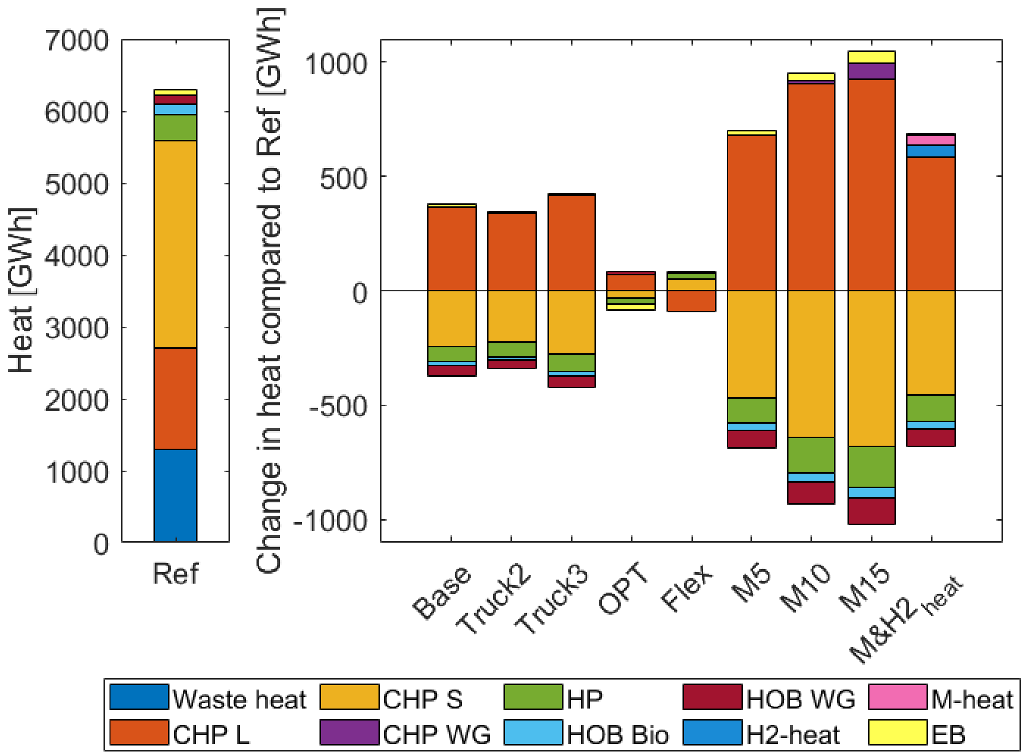

Figure 4.21: Heat production for each technology per year for each scenario compared to the Reference scenario

When observing heat production, the OPT and Flex scenarios do not follow the same pattern as the other scenarios. OPT is the most similar since it invest in CHP L but instead of decreasing the production of HOB WG it decrease the production of EB instead. This is because EB is usually used when the electricity price is cheap, when this happens in the OPT scenario it charges the EV instead and can therefore not use the EB as much. The Flex scenario does not follow the same pattern as any of the other scenarios since it decrease the investment in CHP L. This decrease can be explained by the large increase in PV that is possible in the Flex scenario which makes the CHP L unnecessary. The decreased investment in CHP L however leads to that a small amount of heat production is removed which in the case of the Flex scenario is replaced with CHP S and HP. It is reasonable to exchange the CHP L to CHP S since the electricity demand is satisfied with the PV and the HP also seem to be a good choice in a system with a large share of cheep solar power.

The M&H2$_{heat}$ scenario produce less electricity from the CHP L compared to M5 as discussed in previous section. This is true for heat as well. With the remaining heat produced by the waste heat from electrolyser and methanol production. A consequence of this is that the CHP S will produce more heat for M&H2$_{heat}$ compared to M5, which in turn will result in a lowered need for TES which can be seen in figure 4.22. The lowered need for TES can be referred to the more flexible production of the CHP S compared to CHP L.

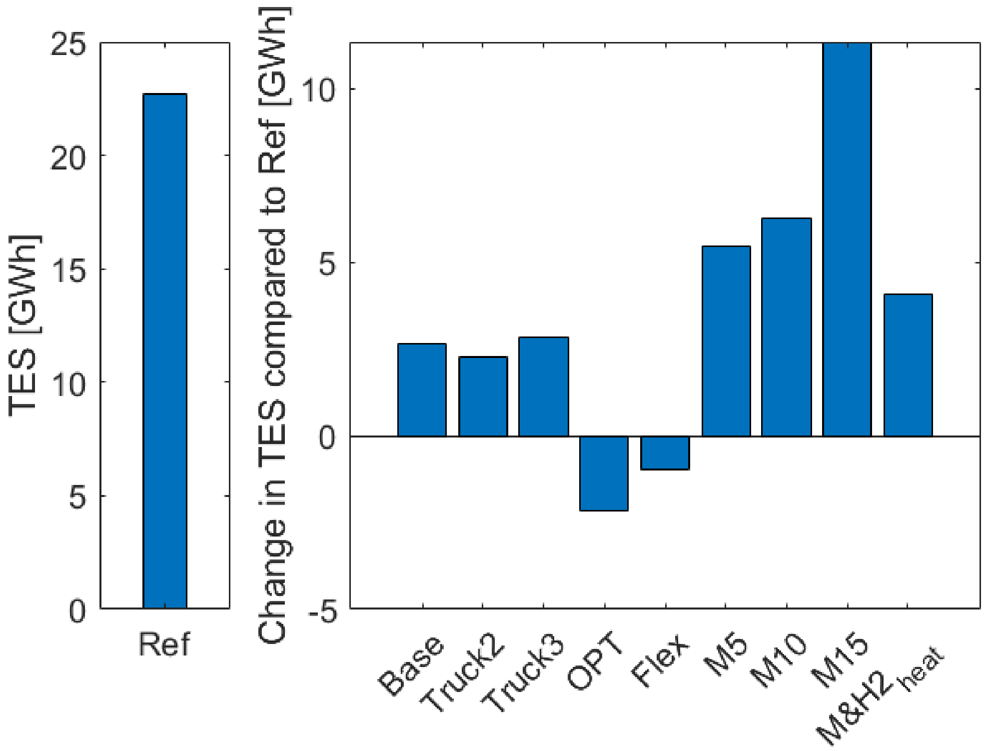

Figure 4.22: Thermal energy storage capacity for each scenario compared to the Reference scenario

4.2.4 Electricity, heat and total system cost

Now that the different scenarios have been observed, it is interesting to look at how the cost for electricity, heat and the total system changes between the scenarios as a result of the added loads from the port. All the different scenarios will be compared to the Reference exactly as in the previous section. The average electricity cost is presented in figure 4.23 and is based on the marginal values of equation 2.2 which is the electricity balance equation. In this equation, D_t also includes the demand from the port presented in section 3.4. Interesting to notice is the relation between electricity cost and the invested electricity production in figure 4.18. Larger investments in production, due to a larger demand from the port, seems to increase the yearly average electricity cost in most scenarios. A reasonable reaction considering the low import prices that becomes a decreased part of the total in an expanding system because of the fixed import capacity. There are however two exceptions, the OPT and Flex scenario. The OPT scenario have a low increase in electricity cost because of the increased flexibility that leads to increased PV production. OPT is however still more expensive than the Reference scenario, which is because of the increased demand from the port compared to the Reference scenario. The Flex scenario can however become even cheaper than the Reference scenario, this is of course because of the massive flexibility that is added for free to the Flex scenario.

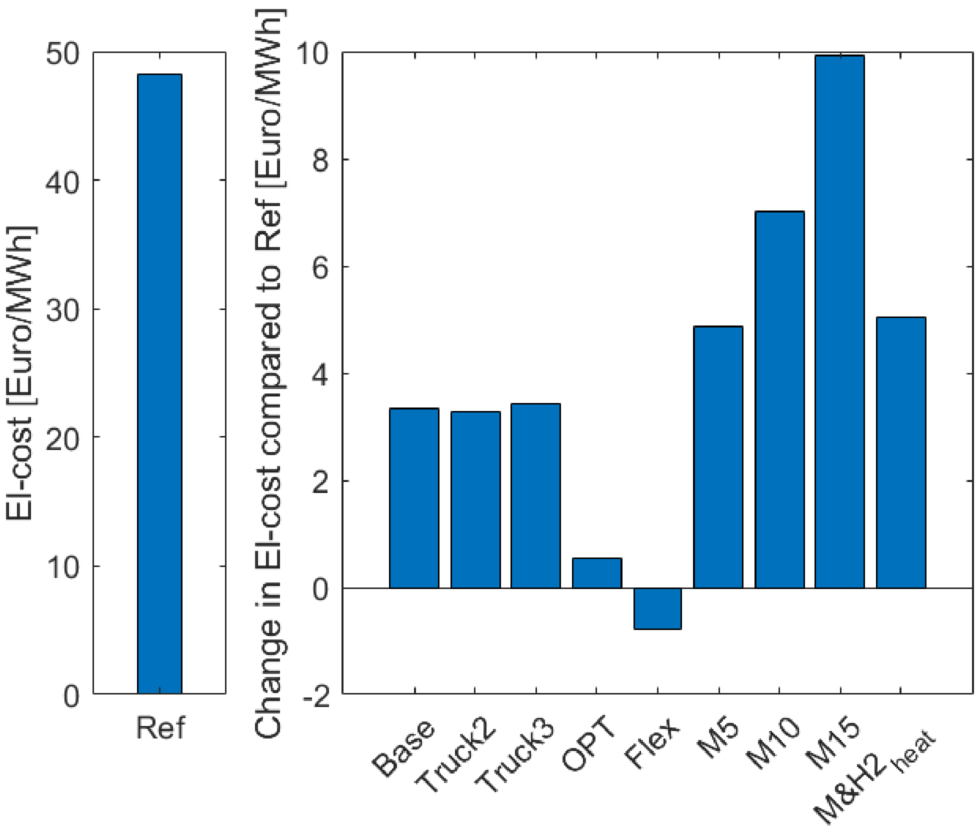

Figure 4.23: Yearly average electricity cost for each scenario compared to the Reference scenario

Similar to the electricity, the average heat cost was calculated based on the marginal values of the heat balance presented in equation 2.3. This is presented in figure 4.24 which shows that the average heat cost is lower than the electricity cost, which could be expected. What can be more interesting to look at is that the cost for electricity and heat are almost opposites, when observing the differences. This effect can be referred to the increased investments in CHP L and the decreased investments in HP and HOB. The combination of using constant heat production and TES instead of peak heat production technologies, as discussed in section 4.2.3, result in a cheaper heat cost.

The OPT and Flex scenario are the outliers in heat cost as well as in the electricity cost. But not that they become cheaper than the other scenarios but rather the opposite. They become more expensive because of the small investments in CHP L and large investments in PV. This combination will result in more expensive heat since no cheap heat is produced with CHP L and the PV does not produce any heat at all and will therefore not contribute to a lowered heat cost.

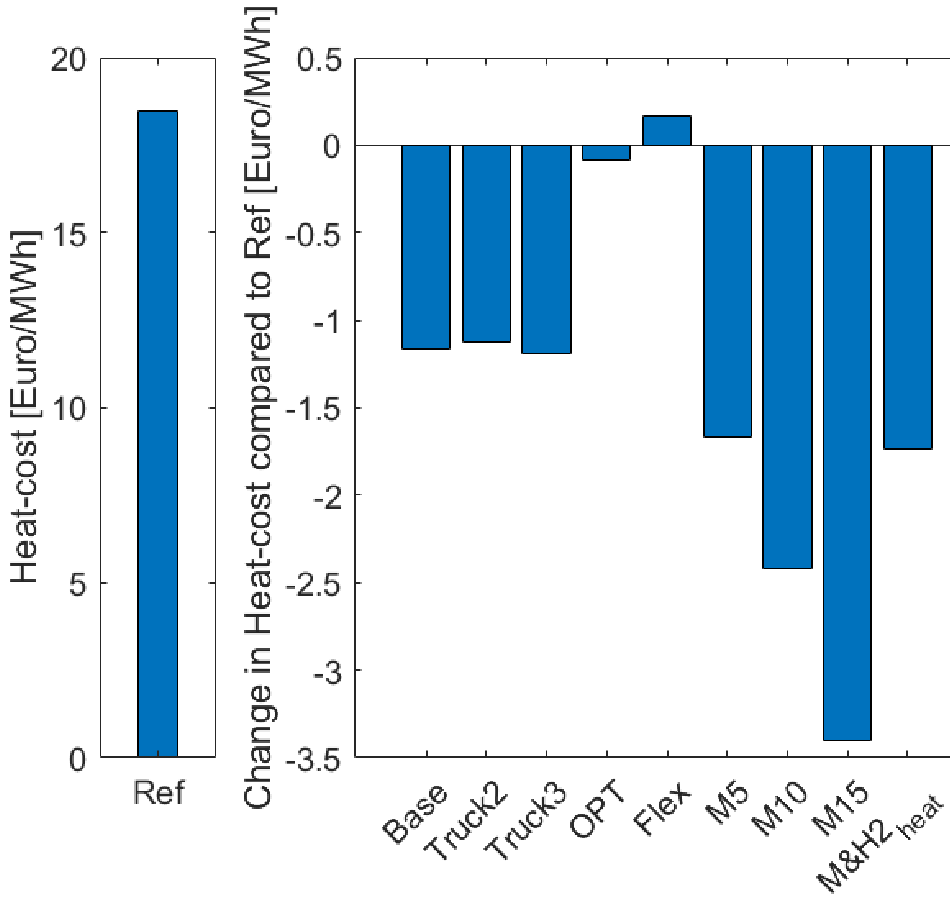

Figure 4.24: Yearly average heat cost for each scenario compared to the Reference scenario

The total cost for the system will, similar to the electricity cost, increase with the increased demand from the port which can be seen in figure 4.25. But since the total system cost consist of investment and dispatch cost will some scenarios be cheaper even if the they have the same amount of energy production. The OPT and Flex are two examples that are cheaper than Base even though they have exactly the same electricity and heat demand as the Base scenario. The lower cost of these two are because of the increased flexibility that they have compared to the Base scenario and therefore the opportunity to invest in cheaper electricity production. Also that this increase in flexibility is "free" since no cost for BECs is included in this model unlike the option to invest in stationary batteries. Truck 3 scenario also have an increased flexibility because of the opportunity to produce and store H2 instead of charging trucks in fixed hours during the day. The cost will however increase because of the increased need of energy when FCTs are used instead of BETs and the net effect seem to be more expensive. The same is true for the methanol scenarios. The methanol scenarios can in theory invest in an oversized methanol production unit and only produce during low electricity cost hours and store in tanks. The methanol production unit is however quite expensive and therefore the methanol production use very little flexibility. Besides flexibility can the total system cost decrease because of the use of other technologies which is the case for the M&H2$_{heat}$ scenario. As for the electricity and heat cost is the difference to small to see in the figure but the total system cost for M5 is higher than for M&H2$_{heat}$. Which is reasonable since M&H2$_{heat}$ basically utilise more of the input energy in the H2 and methanol process.

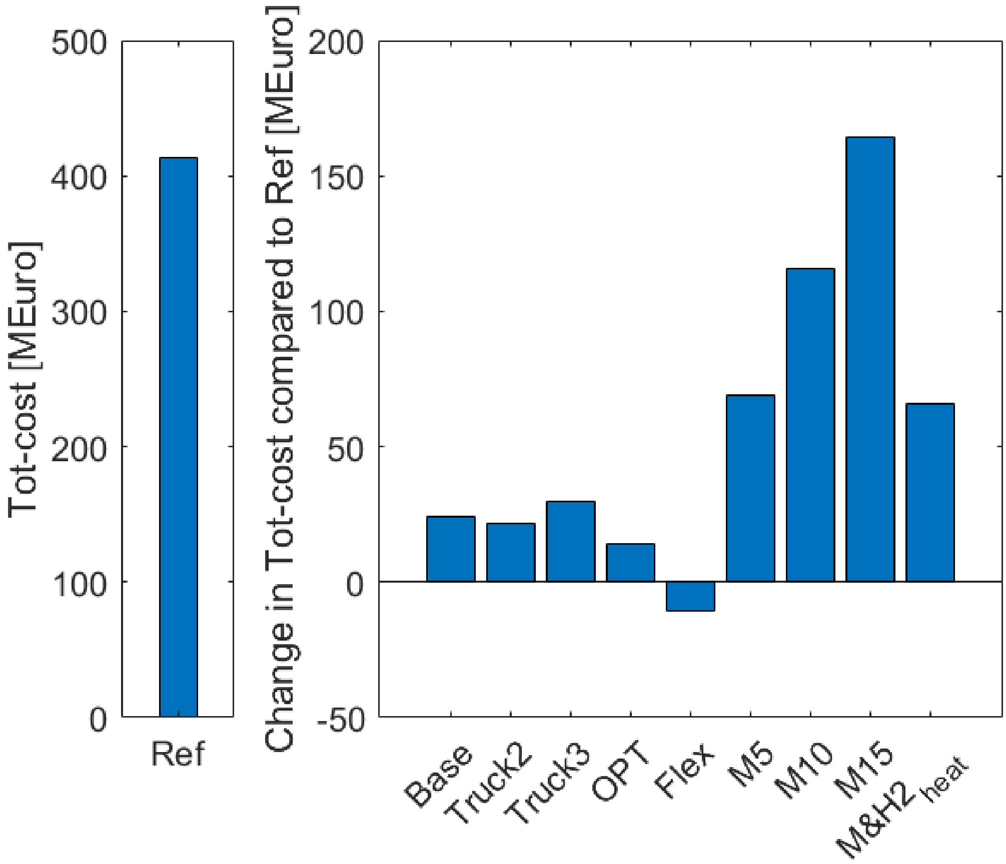

Figure 4.25: Total cost for each scenario compared to the Reference scenario

4.2.5 PV limitation

Since the annual production from PV became about 2000GWh for the Reference scenario (and even more for the other scenarios) and the limit for PV presented in section 2.4 was 650GWh, the production from PV was limited to understand the impact of the amount of solar PV. This section will therefore investigate the Gothenburg energy system with a PV capacity limit set to 0.65GW since the full load hours for PV in Gothenburg is about 1000h. Because of this large change in the system a new Reference scenario(Ref-PV065) was simulated which is exactly the same as the original Reference scenario but with a maximum of 0.65GW PV capacity. Ref-PV065 will then be compared to a new Base scenario(Base-PV065) which is exactly the same as the original Base scenario but with the limit on PV capacity set to 0.65GW to compare the impact of the port loads on the Gothenburg energy system with regard to this limitation.

Figure 4.26 below shows the electricity generation of Ref-PV065 and Base-PV065. From this figure it is clear that the import is the major electricity supplier for both scenarios. The PV production is at the maximum capacity in Ref-PV065 and can therefore not be expanded further in Base-PV065. The remaining electricity production is covered by CHP L and CHP S. To meet the added demand from the port, Base-PV065 increase the electricity production similar to the distribution that can be observed in Ref-PV065. Most of the increased electricity consists of increased import with a small increase in CHP L and GT and a small decrease in CHP S. Some of the PV production can in Base-PV065 be used to cover the new port loads and therefore reduce the need for battery investments as can be seen in appendix B.1.

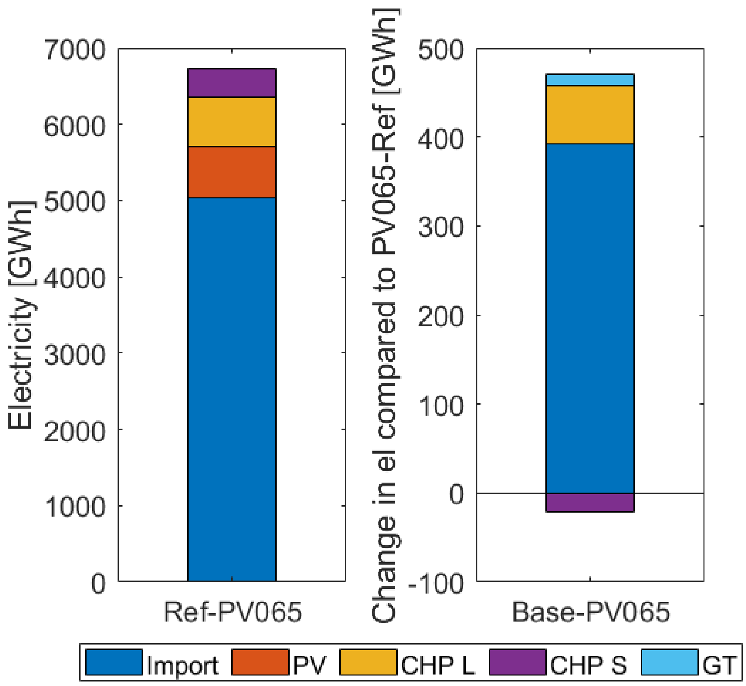

Figure 4.26: Electricity production for each technology per year for the PV065-Reference scenario and PV065-Base scenario compared to the PV065-Reference scenario

The heat production for Ref-PV065 will not be affected to the same extent as the electricity production since the limitation added is related to a technology that only produce electricity. The yearly heat production for Ref-PV065, presented in figure 4.27, is therefore similar to the Reference scenario presented in figure 4.21. The share of heat from CHP L is the most significant difference, which is higher in Ref-PV065 compared to the reference scenario. The Base-PV065 scenario in figure 4.27 follow the same pattern as the Base scenario presented in figure 4.21.

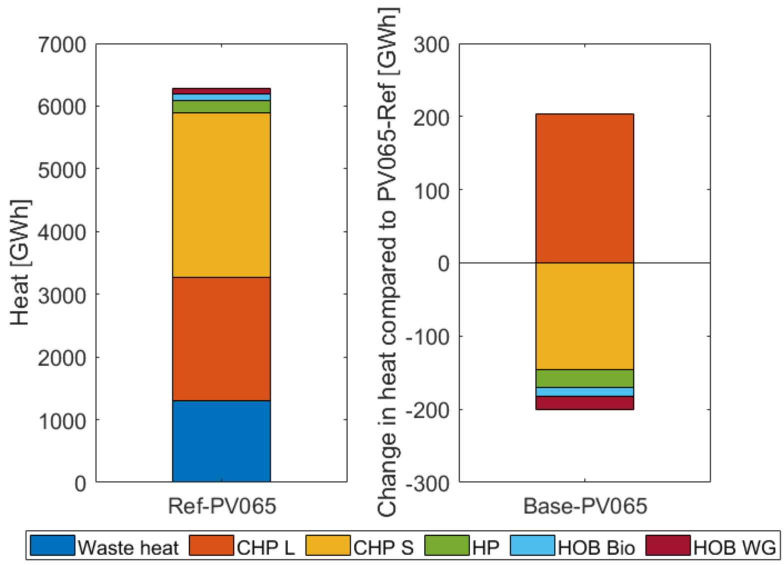

Figure 4.27: Heat production for each technology per year for the PV065-Reference scenario and PV065-Base scenario compared to the PV065-Reference scenario

The yearly average electricity cost for the Ref-PV065 and Base-PV065 can be seen in figure 4.28 below. The increase that can be observed in the Base-PV065 compared to the Ref-PV065 is expected since it has a higher electricity demand due to the added loads from the port. It is however interesting to notice the average electricity cost for these scenarios compared to the regular Ref and Base scenario which can be seen in figure 4.23. The Ref-PV065 is about 7Euro/MWh more expensive compared to Ref and the Base-PV065 is about 5Euro/MWh more expensive compared to Base.

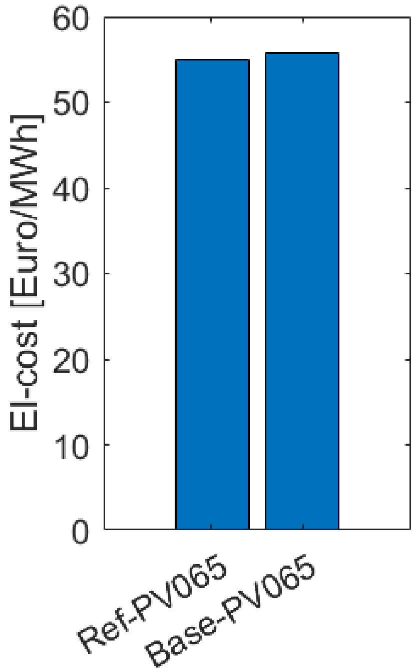

Figure 4.28: The yearly average electricity cost for the PV065-Reference and PV065-Base scenario

5 Discussion

The purpose of this project was to investigate the electrification of the Port of Gothenburg and how it might affect the Gothenburg energy system. Multiple future scenarios were investigated to include a variety of possible futures. The previous section described the outcome of the different scenarios while this section will discuss how they differ and why. The section also presents a discussion of uncertainties in the project as well as future work which could be performed to complement the work done in this project.

5.1 Interpretation of results

The previous section presents results of both the fixed and flexible loads which are likely to be added to the port in a future zero emission scenario as well as the energy production required to meet the demand of both the new loads as well as the rest of Gothenburg. The total load presented for the base scenario in figure 4.8 suggests that the fixed loads from the port have the largest peak during the middle of the day (13:00) when multiple types of vehicles are charged at the same time. This pattern for the fixed loads suggests that the demand could be well suited to be met by production from solar PV. Figure 4.12, which presents the daily distribution of the flexible loads in the port, shows that the hydrogen is produced during the night when the demand from the rest of the city is low as well as the hours in the middle of the day. This result indicates that both the fixed and the flexible loads could be met by production from the solar PV. These results can also be backed by the yearly electricity production presented in figure 4.18 which shows that the added loads enables the use of an increased amount of solar energy for almost all of the presented scenarios. For the production of solar PV it can also be noted that the stationary batteries also increase the use of the PV production by charging during the day to enable help to the system during the hours when there is no sun. However, figure 4.19 shows that the investments in stationary batteries actually decrease when the loads in the port are added. This strengthens the theory that the port loads are well suited for PV production since it suggests that a larger share of the electricity produced by PV is used directly instead of shifted to later hours.

The results clearly shows that the port loads increase the total amount of energy needed in the system which is expected since a large share of energy is added to the system compared to the Reference scenario. In addition to the peaks during the day which can be met by production from solar PV, there is also a demand which could be described as base load and requires electricity continuously during the day. These loads consists of trucks and machines which are charged during the night as well as the onshore power required by ships. These loads are difficult to match with PV production and instead requires a production technology with a high amount of FLH to be able to produce electricity continuously to match the demand. In the model this demand is mainly met by CHP which can produce both electricity and heat for most hours of the year and can thereby contribute to cheaper heat as well as to meet the electricity demand.

The peak production from PV and the base load production for the CHPs contribute to a significant amount of the electricity used in the city but the main part is still electricity imported from outside the system boundaries. This is true for all scenarios and shows the importance of the imported electricity even if significant investments are made in local production. All scenarios are simulated with an upper capacity of imported electricity which represent the present import capacity to the city. Based on the results, this indicates that the loads from the port could be met without extra investments in transmission capacity to the city. This interpretation is however more difficult to make for the scenarios with local production of methanol since they (M10 and M15) include investments in another type of CHP which mainly produce electricity. This could indicate that the amount of imported electricity is close to maximum meaning that it is more profitable to invest in local electricity production instead of importing during the more expensive electricity price hours. The CHP WG is however fuelled with bio gas which also can be directly used for production of methanol (could also be biomass). This means that the large increase in electricity demand could be removed and the bio gas could be directly used for methanol production instead. This would eliminate the extra step of producing electricity and probably increase the overall efficiency of the methanol production. This would be interesting to investigate but since the production of bio fuels was excluded in this project, no further investigation was made.

The main results are presented without the limit on PV production to understand what technologies are best suited to meet the loads in the port. The limit on PV, presented in section 2.4, is also based on the use of PV on roofs as well as one large solar park. This could well be the maximum potential of solar PV in Gothenburg but development in the technology could also see the use of PV on walls and larger implementation of PV on areas which otherwise are unused such, as parking lots. The implementation of PV in the city area could also be dependent on the acceptance of the technology and if the community can see the gain of larger implementation it is not impossible that the limit is raised. The results also shows the impact of the PV limit and presents a scenario where the investments in CHP increase even further to replace the production from PV. The main increase is however in the imported electricity to cover the demand. This increase does not contribute to any investment costs in new technologies but the resulting cost of electricity, presented in figure 4.23 for all regular scenarios and figure 4.28 for PV065 scenarios, shows a significant increase in the costs for limiting the cheap production from PV. This suggests that the system needs to import electricity at more expensive hours compared to the base scenario without the limit on PV. The large increase of imported electricity might also suggest that the amount of imported electricity is close maximum which would mean that an increased demand could lead to investments in pure electricity production which could increase the system cost even more. In general this indicates a great value of cheap local electricity production.

The local production of methanol, optimized in the M5, M10 and M15 scenarios indicates that a large scale production of shipping fuel is very difficult to make a reality, considering the large amounts of energy required already at a production of a few percent of the total fuel provided today. For the production to be reasonable there would probably be need for significant investments in cheap electricity or import capacity. A way of increasing the value of the production could be to make use of the heat from the production and figure 4.21 shows that the production adds a share of heat which can be used to replace other heat production. However, the impact is relatively small considering the added costs of the production.

The heat demand in the city is unaffected by the loads in the port but figure 4.21, which presents the change in heat production, shows a significant difference between the Reference scenario and the scenarios containing the port loads. The main reason for this is the investment in CHP which is added to the system to provide electricity but at the same time produces heat. This heat production enables less investments in more expensive heat production technologies which also can be seen by the decrease in heat costs presented in figure 4.24. In contrast to the heat costs, the mean electricity costs presented in figure 4.23 are higher for all scenarios except for the scenario allowing V2G from BECs. This can be explained by the increased demand of electricity and it might be assumed that a larger amount of electricity is used during hours when the electricity price is high. The electricity price also shows the same pattern as the total system costs presented in figure 4.25 which indicates that electricity cost is a larger share of the total cost compared to the heat cost.

To summarise the results, a significant share of the loads in the port are well suited to be met by PV production because of the fixed diurnal charging patterns which coincides with the potential for solar power. The loads also shows patterns of extra need for base load production to cover the hours of the day when the PV production is unavailable. The limit on transmission capacity to the city does not seem to limit the addition of the port loads until the methanol production is added. When the methanol production is added the system becomes strained since it have to invest in the CHP WG which can produce during hours when the import is insufficient. Another way to see that the system becomes strained with the large amounts of methanol production is the large increase in electricity cost. This increase in electricity cost is both because of that the system needs to import during high cost hours and both because of the production of electricity with the CHP WG. The system also becomes strained when limiting the production from PV. This can be seen in the amount of import and the electricity cost, both of which increase significantly. This indicates that the system is strained since it must import regardless of the price during more hours of the year.

5.2 Uncertainties in work

The profiles presented for the loads in the port have been made by assumptions based on present use of the vehicles. The development of these vehicles could present differences in efficiency as well as how the vehicles are operated which could result in changes of the demand curves presented in the thesis. An example of this could be the loads from the BETs which are based on the assumption that all trucks needs to be charged during the day which results in a peak during the middle of the day. A significant development of batteries could make this assumption irrelevant and thereby change the load profile for both the trucks and the port. The fixed loads are also assumed to be located on certain hours based on present patterns. If these hours are changed, then the profiles would also change which could impact the results.

The electrification of ships also contributes to uncertainties in the work since it is difficult to asses in what direction the sector will take to reduce its emissions. Onshore power is a good way of reducing the local emissions close to the port and by allowing the ships to run on engines only during extra high demand hours, the emissions could be reduced without increasing the electricity demand during the most expensive hours. However, to implement the technology on a large scale it is not enough that a few ports invest in the needed infrastructure since the ships will need the onshore power on most stops for the investment to be feasible. This means that for the technology to have a real breakthrough, a large share of the ports needs to provide the possibility for onshore power. Another technology which could lead to different loads from ships in the port is hybrid technology which could be a solution to increase the efficiency of the ships and decrease the emissions. From the perspective of the port, the hybrid technology could mean that the ships would require direct charging from the grid while at berth and could thereby increase the impact from the ships. However, the hybrids could also contribute to flexibility in the system by allowing flexible charging.

Another factor which could affect the presented results is the charging of BECs. The charging of BECs are not included as loads in the port but still have the opportunity to affect the results by adding a large share of flexibility to the system. Except for the OPT and Flex scenarios, the main results are presented with only fixed charging of the BECs to enable comparisons between the scenarios. The results for OPT and Flex does however show that the flexibility has a significant impact on the system and the Flex scenario, which include the base scenario from the port, even presents a lower total cost than the Reference scenario. This indicates the large impact of using BECs to increase the flexibility in the energy system. The degree of flexibility from the BECs is however difficult to asses and requires additional work. The impact of the BECs is also dependent on the estimation of the available storage capacity which could be impacted of the estimations of the number of BECs as well as the size of each battery.

5.3 Future work

The focus of the thesis has been to investigate the loads in the port and how the energy system of Gothenburg is affected by the new loads. The work has however not included "bottlenecks" in the system and instead investigated the total loads and production from the entire system. This could be the basis for further investigation to understand the impact of the transmission capacity to Hisingen and the port area. The port is also divided into several areas where the transmission capacities are different for the different parts of the port. Here, it is also interesting to understand where the loads are located in the port in relation to possible bottlenecks in the area. The capacity which has been considered is the import capacity to the city. This capacity is, as earlier mentioned, based on the present capacity and could be investigated to see the impact of new investment in the transmission capacity to allow for a larger amount of imported electricity to the city.

The thesis is also based on an assumption of "business as usual" in the port which means that no further development of the port is accounted for. To understand the future loads in the port even further, an investigation of future trade and transport in the port could be performed to estimate the development of the daily amount of vehicles in port.

6 Conclusion

The purpose of the thesis is to investigate an electrification of the Port of Gothenburg and what new loads that would lead to. As an extension of this, the work also aims to understand the impact of these loads on the energy system of the city of Gothenburg. The thesis presents several scenarios to understand the impact of different future developments and also to see the impact from different technologies. The work shows that an electrification of the port adds a significant share of loads to the energy system and that investments in the system are required to meet the future demand. Since the Base scenario was used as a reference point for the other port scenarios, the numbers presented below will refer to the Base scenario.

The work shows that the new loads, excluding the methanol production, represent a peak of approximately 100MW during the middle of the day but also that a significant share of the loads are distributed over the day. These new loads increase the overall demand of electricity with about 0.5TWh/year. This indicates that investments in both peak and base load electricity production are required to meet the demand from the port. The system presents significant investments in solar PV which indicates the value of cheap local electricity production. But also that PV production is well suited for the new port loads since they both peak around midday. The system also invests in CHP to provide the system with continuous electricity production in order to meet the new demand.

The city's heat demand is unaffected by new loads from the port but the investments in CHP mean that the production to cover the demand is changed as a result of the added loads. This new heat production contributes with cheaper heat compared to pure heat production technologies which leads to a 6% lower heat cost in the system. The cost of electricity is however 7% higher due to the required investments which also affect the total system cost when the port is included. The total system cost increase with about 6%.

The annual production limit of 650GWh from PV due to lack of area has a significant impact on the way in which the electrification of the port is met. Both because it is a large reduction of the yearly energy production of about 2000GWh. But also because the work shows that the loads are well suited for PV production and restrictions in the technology would indicate that investments in other production technologies, less equipped to meet the demand, would be required. This also have a direct impact of the electricity cost in the system which would increase with about 10%.

A future study including an investigation of bottlenecks to Gothenburg, Hisingen and the port would be of great interest. The import capacity to Gothenburg would be interesting to see since the system would most probably make different investments with increased import capacity. The bottlenecks to Hisingen and the port is also important to observe since they might show that additional transfer capacity investments are required. It could also show that the electrification alternatives has to consider these bottlenecks and reduce peaks by increasing the flexibility of the loads.

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A
Appendix

A.1 Electricity price

Figure A.1 presents the electricity price used as import to the city of Gothenburg in the optimisation model. The electricity price is a projection for 2050 with 100% electrification of cars electrified and charged without smart charging.

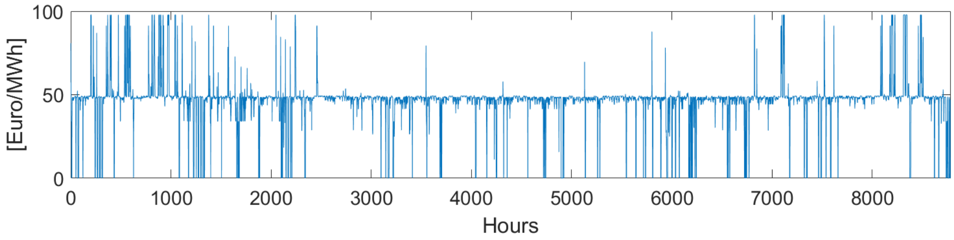

Figure A.1: Electricity price of imported electricity

A.2 Model costs

Table A.1 presents costs and technical data for the production units of electricity and heat which are used by the investment model to optimise the system[13][53]. The costs for the production technologies of hydrogen and methanol are also presented in the table[13]. Table A.2 presents the costs and technical data for the storage technologies considered in the project[53].

Table A.1: Costs and technical data for local production units of electricity and heat as well as the production technologies for H2 and methanol

	Inv. cost [€/kW]	Fix. O&M [€/kW]	Var. O&M [€/MWh]	Life-time [Years]	Eff. [%]	PTH ratio
Electricty production						
Solar PV	418	6,5	1,1	40	[1]	
GT (Biogas)	450	15	0,4	30	36,9	
CHP[3]					*El.*	
CHP_L (Biomass)	3000	86,3	3,8	40	27,6	0,33
CHP_S (Biomass)	6000	277,9	7,9	40	13,3	0,14
CHP_WG (Biogas)	900	20	3	30	55	1,6
CHP_WA (Waste)	6500	149,6	23,3	40	23,5	0,3
Heat production					*Heat*	
EB	50	1	0,9	20	95	
HP	530	1	1,6	25	3 COP	
HOB (Biomass)	490	29,3	0,7	20	115[2]	
HOB (Biogas)	50	1,7	1	25	104[2]	
HOB (Waste)	1240	50,65	4,10	25	106[2]	
Fuel production					*Fuel*	
Electrolyser	250	10		35	75	
Methanol Prod.	725	53	6,3	20	65	

[1] The efficiency of the solar PV is based on a solar profile which limits the output based on geographical conditions each hour.
[2] The lower heating value is used which relates to a higher efficiency.
[3] All costs for the CHPs are presented per unit electricity.

Table A.2: Costs and technical data for storage technologies

	Inv. cost [€/kWh]	Life-time [Years]	Eff. [%]	C-fact	Loss [%/h]	Const. Loss [%/h]
Electricity storage						
Li-ion Batteries	79	25	95	0,5		
Heat storage						
TES	26,5	25	98	1/6	1/240	4,6/240
PTES	1,3	25	98	1/168	1/240	4,6/240

B
Appendix

B.1 PV limitation figures

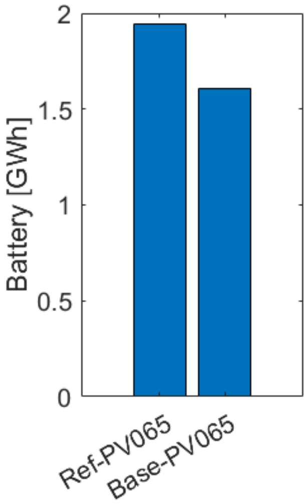

Figure B.1: Battery capacity for the Ref-PV065 and Base-PV065 scenario

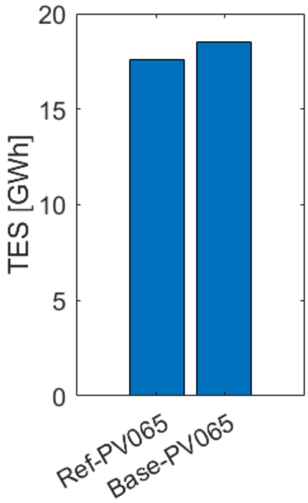

Figure B.2: Thermal energy storage capacity for the Ref-PV065 and Base-PV065 scenario

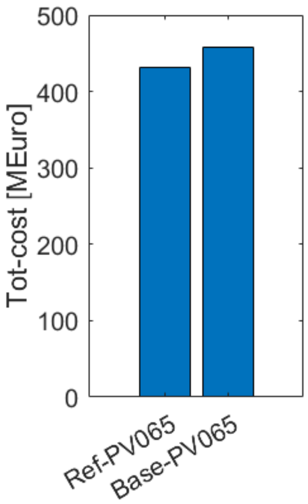

Figure B.3: Total cost for the Ref-PV065 and Base-PV065 scenario

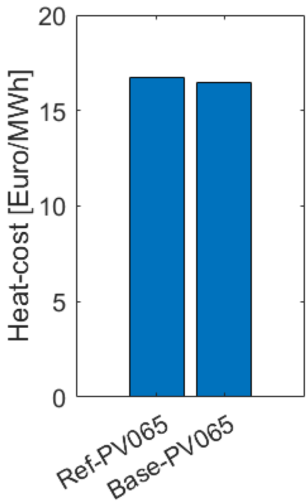

Figure B.4: Yearly average heat cost for the Ref-PV065 and Base-PV065 scenario

B.2 Flexible loads

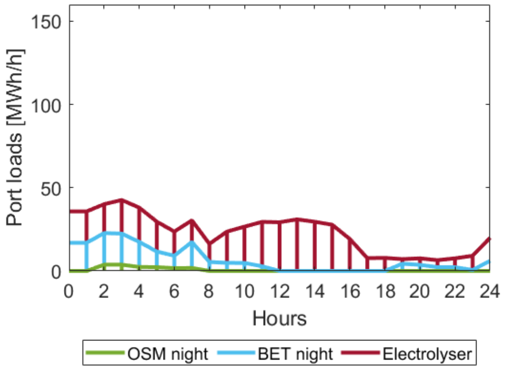

Figure B.5: Base scenario during summer with flexible loads only

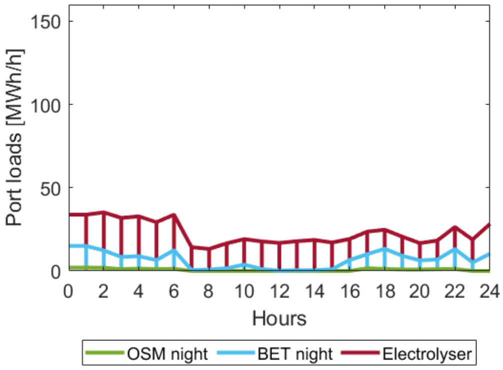

Figure B.6: Base scenario during winter with flexible loads only

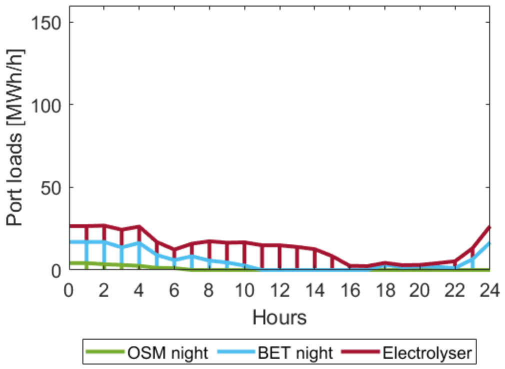

Figure B.7: Truck2 scenario yearly average flexible port loads only

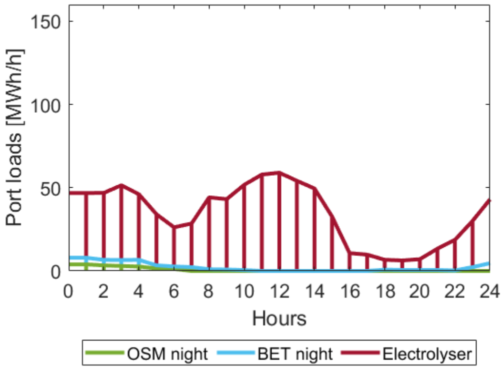

Figure B.8: Truck3 scenario yearly average flexible port loads only

B.3 New production capacity

Figure B.9 and B.10 show the new production capacities in each scenario. The existing capacities are included in all of them and presented in 2.4 and therefore not shown here as well.

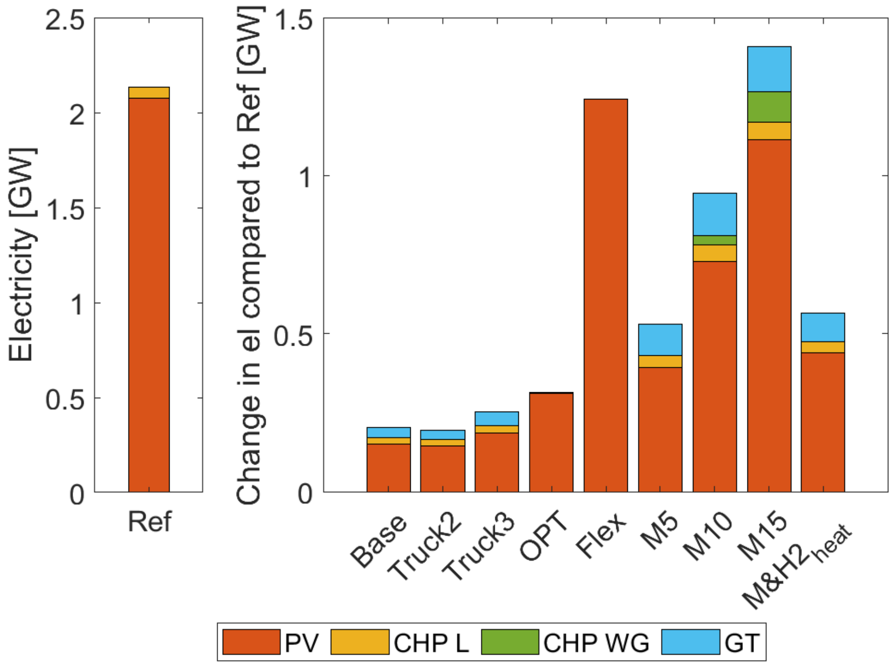

Figure B.9: Electricity capacity for each technology for the Reference scenario and all other scenarios compared to the Reference scenario

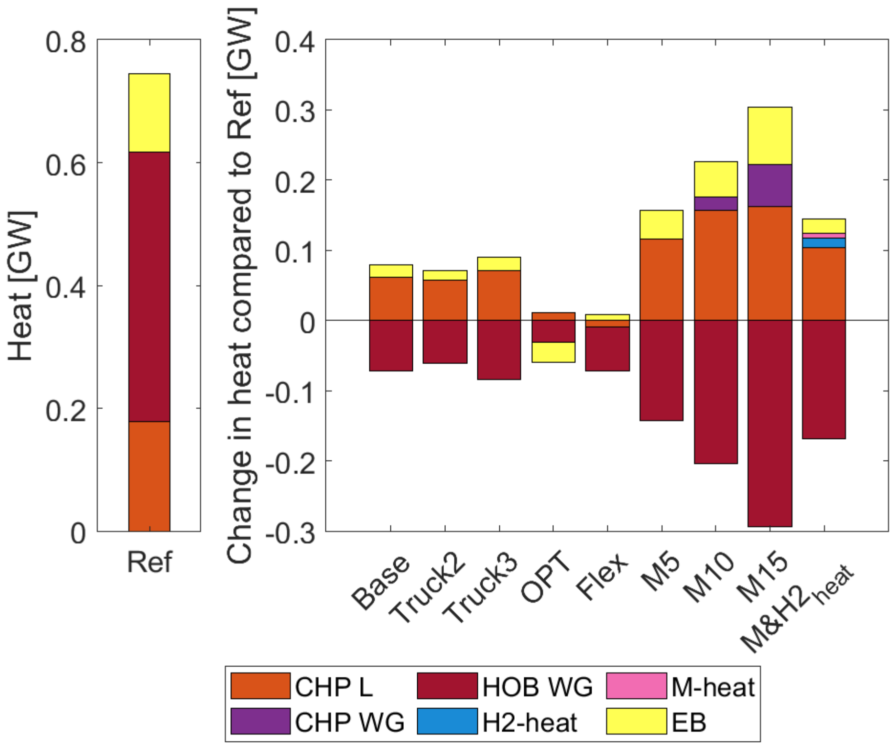

Figure B.10: Heat capacity for each technology for each scenario compared to the Reference scenario

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