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Industrial Electrical Engineering and Automation

Modeling of an energy node

Modeling, simulation and optimization of an energy node

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Abstract

In Sweden, the demand on the electrical grid is increasing with the shift from fossil fuels to renewable energy sources. It is thereby important to optimize the charging stations for electrical vehicles connected to the grid. These charging stations can also include local energy generation and storage, which help decrease the demand on the grid, while supporting the charging of vehicles connected. This results in the creation of an energy node.

In the thesis a model of an energy node is created using the programming language Python. Using data available on traffic flow, weather and energy prices, the model simulates the operation at a selected location, minute by minute over a year.

Energy stored in the energy node is given a value depending on the grid electricity spot price when storing it and the efficiency of storage. This system is used to decide where to store energy generation that is leftover when vehicle loads are already matched, or if it is more profitable to sell the energy to the grid. When local generation is insufficient, it is possible to use the cheapest energy source out of the grid, hydrogen or battery storage.

Using the simulation results, iterative optimization of the energy node subsystem power and energy rating is done to get a cost-effective system. Having optimized the subsystems for the chosen location, it is possible to use these values to simulate different results of interest. Here follows a list of some highlighted results:

- Poor dimensioning of truck charging spots resulted in 7.9 Mkr wasted in truck drivers salary due to being stuck in the energy node. While an increase of only one more charging spot resulted in only 9 Tkr wasted.
- Optimization resulted in around 2-3 MW installed power, 20-22 car charging spots and 3-4 truck charging spots depending on location for the future simulations.

Some of the other results analyzed in the thesis are: full lifetime costs and visualization of daily/yearly operation.

Sammanfattning

I Sverige ökar belastningen på elnätet i takt med övergången från fossila bränslen till förnybara energikällor. Det är därför viktigt att optimera de energinoder som är anslutna till nätet. Energinoderna omfattar också lokal energiproduktion och lagring, vilket bidrar till att minska belastning på elnätet och samtidigt stödja laddning av fordon som är anslutna till energinoden.

I rapporten skapas en modell av en energinod med hjälp av programmeringsspråket Python. Med hjälp av tillgängliga data om trafikflöde, väder och energipriser simulerar modellen driften på en utvald plats, minut för minut under ett år.

Energi som lagras i energinoden har ett värde som beror på spotpriset på elnätet när energin lagras och lagringens effektivitet. Detta system används för att bestämma var man ska lagra energiproduktion som blir över när fordonsbelastningen redan är anpassad, eller om det är mer lönsamt att sälja energin till nätet. När den lokala produktionen är otillräcklig är det möjligt att få fram kostnaden för den energi som behövs om den tas från något av lagren eller från nätet. På så sätt används alltid den billigaste energikällan.

Med hjälp av simuleringar görs en iterativ optimering av energinodens delsystem för att få ett kostnadseffektivt system. Efter att ha optimerat delsystemen för den valda platsen är det möjligt att använda dessa värden för att simulera olika resultat av intresse.
Här följer en lista över några av de mest uppmärksammade resultaten:

- Dålig dimensionering av laddplatser för lastbilar resulterade i att 7,9 Mkr går i förlust i lastbilschaufförens löner på grund av att de fastnade i energinoden. Medan en ökning med ytterligare en laddplats resulterade i endast 9 Tkr i slöseri.
- Optimeringen resulterade i cirka 2-3 MW installerad effekt, 20-22 laddplatser för bilar och 3-4 laddplatser för lastbilar beroende på plats för de framtida simuleringarna.

Några av de resultat som analyseras i avhandlingen är: kostnader för hela livstiden och visualisering av daglig/årlig drift.

Preface

After years of studying with a constant narrowing of my field of expertise, it is time to apply the knowledge gathered with this master thesis.

I would like to express my gratitude towards my main supervisor, Professor Mats Alaküla, for his guidance and support throughout the whole project. His striving for answers to unexpected simulation results made the model what it is today and inspired the same way of thinking. Thank you, it would not have been possible without you. I would also like to thank Professor Öivind Andersson, who initially had another master thesis intended for me which was to model a fuel cell. Even though this did not pan out, it gave me invaluable knowledge of how the fuel cell works, that is applicable to this project.

Additionally I am thankful for the inspiration and guidance Huan Li gave with an insight into how the model could be structured. A thanks to doctoral student Max Collins is also appropriate, for the very helpful consultation when it came to completely understanding the results from the simulations.

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Abbreviations

- EV: Electrical vehicle
- PV: Photovoltaic
- LCOE: Levelized cost of energy
- NOCT: Nominal operating cell temperature
- AC: Alternating current
- DC: Direct current
- SoC: State of charge
- FIFO: First in first out
- Kr: Swedish krona (SEK)
- SCB: “Statistiska centralbyrån”, “Statistics Sweden”
- SMHI: “Swedish meteorological and hydrological institute”
- LTH: “Lunds tekniska högskola”, “Faculty of Engineering in Lund”

1 Introduction

1.1 Background

Sweden has set a goal of fully renewable electricity production by 2040 [1]. At the same time the electrification of the vehicle fleet is increasing exponentially [2]. The increase in non-dispatchable energy sources (solar, wind) will result in challenges for the power balance while the increase of electrical vehicles results in a higher load on the grid. This will result in a necessity for well optimized charging stations that have a controllable power draw from the grid. The power draw of the charging station from the grid is decreased with the inclusion of local energy generation and storage. The generation and storage are vital parts of what we here call an “Energy node”.

A energy node is characterized by:
- Connection to the electric grid is weaker than the local need for power
- Local generation of electrical energy
- Local energy storage
- Known external load at the connection point to the power grid
- Possibility to charge e.g. electric vehicles. This charging system can be optimized so that each vehicle is charged as efficiently as possible with the battery's charging curve in mind.

Such a complex system creates research questions about how it best can be constructed to get the most efficient system possible.

1.2 Goals

The goal of the thesis is to build knowledge through modeling and simulation on how an energy node best should be dimensioned for different cases and locations. The optimization of characteristics such as efficiency, decreased grid load and costs are of main focus. Efficiencies should be optimized by selecting subsystems with high efficiencies while grid load and costs should be optimized iteratively with simulations. The template behind the model should be as applicable as possible to new locations. A goal is also to show the possible results that can be obtained with simulations of the model.

Together with achieving a model that can simulate the operation of energy nodes, the main question in this master thesis becomes how should such energy nodes be optimized to deal with the future increase in electricity demand from vehicles.

1.3 Boundaries

There is a great variety of both energy sources and energy storage technologies, however for various reasons not all are applicable to an energy node located in Sweden. When it comes to energy sources, one clear boundary is that it should be applicable to most energy node locations in Sweden and be renewable due to the current political and societal push for such energy sources. The boundaries for energy storage technologies are that they should have relatively high efficiency, reasonable costs or be of interest due to other advantages. Boundaries for both the energy storage and generation are further determined and motivated in section 2, where the theory behind the different subsystems are presented.

In order to keep the simulations relevant, the data used for the simulations is from 2019, 2020 and 2021. Only private cars and heavy trucks are used in the model, since adding other types of vehicles is deemed not necessary to achieve the goals of the thesis. The boundaries for which locations are of interest is that there should be a current gas station with a connection with a major highway at the location.

1.4 Outline

To achieve these goals the following procedure is used:

- First an understanding and background is created within all subsystems that are part of the energy node. Focus is on finding which technologies are suitable for each subsystem. This is done in section 2 (subsystems description).
- In section 3 (subsystem modeling) and section 4 (structure of the simulation), a template of the model is created with a deeper dive in how the chosen subsystems should be modeled. Capacity, cost, lifetime, efficiency and other characteristics are determined for each subsystem. The model should be as applicable as possible to different locations and cases. Locations and cases are chosen and simulated, which are presented in section 5 (optimization).
- The following results then work as a guidance to what parameters should be changed to optimize the model at the current location. These results are displayed in section 6 (results). When all subsystems are optimized, results of interest are visualized with graphs to get an understanding of how the energy node model operates under different conditions.
- Section 6 then provides a discussion of the model and its results.

2 Subsystems description

The following section is divided into subsections, each describing the theory behind the subsystems that are included in the energy node. Most effort is put into motivating the different choices of technologies and parts. In figure 1 the theoretical layout of the energy node is displayed. In the figure, numbers highlight each subsystem in the following way:

1. Charging subsystem, given description in subsection 2.1
2. Local generation, given description in subsection 2.2
3. Local storage, given description in subsection 2.3
4. Connection to the electrical grid, given description in subsection 2.4

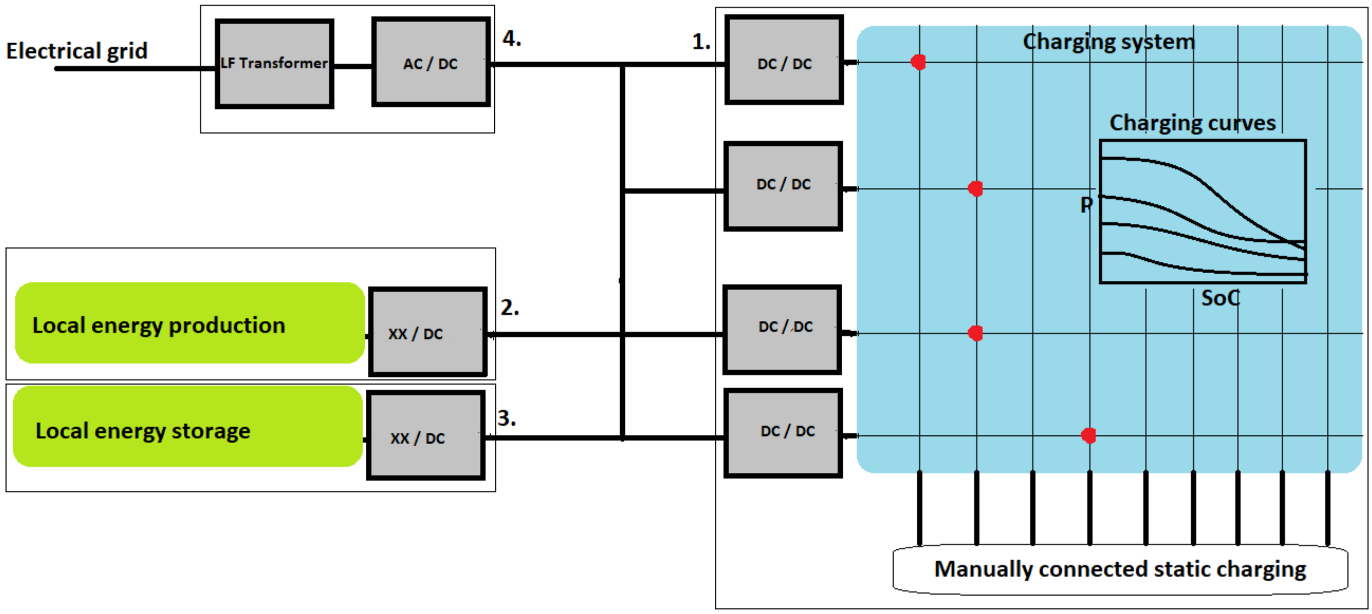

Figure 1: Possible layout of a energy node

2.1 Charging

In figure 1, the charging subsystem is highlighted by the number 1. The chosen charging system is a continuation of what Axel Stenström did in his master thesis, "A modular switching system as a flexible charging solution for a logistics terminal" [3] at LTH. This is illustrated in figure 2 from the same thesis. When structuring a charging system it is tempting to install electric power converters with high power on each charging spot, with somewhere around 200 kW power per charging spot. This can become very expensive and ineffective. Mainly due to the charging curve of vehicle batteries which decreases the needed power depending on how much the state of charge has increased, to protect them from damage. Meaning that most of the time batteries are not charging with full load, and having a 200 kW converter that only uses around 100 kW most of the time can be wasteful.

The idea is to create a system of many smaller converters that can be allocated with switches to the desired charging spot based on what that vehicle needs at the moment. In figure 2 this is illustrated with numbers 303-211 representing the low power electronic converters, 801-836 representing switches and port 1 and 2 representing charging spots.

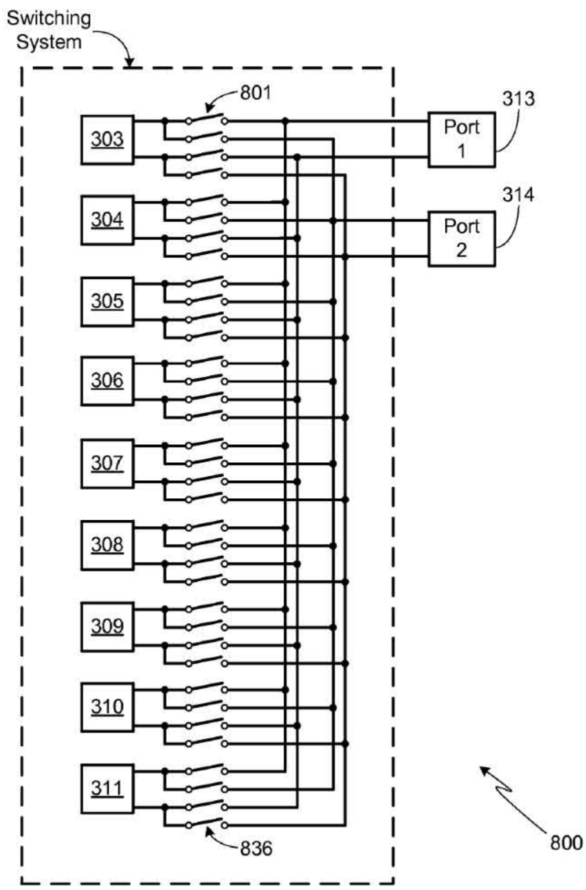

Figure 2: Switch system for charging blocks 303-311 from two ports 1 and 2

2.2 Local generation

There are multiple options when it comes to possible local generation sources. However in this thesis limitations are made. Firstly only renewable energy sources are considered, due to the current and future shift towards environmentally friendly energy. Secondly, energy sources like hydro, marine and bioenergy are omitted due to either having relatively large capital costs, low efficiencies or taking up too much area to be considered an addon to an energy node. The two energy sources given focus will thereby be solar and wind.

2.2.1 Solar power

At the outer surface of the earth's atmosphere the intensity of the radiation is around 1.36 kW/m^2, while at sea level it decreases to less than 1 kW/m^2. This energy resource can be captured by photovoltaic electricity generation or solar thermal processes to generate electricity. With photovoltaic panels the generation is direct, while solar thermal processes use the heat generated from the irradiance.

To use solar thermal processes as electricity generation, the direct sunlight is used to heat liquid which then becomes gas and drives a turbine. However, to be cost efficient, a solar insolation of more than 1800 kWh/m^2 a year and a flat big area with available water is needed [4]. In the thesis, solar thermal energy generation is not considered since Sweden has lower than 1800 kWh/m^2 insolation.

The advantages of photovoltaic cells for electricity generations are the following:

- No moving parts and robust packaging resulting in very little maintenance and a life of more than 20 years.
- Renewable energy source.
- The possibility of building integration.
- One of the lowest levelized cost of electricity, LCOE, for all energy sources [5].

There are three generations of photovoltaic technology:

- First generation uses waffles of mono- or poly-crystalline silicon.
- Second generation is thin film technology.
- Third generation are dye-sensitized and organic/polymer solar cells sometimes using Perovskite materials.

Second and third generation technologies are promising when it comes to being environmentally friendly, theoretical high efficiency and building integration. However as of writing this thesis, they are not yet commercially viable and are not considered. When it comes to silicon solar cells, the two variants are mono- and poly-crystalline. Where monocrystalline are more expensive to produce but also have better efficiency and are more common. Thereby the mono-crystalline silicon is the technology that is chosen for the model and displayed in figure 3. A fixed mounting system is chosen for lower cost.

Figure 3: mono-crystalline silicon solar panels [6]

2.2.2 Wind power

At the end of 2021, nearly 25% of Sweden's energy consumption was supplied by the 4754 wind turbines installed with a total power of 12.1 GW [7]. The advantages of wind energy is that each turbine is able to produce high energy, relatively quick construction and low LCOE [8]. However before considering wind power for a charging station, it is important to consider the disadvantages of onshore wind turbines.

- Visual impact.
- Lower mean wind speeds/turbulence compared to offshore.
- Complicated approval period.

Before construction of a wind turbine, screenings and applications need to be approved which often take around 12-18 months. In Sweden only 22% of all onshore wind turbine projects were approved during 2021. Out of the 454 projects that did not get approval, 170 were due to municipal veto while 284 were denied due to environmental reasons [9]. Since 2014 the highest approval rate was in 2016 at 57%. These statistics and the length of pre development, show that wind turbines are complicated to include in an energy node. However if all requirements are met, the following technologies need to be considered.

There are generally two types of wind turbines based on their orientation, vertical and horizontal axis. An advantage of horizontal wind turbines is their scalability in size while vertical turbines need big open areas and ideally located seaside to receive higher wind speeds. These reasons have resulted in horizontal wind turbines being more popular commercially and also why they are of more interest for the model of the energy node.

The horizontal wind turbines can be either upwind or downwind. Upwind turbines face the wind with the turbine blades in front of the nacelle while downwind have them behind and face away from the wind. The biggest advantage to the upwind turbines is the avoidance of wind shade behind the tower, which is also why they are more commercially viable and used in the energy node model. In figure 4 an upwind turbine is displayed.

Mainly due to their low approval rate and long pre-development time, wind turbines are not as easily applicable to energy nodes compared with solar panels. It is also worth noting that after being approved, the construction of the wind turbines can be relatively fast, only lasting around 6-18 months. The time of both pre-development and construction of a solar park takes approximately 1-2 years [10], as a comparison to the around 1-1.5 years of only pre-development for a wind park.
In conclusion wind turbines will not be given the same focus as solar panels in this thesis, but will instead have a smaller study in what they can contribute with to an energy node in section 5.2.1. Hopefully giving insight if future energy node models should include more detailed studies with wind turbines.

Figure 4: A 2MW upwind turbine [11]

2.3 Local storage

Limitations are also made when it comes to local storage options. One of the main focuses is the importance of high efficiencies, to avoid energy losses. Secondly it is important that the components of the local storage are cost efficient. These two limitations make batteries the first choice of storage. However batteries have high self-discharge which is why hydrogen is also looked into as an optional local storage technology.

2.3.1 Batteries

There are two types of battery systems that need to be considered, deep cycle and standby batteries. Deep cycle batteries are charged and discharged daily, while also usually being deeply discharged to provide more power. Standby batteries are used as a power backup, only being discharged during grid power failure or when maintenance work to the grid connection is needed. These are typically only discharged several times a year, while being on standby most of the time. It is however important to always keep them fully charged. Both types of batteries are needed in the energy node. However since power grid failures and maintenance are mostly random encounters, the usage of the standby batteries are not simulated.

Technology wise there are two types of batteries that are most common due to commercial viability and need to be considered, lead acid or lithium-ion. Both store and charge electrons via electrochemical processes, however they use different materials. When it comes to applications, lead acid batteries are cheaper upfront and are usually used when high power is needed fast but not often. However, in the matter of charging time, the lead acid batteries can take up to 10 hours to charge while lithium-ion take 3 hours to a few minutes to charge [12].
With regard to lifetime lithium-ion batteries are superior, with 10-15 years lifetime depending on manufacturer while lead acid only have about 3-12 years. Since the energy node has a long lifetime and needs to have a storage that can charge fast, lithium-ion batteries are used.

The efficiency of lithium-ion batteries is around 95%, taking into account energy loss in the entire discharge/recharge cycle [13]. In figure 5 a car battery is shown, in which many lithium-ion batteries are stacked together creating a battery pack.

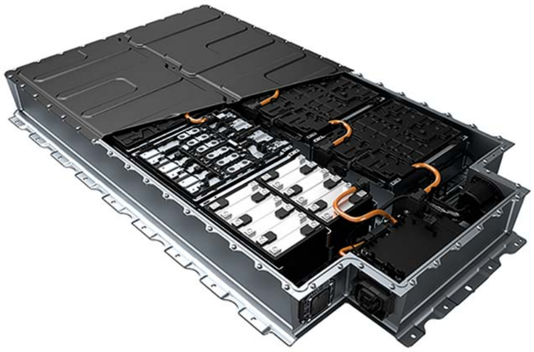

Figure 5: BMW i3 lithium-ion battery pack [14]

2.3.2 Hydrogen

One of the biggest problems with hydrogen energy storage is the low round-trip efficiency of around 25-30%, since hydrogen fuel cells and electrolyzers have a one way efficiency of about 50-60% [15]. This means that for hydrogen to be beneficial for everyday storage, it would have to be significantly cheaper to buy and store, which it at the moment of writing the thesis is not.

Demand and prices of energy show big variations over the year [16]. At the same time the local energy sources (solar and wind) are uncontrollable with possible large variations in minute to hour perspective and at times produce more than the needed demand, while at other times not meeting the demand. These two reasons give way for the need of seasonal energy storage, where energy is stored during the months of cheap energy prices and high local energy production. Which is then used during the months where prices are high and local production low.

When it comes to long term storage the decision on if it should be in batteries or hydrogen should be decided. Initially it might seem like batteries are the better option considering the higher round-trip efficiency. However one of the biggest disadvantages of long time storage in batteries is the high self-discharge when they are not used for long periods of time, which makes them unfit for long time storage.

Having the possibility to store hydrogen is also beneficial for possible charging of hydrogen driven vehicles. One of the major benefits when comparing batteries and hydrogen storage in vehicles is the lower weight and higher gravimetric energy density of hydrogen. The weight of a battery driven vehicle increases at a much higher rate than fuel cell driven vehicles when the range of the vehicle is increased [17].

This shows how beneficial it could be for heavy, long-range vehicles to use hydrogen instead of batteries. Resulting in many companies now investing in an increase in their hydrogen truck fleet. With some estimates showing that 17% of new trucks in 2030 will be hydrogen based, meaning that it would be necessary to increase the number of hydrogen charging spots in the future [17]. Using the same source and looking at electric vehicles, the charging time for hydrogen is about 3-5 minutes compared to the around 30 min it takes to charge car batteries.

Figure 6 illustrates the structure of a hydrogen storage system, where electricity is used to generate hydrogen with an electrolyzer. This hydrogen is then stored in a tank as an energy storage. To use the energy stored, hydrogen energy is converted back into electrical energy with a fuel cell.

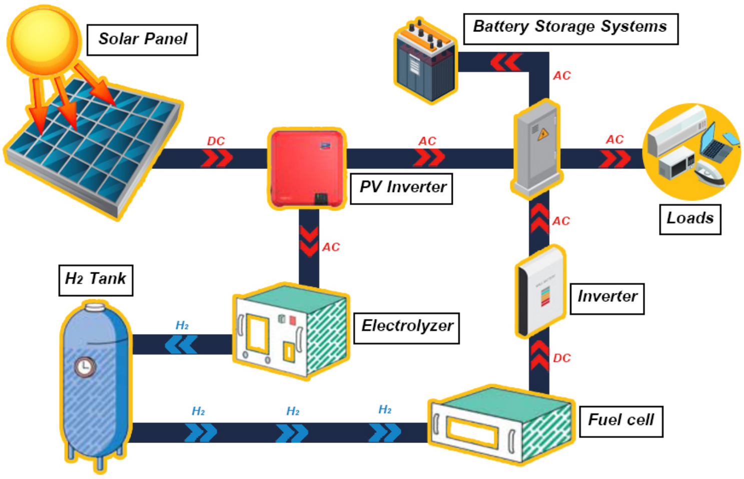

Figure 6: Hydrogen storage system together with battery, generation and load [18]

2.4 Connection to the grid

The connection to the grid is made with a grid frequency transformer followed by a AC/DC converter. When it comes to efficiency, the transformer can be assumed to have an efficiency of around 95-99% [19] while the AC/DC converter has about 95% efficiency [20]. Resulting in an overall efficiency of 90-94% efficiency for the connection with the grid.

3 Subsystem modeling

The following sections provide a general overview of the model, which is built using the programming language Python. The section includes the following subsections.

- Location, where the chosen locations are presented.
- Vehicles, the vehicle models and the necessary characteristics of them are presented.
- Local generation in the simulation, the function of both a solar panel system and a wind turbine system are detailed.
- Local storage in the simulation, the function of both a battery and hydrogen storage system are detailed.
- The grid, the connection to the grid is described in more detail.
- Economics, necessary costs for each subsystem are given.

3.1 Location

The location of the energy node has a huge impact on both the incoming traffic that needs to be charged, the local generation and the spot price of electricity from the grid. For the thesis these three locations are chosen, highlighted in figure 7:

- Ekeröd, at the address: Ekeröd 5278, 242 94 Hörby, located in the south of Sweden.

- Ödeshög, at the address: Liljekonvaljvägen 3, 599 31 Ödeshög, Sweden, located between the two most populated cities in Sweden.

- Norrfjärden, at the address: Håkingevägen 4, 945 91 Norrfjärden, located in the north of Sweden.

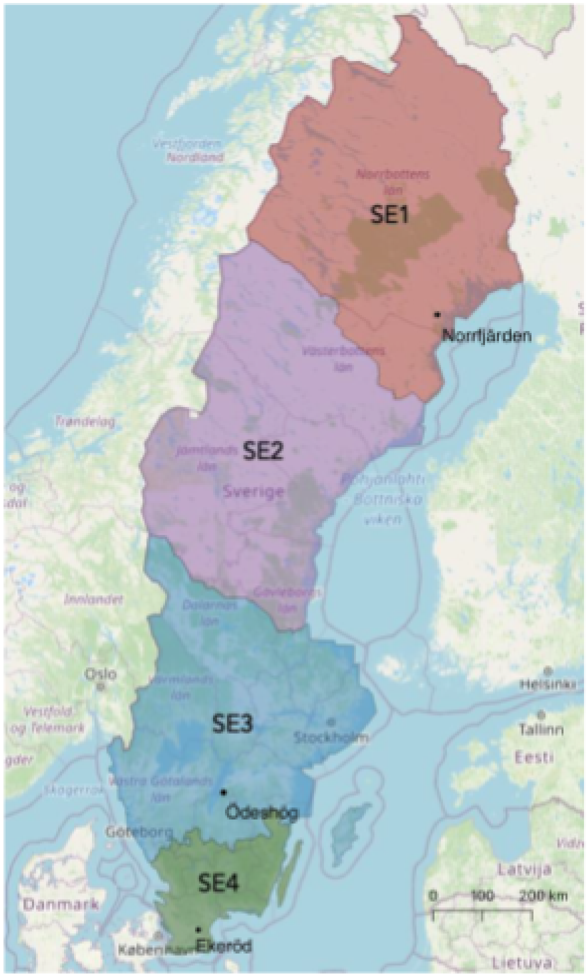

Figure 7: Electricity spot price zones in Sweden

The reason behind these specific locations, is firstly that they are located near highly trafficked highways and already have gas stations. Secondly Sweden is divided into four bidding areas displayed in figure 7 [21], which heavily dictate the costs of grid electricity. Ekeröd is located in SE4, Ödeshög in SE3 and in SE1.

The final reason for the different locations is the different effect the local generation can have on the energy node. Where both Ekeröd and Ödeshög are located in the countryside while Norrfjärden is located close to the sea, meaning potential for higher wind speeds. At the same time the further south the location is in Sweden, the better the chances are for higher solar power production.

3.2 Vehicles

When modeling the vehicles that enter the energy node for charging, it is necessary to include the starting state of charge. This is randomized between 10% and 30%, to give the simulation a sense of human randomness. The vehicles also include the charging curve for the specific vehicle model that indicates the charging power that the battery would prefer to receive based on its current state of charge.

There are three different types of car models in the system, which are based on the most common electrical cars during 2022 in Sweden [22].

- Tesla model 3 (2017)
- Kia Niro (2017)
- Volkswagen ID.4 (2021)

For electrical trucks, the selection is not as established since there has not been the same commercial success as for electrical cars. Therefore the two models chosen are newer models from Scania and Volvo.

- Scania BEV 25 P (2022)
- Volvo VNR Electric (2022)

3.3 Charging

Based on the switch system described in section 2.1, the charging spots in the energy node can have different numbers of electronic power converters connected to them with the current car's charging needs in mind. A decision needs to be made on what power the electronic power converters should have, where lower rated converters provide bigger flexibility but also more switches. The decision is made to have 50 kW converters that can be allocated accordingly, based on the results of Stenströms master thesis.

To get the number of electric cars and trucks that arrive for charging each minute, data from Trafikverket is used [23]. At each location the data over vehicles driving on the highway connected to the charging station is gathered. Since this data does not directly correlate with the vehicles coming into the charging stations, the following assumptions are made to get the number of electric vehicles entering the energy node each minute.

Two cases are considered, now or future. The “now” case is based on 2021 while the “future” case is based on approximations for 2030. In the “now” case the number of electric cars is assumed to be 6% of the car fleet [24], while 0.084% for the electric trucks. However since there is also an interest in how future energy nodes should be optimized, a future case is created where half the cars and trucks are electric. Meaning that in the "future" case both electric cars and trucks are assumed to be 50% of the vehicle fleet.

Another consideration is needed, which is the fact that all electric vehicles that drive past the energy node do not need charging. The average driving range for electric cars in 2021 was 350 km [25].

While the future is untold, it can be seen that the average range between 2011 and 2021 has increased 152%. Using this number, it is roughly assumed that a hypothetical increase of 152% can be seen in the future in 2030. Making the average driving range equal to 532 km.

As of 2021, there is a political decision in Sweden to have a maximum of 100 km between charging stations [26]. From the same source it is gathered that the European Union wants the max distance between stations to be 60 km. In addition a hypothetical distance of 30 km is also used in the simulations.

Both the range of the electric vehicles and the distance between charging stations contribute to determine the average percentage of electric vehicles passing by that need charging. First a simplification is made, the vehicle's starting points are distributed evenly. In reality this is far from true and should be improved in future models.

By taking the distance between charging stations divided by the average range of an EV (electrical vehicle), it is possible to determine the percentage of the vehicles that started at a length further away than their range and thereby need charging at the energy node.

$$Need\ charging\ =\ \frac{Distance\ between\ stations}{Average\ ev\ range} \quad (1)$$

where

$Need\ charging$: percentage of vehicles that drive past the energy node that need charging [%]

$Distance\ between\ stations$: distance from the specified energy node to the closest energy node. [km]

$Average\ ev\ range$: is the average range of an ev [km]

The final modifier to the number of vehicles entering the system, is the increase in cars and trucks over the years. Analyzing the data from “Statistiska centralbyrån“ (SCB) over the amount of cars and trucks registered in Sweden each year from 2006-2022, an average increase of 10.78% for cars and 23.5% for trucks can be noticed over a 10 year span [27]. Meaning that in the future case, the cars are modified by 1.1078 and trucks 1.235.

Taking these contributions into consideration the final number of electrical vehicles that charge at the energy node each hour is given by equation 2.

$$Electrical\ vehicles\ this\ hour\ =\ Vehicles\ this\ hour\ \times\ Percentage\ of\ vehicle\ fleet\ is\ electrical\ \times\ Need\ charging \quad (2)$$

where

$Electrical\ vehicles\ this\ hour$: number of electrical vehicles that need charging each hour at the energy node

$Vehicles\ this\ hour$: number of vehicles driving past the energy node each hour gathered from Trafikverket

$Percentage\ of\ vehicle\ fleet\ is\ electrical$: percentage of vehicle fleet that is electrical in Sweden [%]

This is done for both cars and trucks separately, using their own specific values. In the future case equations need to be modified to take into account the approximate change in the electrical vehicles driving range. The amount of vehicles that need charging are in the future case determined by equation 3 instead of equation 1.

$$Need\ charging\ =\ \frac{Distance\ between\ station}{Average\ ev\ range\ \times Modifier} \qquad (3)$$

where
$Modifier$: a modifier that takes into account the approximate increase of ev range in the future [%]

The final number of vehicles charging in the future case is then provided by equation 4 instead of equation 2.

$$Electrical\ vehicles\ this\ hour\ = Vehicles\ this\ hour\ \times\ Future\ percentage\ of\ vehicle\ fleet\ is\ electrical\ \times Need\ charging \qquad (4)$$

where
$Future\ percentage\ of\ vehicle\ fleet\ is\ electrical$: percentage of future vehicle fleet that is electrical [%]

The data from “Trafikverket” [23] only shows vehicles passing per hour, however the model has a time resolution for minutes. The model distributes the hourly traffic flow randomly over the minutes of each hour, using pseudorandom mathematics. Each vehicle is given a random value between 0-59, representing the minute it enters the system during its hour.

To get the charging curve for each vehicle coming into the energy node, the real charging curves are sampled to get a digital representation of their values. There is a limit on how much power each charging spot can provide, which is determined by which kind of chargers that are installed. In the case of the electrical cars, at the moment of writing this thesis, most cars can not be charged with more than 150 kW. This means that having higher superchargers installed at the car spots is wasteful. Thereby the chosen power limit for chargers at the car spots is 150 kW. However the trucks have much higher power expectations, which results in for the now case 350 kW chargers being chosen. In the future case the values of the truck charging stations are estimated to reach values of 1 MW which is used in the future simulations [28]. Figure 8 and 9 display the charging curves for the chosen models now and in the future.

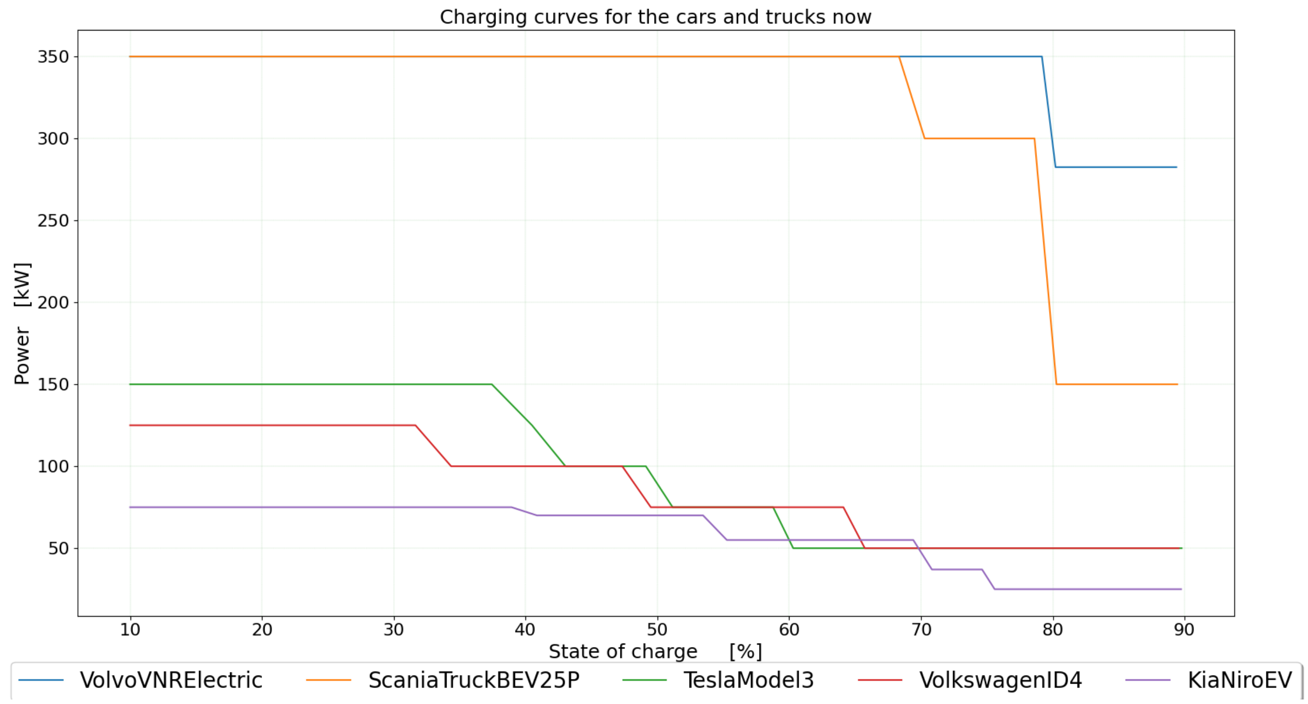

Figure 8: Charging curves in the now case

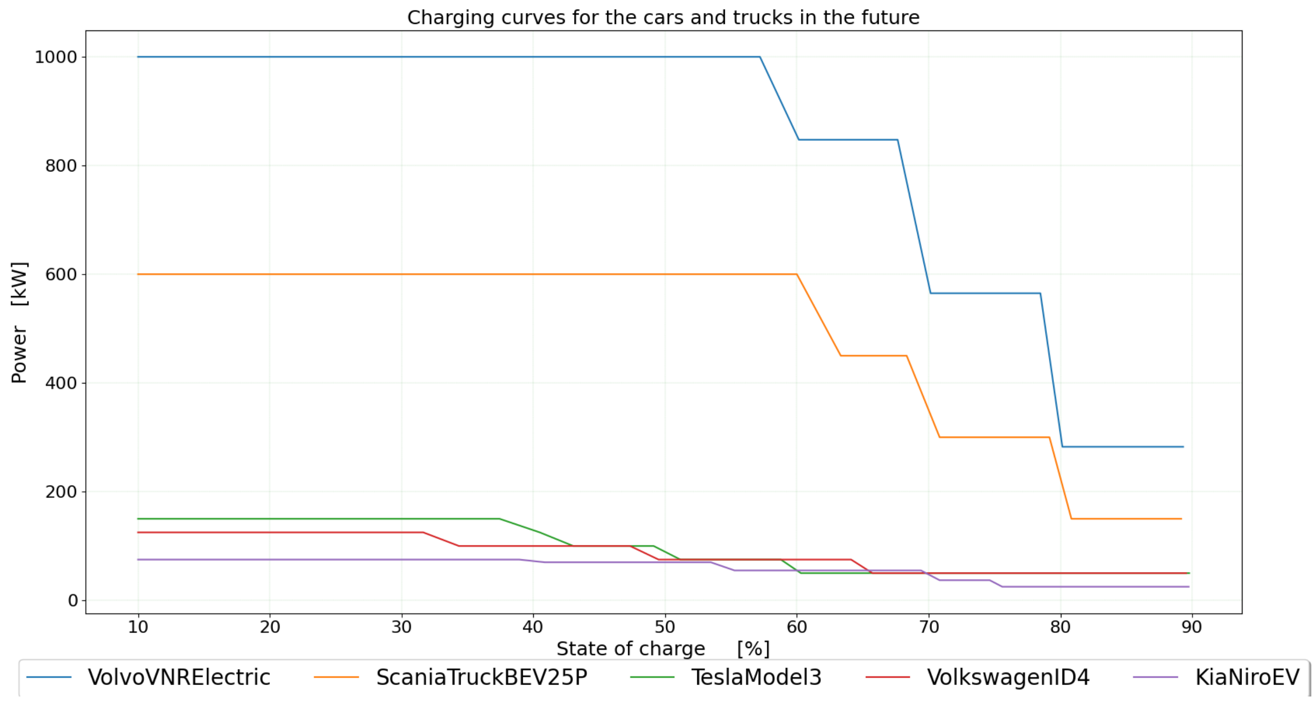

Figure 9: Charging curves in the future case

Using these charging curves and a system in which each minute the vehicles are given the power they need, charging times for the cars which are affected by a 150 kW limit are shown in table 1.

Table 1: Charging time between 10-90% SoC for the car models

Volkswagen ID4, 77 kWh	40 min
Kia Niro EV, 64.8 kWh	47 min
Tesla Model 3, 82 kWh	41 min

Table 2 shows the average charging time for trucks in the two cases used.

Table 2: Charging time between 10-90% SoC for the truck models, using different possible power settings

	Now, 350 kW	**Future, 1 MW**
Volvo VNR Electric, 565 kWh	68 min	27 min
Scania Truck BEV25P, 300 kWh	37 min	25 min

3.3.1 Incomplete data

The hourly data from “Trafikverket” [23] over the traffic flow on different roads during the year is not always complete. In the Ödeshög location, only data for the hourly variations during a day could be collected. Figure 10 shows the variation during 07-03-2022 at the Ödeshög location. While data from both the Ekeröd and Norrfjärden location could be used directly since it had hour data for each day over a whole year.

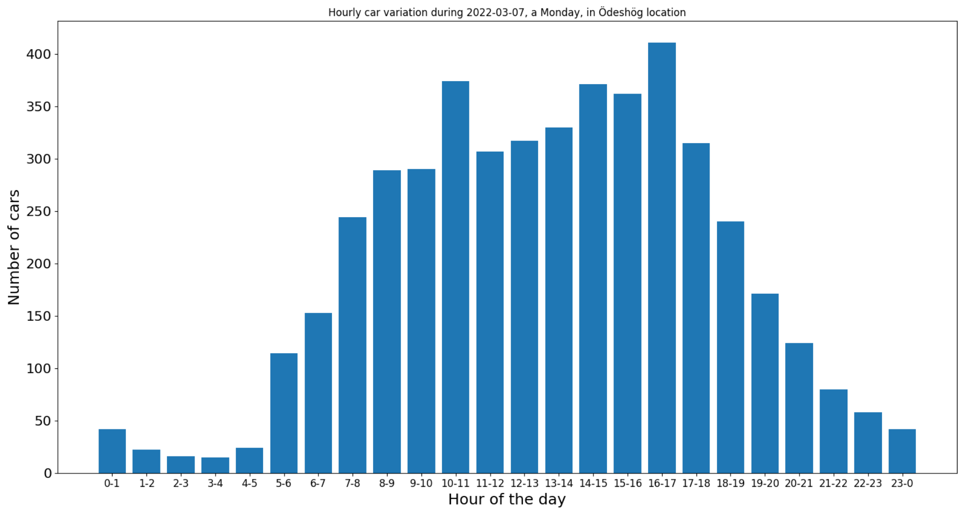

Figure 10: Hourly variation during monday 07-03-2022 gathered from “Trafikverket”

To make this data applicable to a whole year, modifications need to be done. First the day of the week needs to be noted, since variations over the week should be accounted for. By assuming that the weekly variation patterns stay the same independent of the time of year, it is possible to use hourly variation real data from any day of the week and get how it would look if it is another day of the week.

From the data station in Ödeshög, variations over the selected week are collected in the total number of cars and trucks driving each day, displayed in table 3.

Table 3: Total number of cars and trucks driving through the Ödeshög location during each day during week number 11, 2022

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Cars	22212	21478	22419	23662	24654	18306	21858
Trucks	5135	5552	5505	5294	4301	1430	2024

To calculate the modifiers needed to change from data over one day to data of a whole week equation 5 is used.

$$M_d = D_d / D_o \qquad (5)$$

where
d: the weekday which the original data should be modified to represent
M_d: modifier for weekday d
D_d: data from weekday d
D_o: data from the day that the hourly variations originate from

Since the hourly variation during a day data in Ödeshög is dated 2022-03-07, which was a Monday, the modifiers become the once displayed in table 4.

Table 4: Modifiers for each day in Ödeshög simulation

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
Cars	$\frac{22212}{22212}$	$\frac{21478}{22212}$	$\frac{22419}{22212}$	$\frac{23661}{22212}$	$\frac{24654}{22212}$	$\frac{18306}{22212}$	$\frac{21858}{22212}$
Trucks	$\frac{5135}{5135}$	$\frac{5552}{5135}$	$\frac{5505}{5135}$	$\frac{5294}{5135}$	$\frac{4301}{5135}$	$\frac{1430}{5135}$	$\frac{2024}{5135}$

These modifiers are then used to simulate the data for each day during a week, by multiplying the hourly data already retrieved from Trafikverket with the corresponding modifier depending on which day should be simulated. The results are displayed in figure 11.

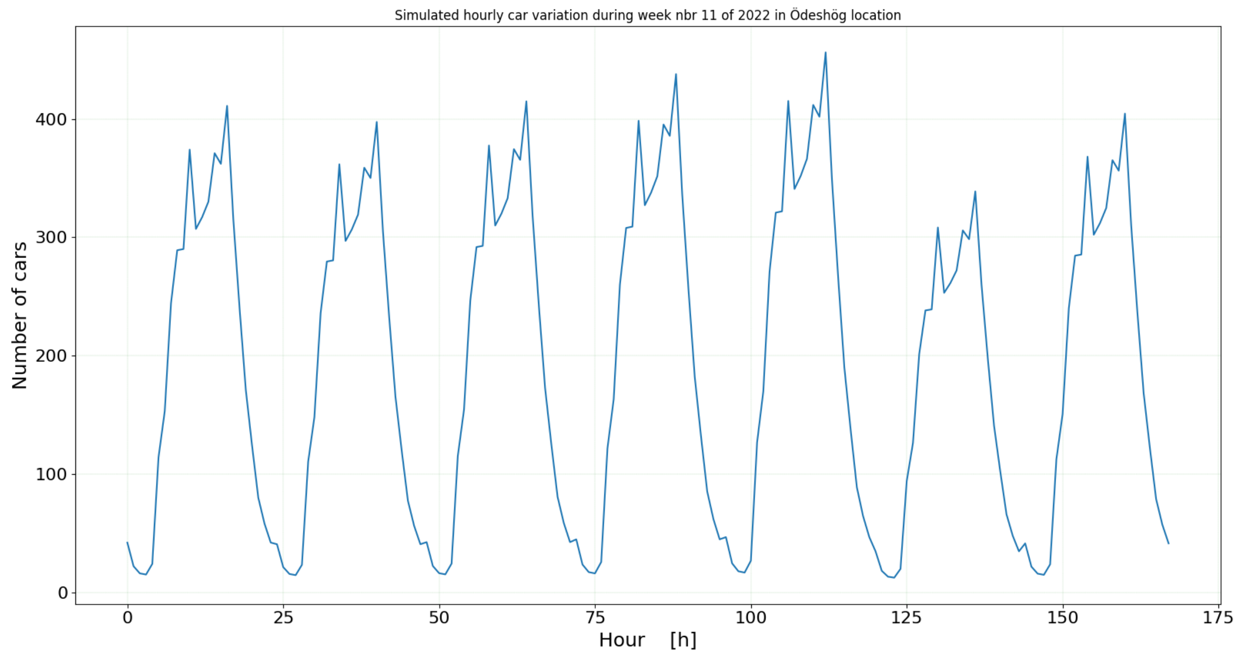

Figure 11: Simulated weekly variation during week number 11 of 2022 in Ödeshög

These now need to be modified over the year with monthly variations in consideration. The same process as with the week variation is conducted to finally get the full hourly data over the year, shown in figure 12.

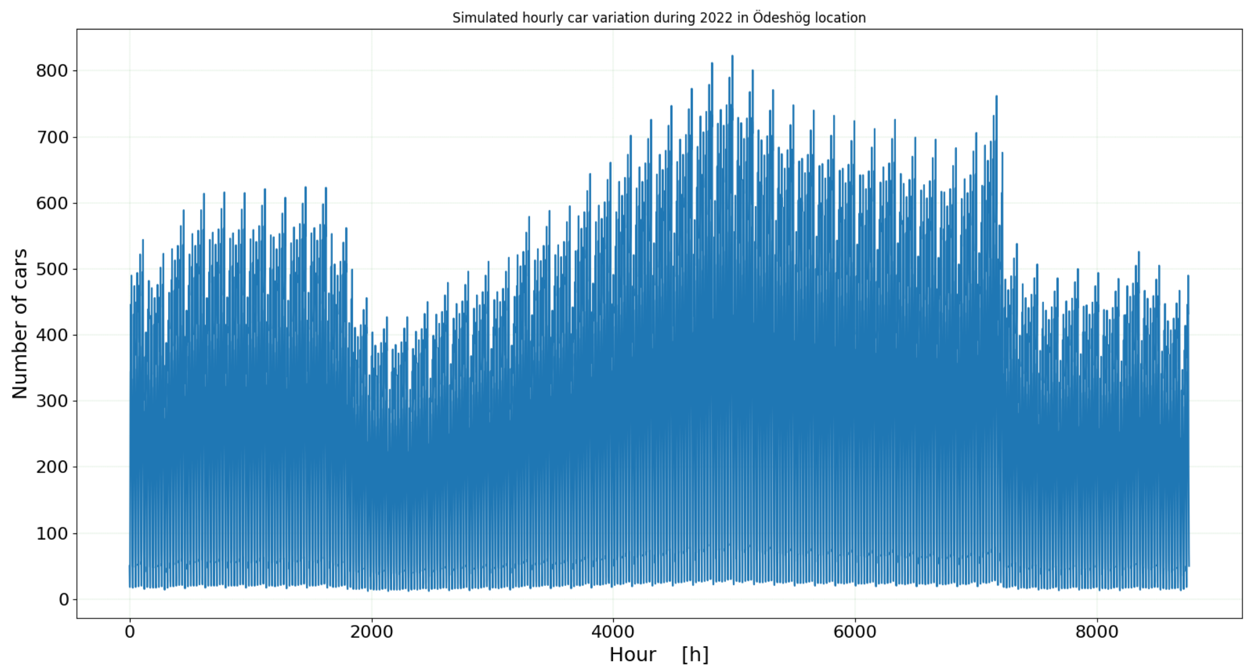

Figure 12: Simulated yearly variation during 2022 in Ödeshög

When comparing the final simulated values with real values from Norrfjärden and Ekeröd displayed in appendix 1, there are no alarming anomalies. It should be noted that different locations can have different kinds of variations over the year, but as seen the variation traits are acceptably alike for the simulated data of Ödeshög to be used, with peaks during summer and lower flow during winter.

3.3.2 Questionable data

It should be noted that when looking at the traffic data over the years of 2019, 2020 and 2021 for all locations, some irregularities are noted. As an example figure 13 shows the traffic data in Ekeröd during 2021. During the night of 2020-05-10 between 23.00-00.00, 1496 cars were recorded before dropping to 0 again after midnight. Since the model and simulations are meant to represent the everyday function of the energy node, irregularities like these should not affect the optimization. In this case and other cases of highly abnormal traffic data, the data is regulated by looking at the data before and after the hour and replacing the abnormality with the average of the two. It can be noted in figure 13 that there are also abnormalities where the data is zero for a longer period of time. However this can be seen as a maintenance and is not modified.

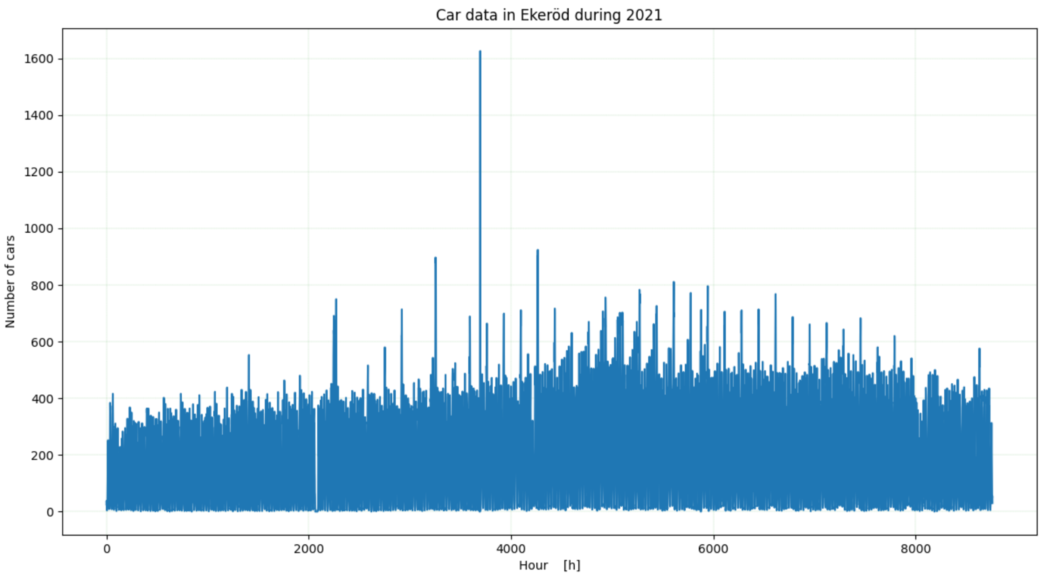

Figure 13: Data on traffic flow in Ekeröd 2021 gathered from "Trafikverket"

3.4 Local generation in the simulation

3.4.1 Solar power

When looking at the most common solar panels on the market, one of the leading companies is LONGi Solar from China [29]. Out of their products, the Longi lr4-60hph-380m is used in the model, with the characteristics displayed in figure 5. The choice is made on the basis of being a modern solar panel model, released 2020.

Table 5: Characteristics of the Longi lr4-60hph-380m solar panel [30]

NOCT* rated power	283.8 W
Size	1.75 x 1 m
Efficiency	20.9 %
Lifetime	25 years
NOCT* irradiance	800 W/m^2
NOCT* ambient temperature	20 ℃
Operating temperature	40 ℃
Temperature coefficient	- 0.350 % / ℃
NOCT* = Nominal operating cell temperature	

To get the power output from the photovoltaic system, first data over the hourly irradiance and ambient temperature close to the chosen location is gathered from the “Swedish Meteorological and Hydrological Institute '', SMHI [31]. The irradiance data is then divided with the NOCT irradiance of the solar panels, to get a modifier of how close to NOCT the solar panels are each minute.

$$M = \frac{G}{NOCT\ G} \qquad (6)$$

where
M: modifier
G: irradiance [W/m^2]
$NOCT\ G$: nominal operating cell temperature irradiance [℃]

Which results in a preliminary power output of:

$$P_p = M \times P_{rated} \qquad (7)$$

where
P_p: preliminary power [W]
P_{rated}: the rated power of the solar cell [W]

The fact that solar panel performance is affected by the temperature of the cell and thereby also the ambient temperature, needs to be taken into consideration. Efficiency decreases when the cell temperature increases. Using equation (8) [32] for the resulting temperature of the cell:

$$T_{cell} = T_a + M \times (NOCT - NOCT_a) \qquad (8)$$

where

T_{cell}: temperature of the cell	[°C]
T_a: ambient temperature	[°C]
$NOCT$: nominal operating cell temperature	[°C]
$NOCT_a$. nominal operating cell ambient temperature	[°C]

The effect of this cell temperature on the possible output can be calculated by equation 9 [33]:

$$P = P_p \times (1 + T_{coefficient} \times (T_{cell} - T_a) \qquad (9)$$

where

P: power	[W]
$T_{coefficient}$: temperature coefficient of the photovoltaic cell	[% / °C]
T_{cell}: temperature of the cell	[°C]
T_a: ambient temperature	[°C]

System losses occur, which causes the power delivered from the system to be less than the power produced by the PV modules. Losses in cables, power inverters and dirt/snow are common attributes to these losses. This value is set to a common default value of 14% [34], for a more accurate model these losses should be analyzed deeper. For simplicity and cheaper design, a fixed mounting system is applied. Meaning that the panels are not always angled perfectly with the sun, resulting in an efficiency loss that can be approximated to 30% [35].

Taking these two losses into account, equation 10 is achieved for the final output of the solar panels.

$$P_f = P \times (1 - 0.14) \times (1 - 0.3) \qquad (10)$$

where

P_f: final power output	[W]

To get the solar power generated by the whole system, the amount of solar panels that fit in the selected area is calculated and then multiplied by the output power of each panel, resulting in the final power generated each minute list. Figure 14 displays Sweden's largest solar farm which is able to produce 14 MW power.

Figure 14: Sweden's largest solar farm as of 2022, 35 hectare and 14 MW [36]

3.4.2 Wind power

The chosen wind turbine has the parameters shown in table 6, which are all based on common values [37]:

Table 6: Common values for onshore wind turbines

Rated power	2 MW
Hub height	90 m
Diameter	110 m
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Efficiency	90 %
Capacity factor	30 %

To get the power output from a wind turbine placed at each location, the wind speed at each moment needs to be used. This data is gathered from SMHI who provide data of wind speeds at different locations in Sweden [31]. At many places these are also saved and available to download hour wise for a whole year. Since these wind speeds are not gathered at the same height as the wind turbine, they need to be converted using the log law [38] in equation 11.

$$U(z) = U(z_r) \times \frac{ln(\frac{z}{z_0})}{ln(\frac{z_r}{z_0})} \qquad (11)$$

where

z: height above ground	[m]
$U(z)$: wind speed at height z	[m/s]
z_r: reference height	[m]
$U(z_r)$: wind speed at reference height	[m/s]
z_0: roughness length of the terrain surface	[m]

The surface roughness length is determined by the values in table 7.

Table 7: Surface roughness length, used in equation 11

Terrain description	z_0 **[mm]**
Very smooth, ice or mud	0.01
Calm open sea	0.20
Blown sea	0.50
Snow surface	3.00
Lawn surface	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, few buildings	250.00

The power generated each hour is calculated by using wind power equation (12).

$$P = \frac{1}{2} \times \varrho \times A \times U^3 \times \eta \times c_p \qquad (12)$$

where

ϱ: density of the wind	$[kg / m^3]$
A: sweep area of the wind turbine rotors	$[m^2]$
U: wind speed	[m/s]
η: efficiency of the whole wind turbine	[%]
c_p: capacity factor	[%]

Using equation 12 and taking into account the rated power, which cannot be overstepped and the cut in/out wind speeds, the power curve in figure 15 is accomplished.

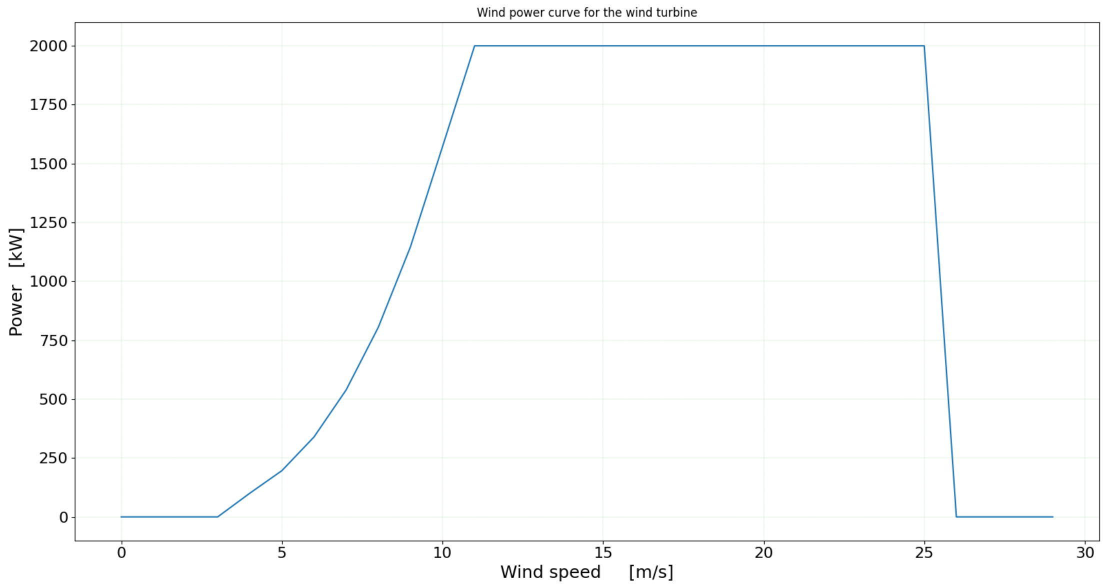

Figure 15: Power curve for the chosen wind turbine

The local generation is gathered in lists that contain the power in kilowatt generated each minute during a year.

3.5 Local storage in the simulation

The chosen batteries for the energy node takes inspiration from a hybrid solar/wind power farm in the Netherlands constructed by “Vattenfall”, where a large number of BMW i3 lithium-ion batteries are used to create a battery pack stored in containers for the system [39] which is displayed in figure 16. One of the attractive features of the BMW i3 battery is its flat charging curve, meaning that there is no need for much control electronics on each battery in the battery pack.

Figure 16: 12 MW battery storage at the hybrid solar/wind power farm in Netherlands, gathered from the source mentioned above

The major hydrogen storage parts are the tank, the electrolysers, the compressors and fuel cells. These are however not given specific values, but instead common characteristics are used. The inside of a hydrogen storage container is displayed in figure 17.

Figure 17: Inside a hydrogen storage container [40]

3.6 Energy control

During every moment of time there is a certain availability of locally generated electric power, from solar and/or wind, with a certain energy cost. There is also an energy cost related to the grid power supply. Finally there is a need for power for charging the vehicles that happen to be connected. This balance can be positive or negative, e.g. there can be more locally generated power available than needed for charging, or vice versa.
To help determine from what source to take the missing energy in an instant, or possibly to what storage to store excess energy, an energy price model is proposed. The price of energy supplied from, or to, the grid is assumed to be known as the spot grid price.
The price on energy stored in the battery is based on the investment cost, expected lifetime (calendar and cycling), the energy price with which the battery has been charged and finally the battery charge/discharge efficiency. The price of the energy stored in hydrogen is calculated in a similar way. With all these energy costs established, it is possible to determine the best directions of energy flow in the system at each point in time.

3.6.1 Storing leftover locally generated energy

When storing the power generated in any of the energy storages, the resulting incremental energy stored is given by equation 13.

$$E_g = P_g \times \eta \times \frac{1}{60} \qquad (13)$$

where

E_g: generated energy to be stored [kWh]

P_g: generated power to be stored [W]

η: one way efficiency of energy storage, for battery 97.5% [41] and hydrogen 54% [42] [%]

$\frac{1}{60}$: since the simulation is done in minutes [h]

The energy cost for the total energy in the storage is updated to take into account the added energy and its cost, using equation 14. The price of the generated energy is equal to the cost of the energy that could be sold to the grid, seeing it as a momentary loss in profit.

$$new\ C_s = \frac{C_s \times E_s + C_g \times E_g}{E_s + E_g} \qquad (14)$$

where

C_s : cost of storage energy [kr/kWh]

C_g: cost of generated energy [kr/kWh]

E_s: storage energy [kWh]

E_g: generated energy to be stored [kWh]

When deciding in which energy storage to store leftover generated energy or if it should be sold to the grid, first the effect on the energy price for each storing option is calculated using the equation 14. However instead of using equation 13, to calculate the energy that should be stored, the following equation is used that takes into account the roundtrip efficiency

$$E_g = P_g \times \frac{1}{60} \times \eta' \qquad (15)$$

where

E_g: generated energy to be stored [kWh]

P_g: generated power to be stored [W]

$\frac{1}{60}$: since the simulation is done in minutes [h]

η': round trip (charging + discharging) efficiency of energy storage,

where $\eta' = \eta^2$ and η is the same efficiency as in equation 13 [%]

The lowest new energy price is chosen as the place to store or sell the energy. While selling energy, there is a chosen limit to how much power is allowed to be sold each minute which is set to 1 MW in this thesis. This rule is in place since the grid connection should not be unlimited and instead is decided by the highest of installed power which equals the maximum usage of grid power or the 1 MW for selling to the grid. If this limit is reached, the rest of the leftover generated power is stored first in the battery if there is enough storage left, else in hydrogen storage. If neither has enough storage, the power is seen as lost.

3.6.2 What energy source to use when locally generation does not match load

Before deciding which energy source to use when the local generation is not enough to meet the load of the current vehicle charging, the prices for each choice are calculated using equation 16.

$$C = P \times \frac{1}{60} \times \frac{1}{\eta} \times C_s \qquad (16)$$

where

C: cost	[kr]
P: power needed	[W]
$\frac{1}{60}$: since the simulation is done in minutes	[h]
η: efficiency of energy storage	[%]
C_s: cost of storage energy	[kr/kWh]

In the case of calculating the grid cost, the spot price is used. Since cost is in kr/kWh, the power is divided by 60 to get the kWh needed, while also being divided by the efficiency of the energy sources since more energy is needed from energy sources with low efficiencies. After calculating the cost of using the grid, battery or hydrogen, the cheapest option is chosen.

3.7 The grid

To get the cost of the electricity bought from the grid in Sweden, the spot price is used for each month in kr/kWh. Since the spot prices vary heavily during the day, going from cheapest at night and highest at rush hour, there is a need to take this into consideration. Unlike the weather and traffic data, hourly data over grid spot prices during whole years is not possible to find. Instead a sampled version over the average daily variation during a year is used to get a modifier [43]. This modifier is then used on the data over monthly variation [44], to simulate the daily variations over a year. The modifying process here is the same as in section 3.3.1 where traffic data was modified. Simulation results at the Ekeröd location are displayed in figure 18, 19 and 20.

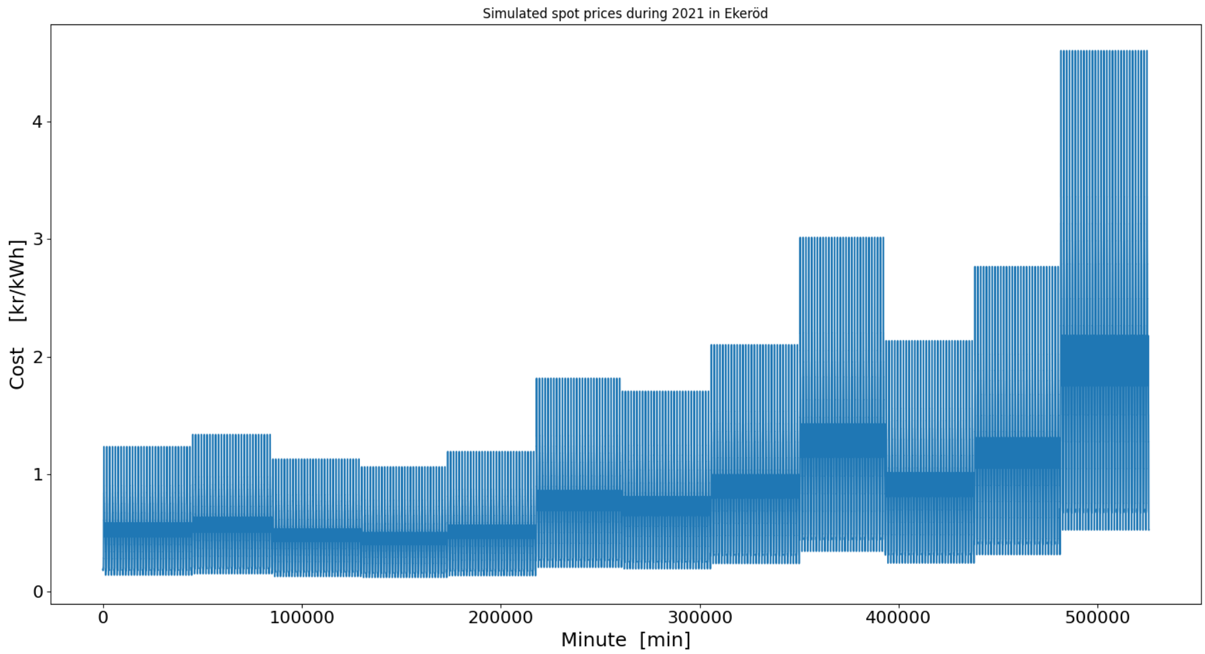

Figure 18: Simulated spot prices over the year of 2021 in Ekeröd

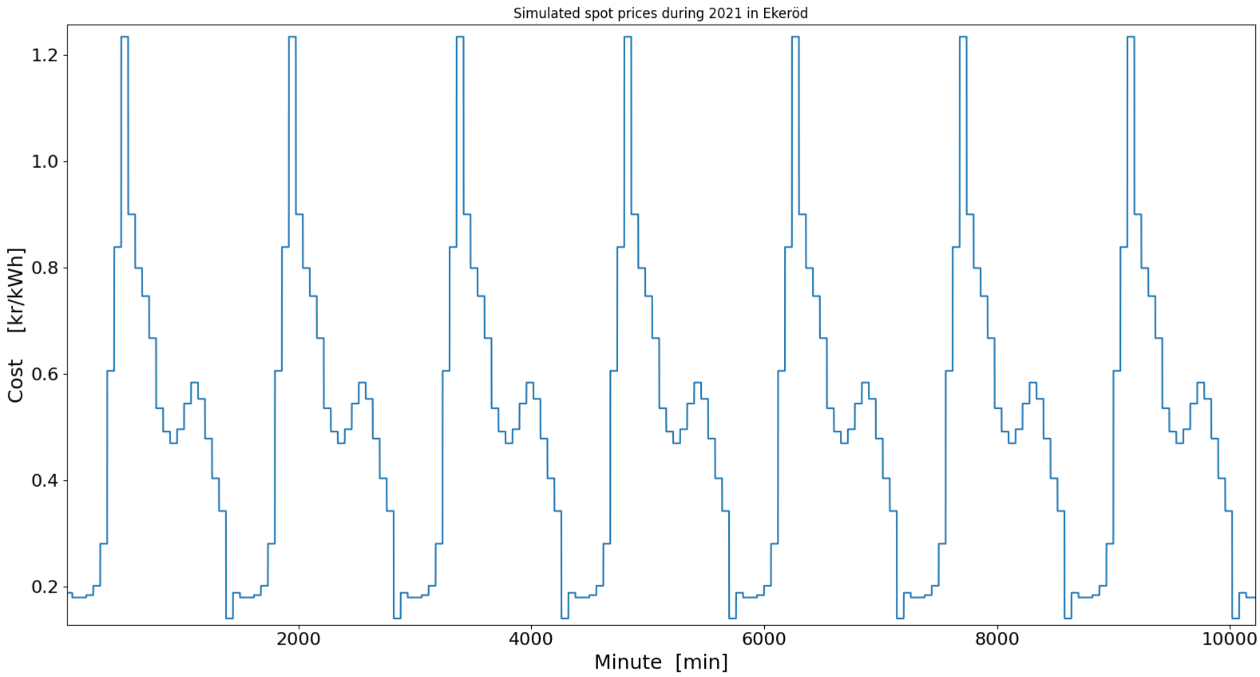

Figure 19: Simulated spot prices over seven days in Ekeröd

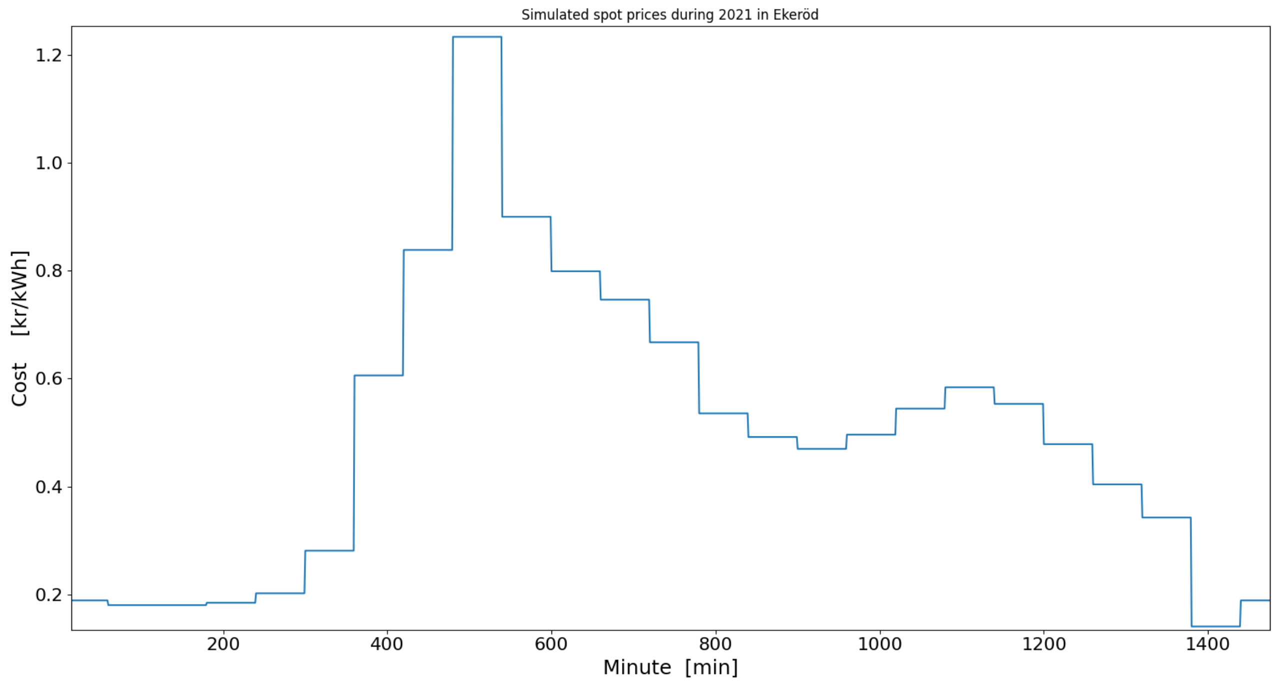

Figure 20: Simulated spot price variation over a day

Taking these figures into consideration, a big difference between the lowest daily spot price (during the night) and highest (during peak rush hour) is noticed. To take advantage of this, the energy node is designed to buy energy during hours when the vehicle load and energy price is low. However during operation, the system can only approximate future increases or decreases in energy prices.

These approximations can be very error prone, when looking at how unpredictable the spot prices are from year to year shown in appendix 1. Instead the average energy price the last 24 hours is gathered each hour. If the present spot price is 50% of the average, the system chooses to buy energy from the grid to store in the most profitable of the energy storages. This creates a system in which there is a big possibility of the energy being bought, being of profitable use later when prices should reach higher levels.

Since the energy node has a weak connection to the grid, it is not reasonable to buy energy from the grid that would result in the total energy demand on the grid exceeding the installed power. To avoid this, it is only allowed to buy the energy that is left when subtracting the present charging load power from the locally generated power.

3.8 Economics

Table 8 displays the exchanging rates for the relevant currencies used in the thesis. It should be noted that when referring to the currency kr, it is the Swedish currency that is implied.

Table 8: Conversion factors used in the thesis

Currency	kr / currency
Euro	11.367
Dollar	10.6889
Gathered from xe.com, 10 mars 2023 13:48 CET [45]	

When calculating costs for each subsystem's major parts, table 9 is used.

Table 9: Cost of major subsystem parts

Part	Cost
Solar panels	1.21 tkr/solar panel [46]
Battery pack cost	1.6 tkr/kWh [47]
Hydrogen tank	67 kr/kWh*
Fuel cells	15 tkr/kW [48]
Compressor	454 kr/kW [48]
Electrolyser	15 tkr/kW [49]
Converters	731 kr/kW [3]
* The reasoning and references behind the cost of the hydrogen tank is provided after the table	

The hydrogen tank cost is determined by first looking at the cost of a 68 m^3 vessel, which is $600,000 / tank [50]. The gravimetric density is defined as 42 kg/m^3 [51], followed by an energy density of 33.6 kWh/kg^3 [52]. This gives a storage cost of energy equal to 67 kr/kWh, which here is assumed to be independent of storage size. This assumption is a simplification and how it may change with size should be further investigated, for a more accurate storage cost of energy.

For the subsystems where cost depends on the energy capacity of the system, equation 17 is used.

$$C_c = S_c \times C_s \qquad (17)$$

where

C_c = Capital cost	[kr]
S_c = Storage capacity	[kWh]
C_s = Storage cost	[kr/kWh]

In the case of systems like the power electronic converters where cost depends on the power, equation 18 is used.

$$C_c = P \times C_p \qquad (18)$$

where

P = Power	[kW]
C_p = Power cost	[kr/kW]

These capital costs are then adapted to the amount of replacements needed during the time that is analyzed, using equation 19.

$$C_{subsystem} = C_c \times upper(\frac{Time}{Lifespan}) \quad (19)$$

where

$C_{subsystem}$: Subsystem cost [kr]

$upper(\frac{Time}{Lifespan})$: the upper integer value, to get the amount of replacements needed

The total system cost over a specified time is defined by equation 20.

$$C_{system} = C_{co} + C_s + C_b + C_{ht} + C_f + C_{co} + C_e - P_g \qquad (20)$$

where

C_{system}: System cost	[kr]
C_{co}: Power electronic converters cost	[kr]
C_s: Solar panel system cost	[kr]
C_b: Battery pack cost	[kr]
C_{ht}: Hydrogen tank cost	[kr]
C_f: Fuel cell cost	[kr]
C_{co}: Compressor cost	[kr]
C_e: Electrolyser cost	[kr]
P_g: Profit from energy sold to the grid	[kr]

4 Structure of the simulation

With all the needed data gathered in lists, the simulation of the energy node can now begin. Simulation takes place over a year, going through each minute step by step starting from the first minute of the year. A detailed description of each minute is given here:

1. Add the cars and trucks coming in this minute to two separate queues, one for cars and one for trucks. Using the process described in section 3.3.
2. If there are free charging spots, vehicles are moved from the queue with FIFO, First In First Out, structure. This is done until there are no more charging spots or the queue is empty.
3. Allocating 50 kilowatt converters to the vehicles charging. This is done in a loop starting with priority on the cars that have been charging the longest, which is then also done for the trucks. In the loop, the charging curve for each vehicle is considered so that no vehicle gets more power electronic converters than it needs. This is done until all cars and trucks have the converter power they need and can have without overreaching their limit or there are no converters left.
4. If there are converters left, they are now distributed in the same way as previous, but only once and only to the vehicles that need one more converter allocated to them. The reason for this is the following example situation:

    - A vehicle needs 75 kilowatt power according to its charging curve. This means that in stage 3, it only gets one 50 kilowatt power since giving it one more would mean it has 100 kilowatt power allocated to it. Which is not acceptable at stage 3. However if all cars and trucks have the converters they need without overreaching and there still are converters left, there is no reason not to distribute the converters left to vehicles in the same situation as the example car.

5. If there still are converters left, they are distributed to the battery pack to eventually be used to buy energy from the grid.
6. The vehicles are now charged using the power generated locally this minute and the process described in section 3.3 and 3.6.

    a. If the generated power does not match the vehicle load, the most profitable energy source out of the grid, battery or hydrogen storage is used.
    b. Else if the generated power matches the vehicle load and there still is generated power left, it is stored or sold to the grid depending on which is the most profitable.

7. If there are vehicles that have 90% or more state of charge, they are removed from their charging spots.
8. The possibility of buying energy from the grid is considered using the system rules explained in section 3.7.
9. All the needed/wanted information from this minute is gathered. The simulation increases the time by one minute and loops back to stage 1 unless the last minute of the year is reached.

A flow chart is displayed in figure 21, which together with the previous text description is intended to explain the simulation process. It is also possible to take a look at the simulation results displayed in section 5.3.1 and 5.3.2, to get a picture of how the simulation operates during a day.

The model is structured as a class that takes the inputs needed for the simulation of the energy node and returns the outputs that are essential for analysis of the system. 12 inputs are used for the model due to the fact that the energy node has many subsystems that need to be defined. The simulation gives 36 outputs in the form of lists or numbers. The reason behind such a large number of outputs is the option for the user to study as many different interests as possible without having to make changes to the model. Both the inputs and outputs of the model are listed in appendix 3.

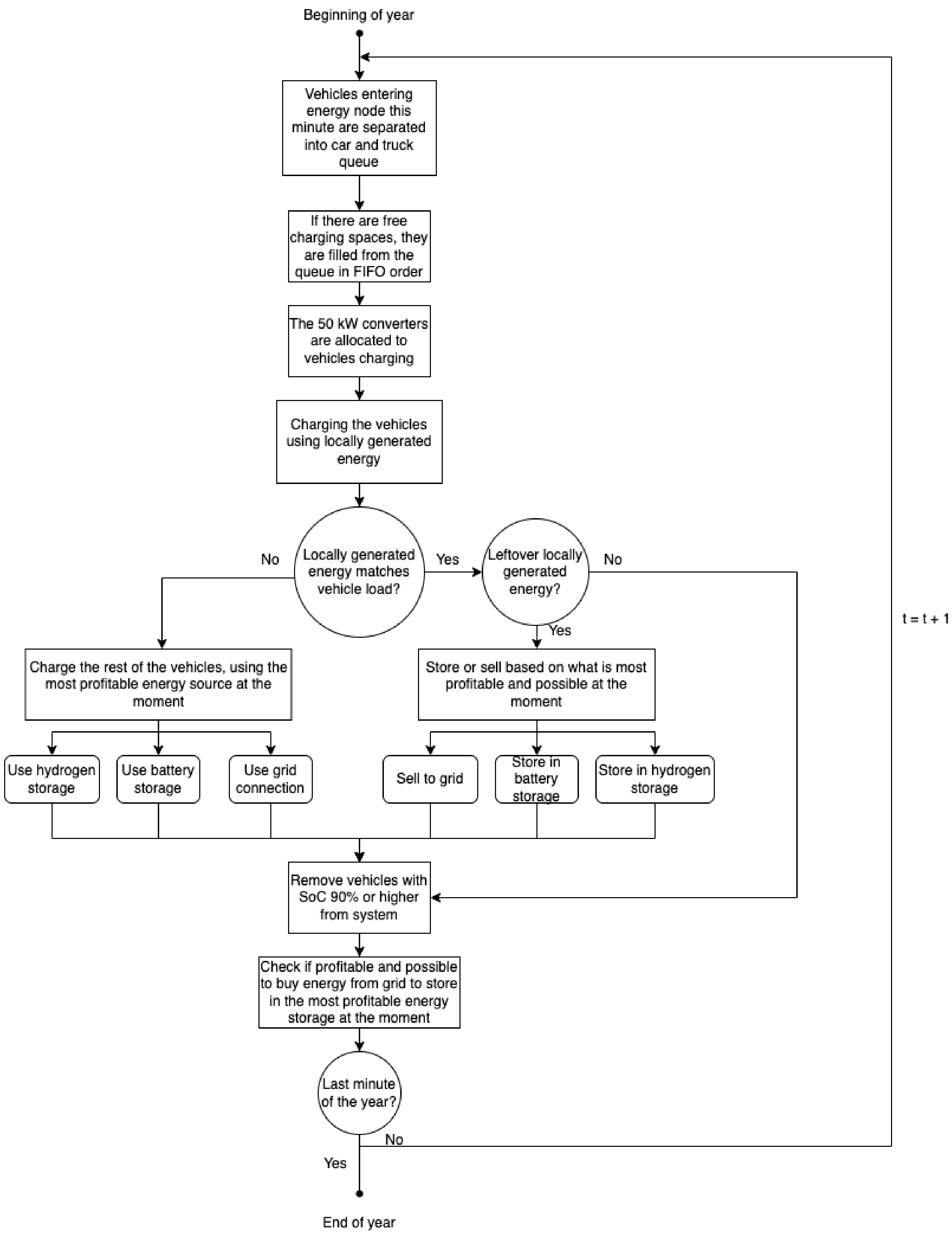

Figure 21: Flow chart over the simulation process

5 Optimization

To optimize the energy node, all subsystems need to be optimized. However since the subsystems affect each other in different ways, the optimization needs to take a certain order.

1. The installed power and number of charging spots need to be optimized, since they only depend on the load. The installed power decides how many 50 kW converters are available to be used for charging and thereby the maximum power output of the charging subsystem.
2. After finding the optimal installed power and number of charging spots for each case, the effect of changing the number of spots by one is studied.
3. A study on how the optimization not only has a queue time effect on the system, but also a financial one.
4. The local generation and storage are then simulated and optimized.
5. The optimization parameters are used to simulate results of interest.

When optimizing the installed power and number of charging spots, the aim is to have as low installed power and as few charging spots as possible to minimize the system cost given by equation 20 in section 3.8, while not exceeding a selected maximum queue time for the vehicles. This is done to have as low system cost as possible while still providing the load needed. To get the optimal installed power and number of charging spots of the energy node, simulation optimization is applied. This means using a trivial initial setup of installed power and number of charging spots to simulate the system over the year. If the simulation exceeds the limit for allowed queue time, the setup is adjusted accordingly with more charging spots or power electronic converters to get lower queue times. This is done in large steps, until the queue limit is no longer exceeded. Then the number of charging spots and electronic power converters is reduced in small steps to see how close to the limit it is possible to get. This results in an iterative optimization of the energy nodes installed power and number of charging spots.

Since the simulation includes randomized elements, there is a possibility of different results with the same initial setup. The optimization is thereby repeated for each case till two optimizations provide the same successful results, to decrease the risk of the limit being exceeded by randomized elements. This process is repeated for all three locations. Three scenarios are optimized with regards to time and distance between charging stations, which affect the amount of vehicles entering the system based on the charging model described in section 3.3.

- Now, 100 km between energy nodes, 6% of the car fleet is electric and 0.084% of the truck fleet is electric.
- Future, 60 km between energy nodes, 50% of the car fleet is electric and 50% of the truck fleet is electric.
- Future, 30 km between energy nodes, 50% of the car fleet is electric and 50% of the truck fleet is electric.

6 Results

The following results are gained from simulations with necessary data gathered from 2021, unless specified otherwise.

5.1 Optimization of installed power and number of charging spots

Table 10 displays the results for an optimization that allows 30 min waiting time for both trucks and cars. If there are no cars or trucks charged, meaning that the number of electrical vehicles of that type is too few on the selected energy node location, the number of charging stations is set to one since there still is a chance that one of the few electrical vehicles of the type enters the energy node during the year.

Table 10: Optimization results for different cases, displayed in installed power / car charging spots / truck charging spots. Including the number of cars and trucks going through the system.

Scenario, Distance between charging stations	**Ekeröd**	**Ödeshög**	**Norrfjärden**
	Installed power / Car charging spots / Truck charging spots/ (number of cars, number of trucks charged)		
Now, 100 km	0.4 MW / 4 / 1 (8640 cars, 0 trucks)	0.6 MW / 4 / 1 (11489 cars, 0 trucks)	0.4 MW / 4 / 1 (11880 cars, 0 trucks)
Future, 60 km	4.2 MW / 39 / 4 (108863 cars, 17434 trucks)	9.2 MW / 30 / 7 (143,648 cars, 54635 trucks)	5.8 MW / 38 / 5 (145127 cars, 29694 trucks)
Future, 30 km	2.2 MW / 21 / 3 (54282 cars, 8583 trucks)	3.2 MW / 22 / 4 (71928 cars, 27290 trucks)	3.2 MW / 20 / 3 (74109 cars, 15749 trucks)

To illustrate the effect of allowing longer queue times, table 11 shows the optimisation of the future case for each location but instead the limit for allowed queue time is 120 minutes for cars and trucks.

Table 11: Optimization results for different cases, displayed in installed power / car charging spots / truck charging spots if 120 minutes wait time is allowed

Installed power / Car charging spots / Truck charging spots	**Ekeröd**	**Ödeshög**	**Norrfjärden**
Future, 30 km	2 MW / 23 / 2	2.7 MW / 19 / 3	2.6 MW / 19 / 2

5.1.1 Volatile system

In the following simulations, the objective is to find out how much a change in either distance between charging stations or the number of charging spots for cars and trucks, affects the queue times. By doing this a sensitivity analysis of the system is created. Norrfjärden is chosen for these simulations since it is the most truck dependent out of the two raw traffic data locations(Eketöd and Norrfjärden). The installed power and number of charging spots are the optimized values for the future case with 30 km distance between charging stations. In table 12 these values are repeated.

Table 12: Optimal setup at Norrfjärden location in the future case with 30 km between stations

Installed power	Car charging spots	Truck charging spots
3.2 MW	20	3

First a baseline simulation is conducted, displayed in figure 22, where the queue time for each vehicle is recorded from first to last with optimal setup.

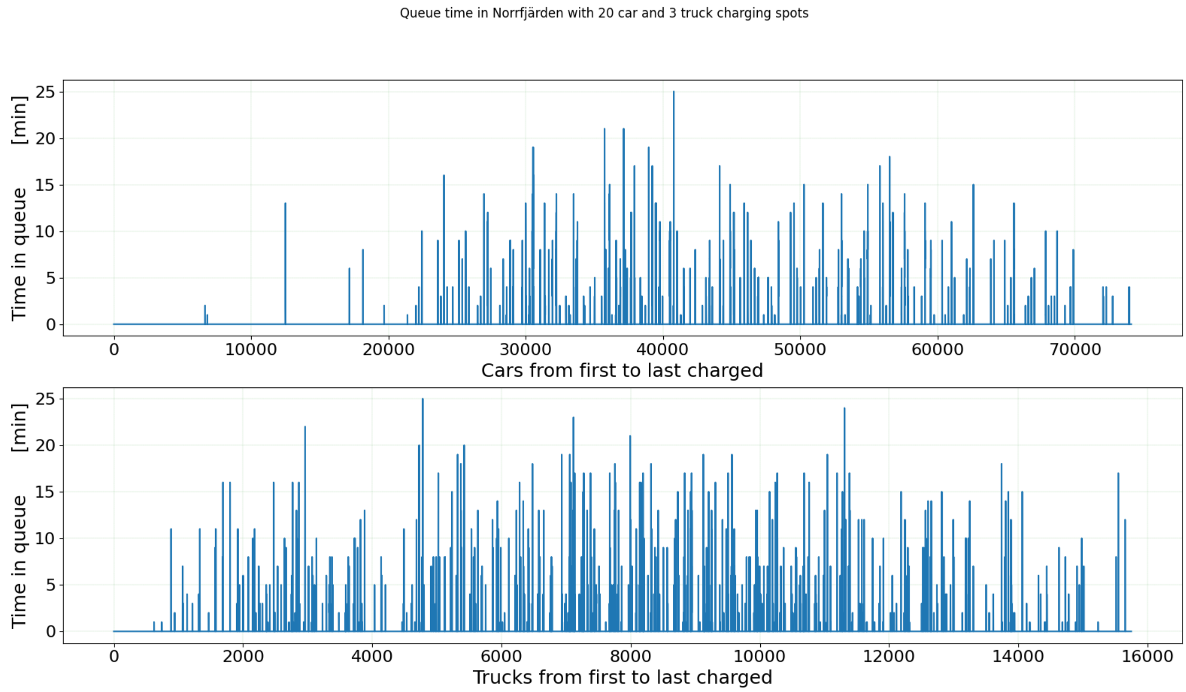

Figure 22: Queue times in Norrfjärden with 20 car and 3 truck charging spots

In figures 23 and 24 the number of charging spots are increased. Since cars and trucks share the converters available, an increase in the number of car charging spots and thereby possible cars charging each minute, affects the availability of converters for trucks. Consequently the number of charging spots are increased separately for each vehicle type.

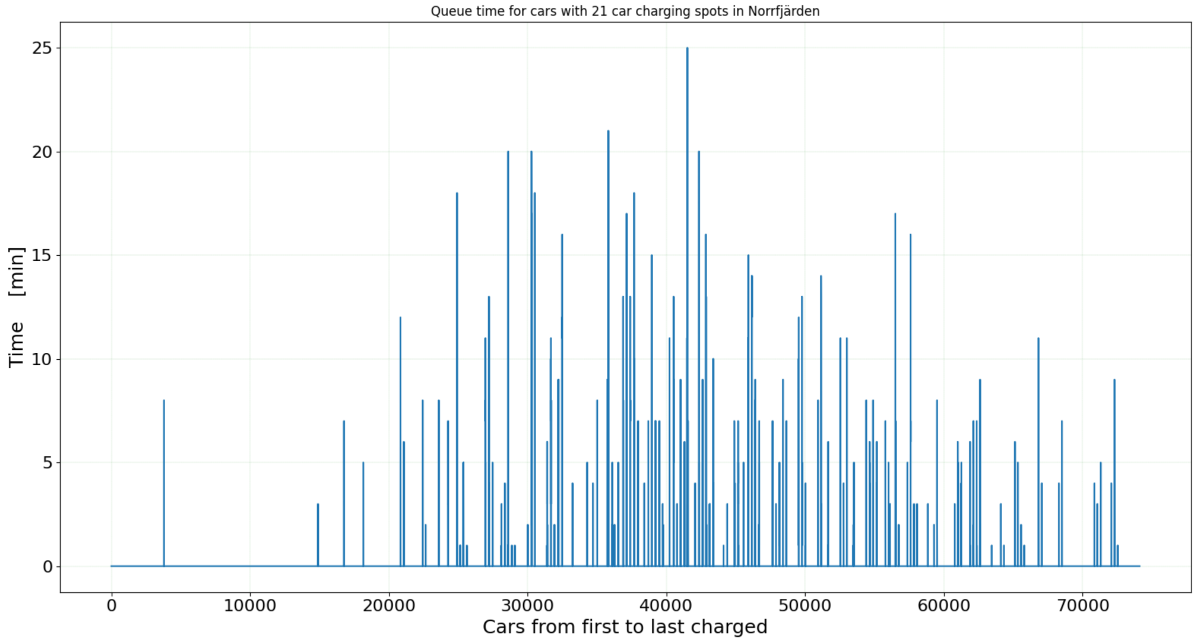

Figure 23: Car queue times in Norrfjärden with 21 car and 3 truck charging spots

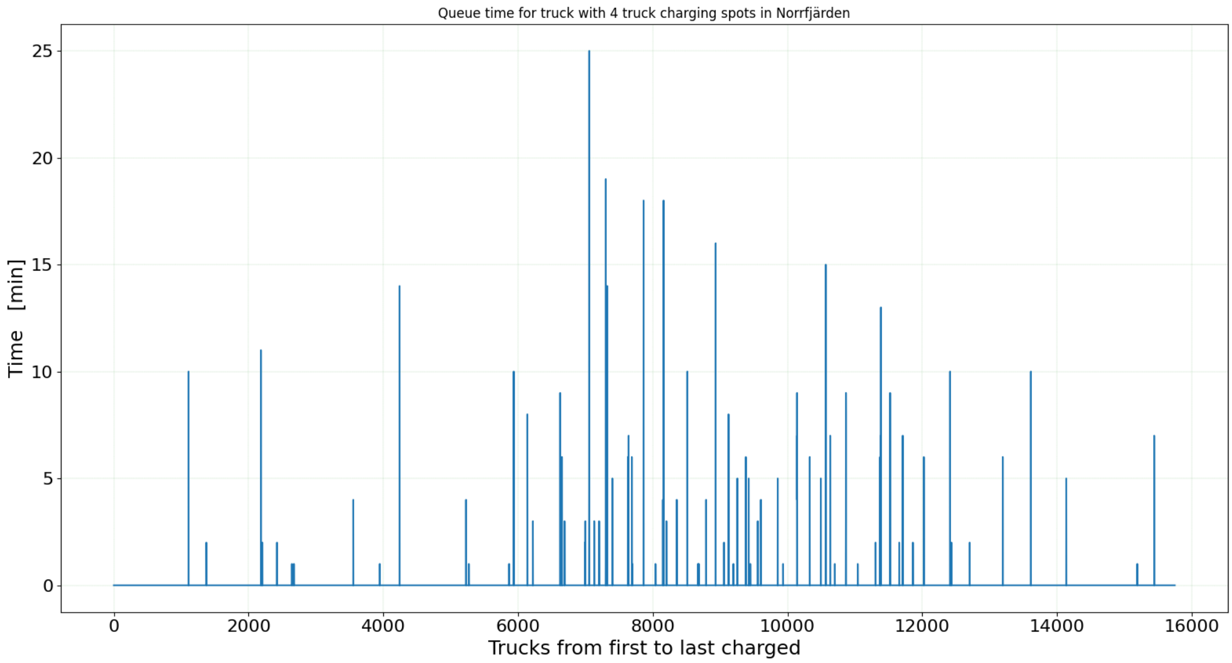

Figure 24: Truck queue times in Norrfjärden with 20 car and 4 truck charging spots

In figure 25 and 26 the same logic as with the increase of the number of charging spots is used but instead the number of charging spots are separately decreased.

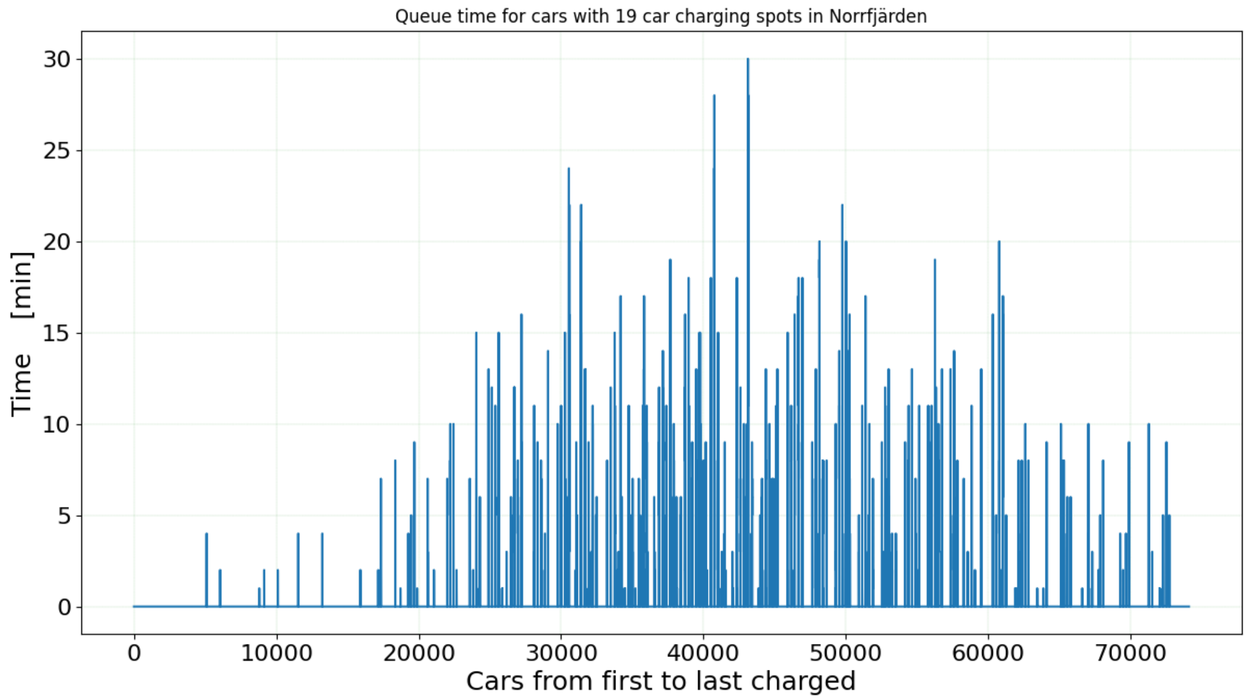

Figure 25: Car queue times in Norrfjärden with 19 car and 3 truck charging spots

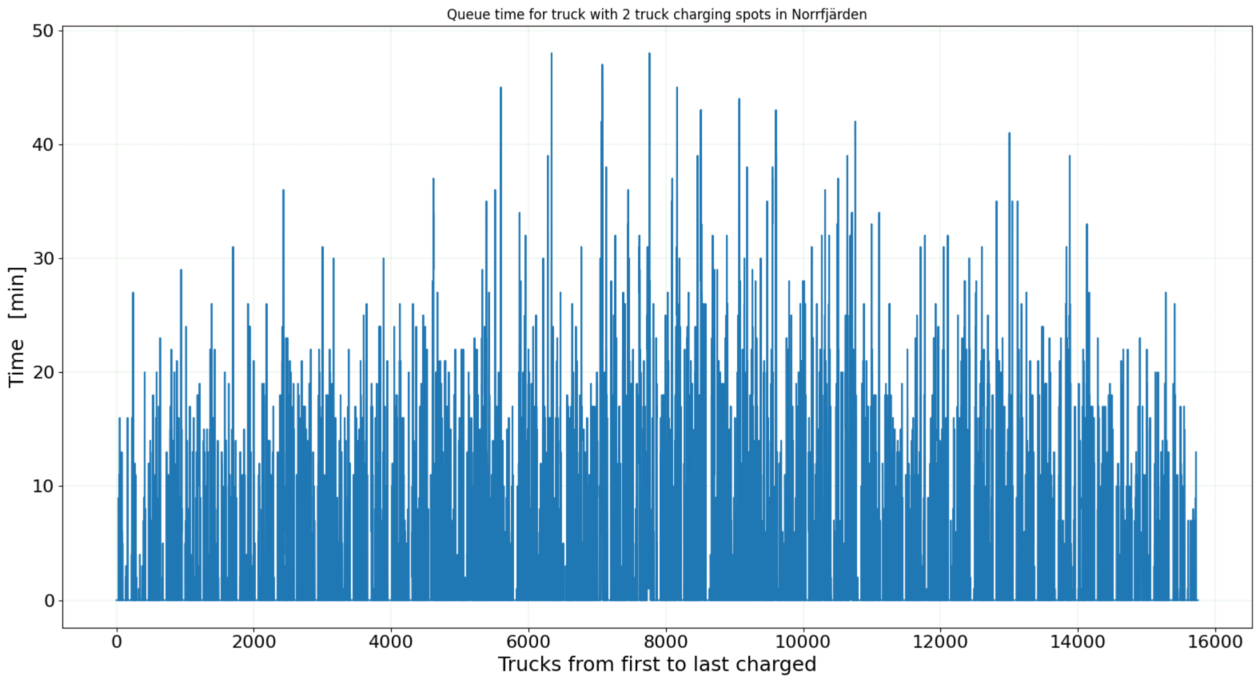

Figure 26: Truck queue times in Norrfjärden with 20 car and 2 truck charging spots

In the next simulation distance between charging stations is increased to 60 km and the resulting graph displayed in figure 27.

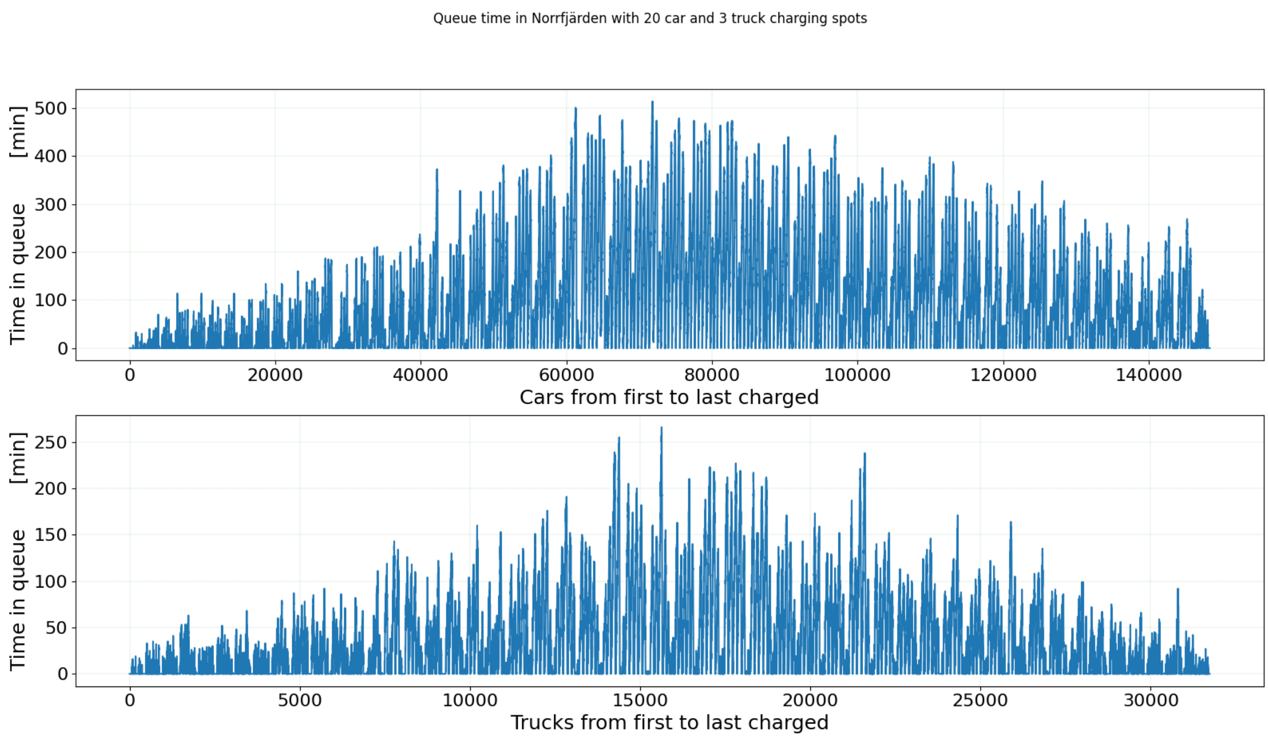

Figure 27: Queue times in Norrfjärden with 20 car and 3 truck charging spots but 60 km between charging stations

When looking at the average queue times for both cars and trucks table 12 shows the volatility of the system.

Table 12: Average queue time for different setups

Average queue time in minutes	**- 1 charging spot**	**30 km / 22 / 4**	**+ 1 charging spot**	**60 km / 22 / 4**
Cars	0.128	0.068	0.053	187.010
Truck	0.337	0.029	0.006	8.663

5.1.2 Cost of truck queue time compared to change in number of charging spots

Norrfjärden is chosen as the location for this simulation, since it is arguably the most truck dependent out of the locations that have unmodified traffic data. The optimized data displayed in table 10 in section 5.1 is used for car spots and installed power. The simulation is run with focus on the time spent in the system for truck drivers. Since truck drivers are at the energy node during work hours, the cost for them not being able to be on the road can be quantified. By law truck drivers in Sweden have to take a 45 minute rest each 4.5 hours [53], in this study it is assumed to be taken while charging and eating lunch. This means that any time longer than 45 minutes spent at the energy node results in a loss of money for the truck company, since the driver is being paid while not being able to be in motion.

On average a truck driver in Sweden earns 185 kr/h [54] with a bonus of 32.39 kr/h or 64.79 kr/h based on how uncomfortable the work hour is [55]. Using these values and the fact that a simulation keeps record of the time truck drivers spend at the truck station, it is possible to get the money lost over a year for all electrical truck drivers for different number of truck charging spots. This is illustrated in table 13.

Table 13: Annual total cost in truck driver salary, while being stuck in energy node

Truck charging spots	1	2	3	4	5	6
Cost for truck drivers yearly	7.9 Mkr	9.0 Tkr	10.1 Tkr	9.0 Tkr	308 kr	342 kr

Table 13 gives the idea of not only time lost due to poorly structured energy nodes, but also a financial effect. It is also noted that three charging spots resulted in 1 Tkr increase compared to two charging spots, this is likely due to the randomized qualities implemented in the model. Resulting in a worse bottleneck created in the simulation with three charging spots.

5.2 Local generation and storage optimization

Since the local generation and storage are intertwined when it comes to their results, they are optimized together. By simulating different storage combinations for each solar panel area of interest and recording the system cost, it is possible to get a surface plot which illustrates which combination results in the lowest system cost based on equation 20 from section 3.8. This is then done for a selected number of solar panel areas. The time period is based on the solar panels lifetime of 25 years. Figure 28, 29, 30 and 31 illustrate the results for different solar panel surface areas at the Ekeröd location. The optimal setup for the installed power and number of charging spots is used and displayed in table 14.

Table 14: Optimal setup for Ekeröd location in future case with 30 km between stations

Installed power	Car charging spots	Truck charging spots
2.2 MW	21	3

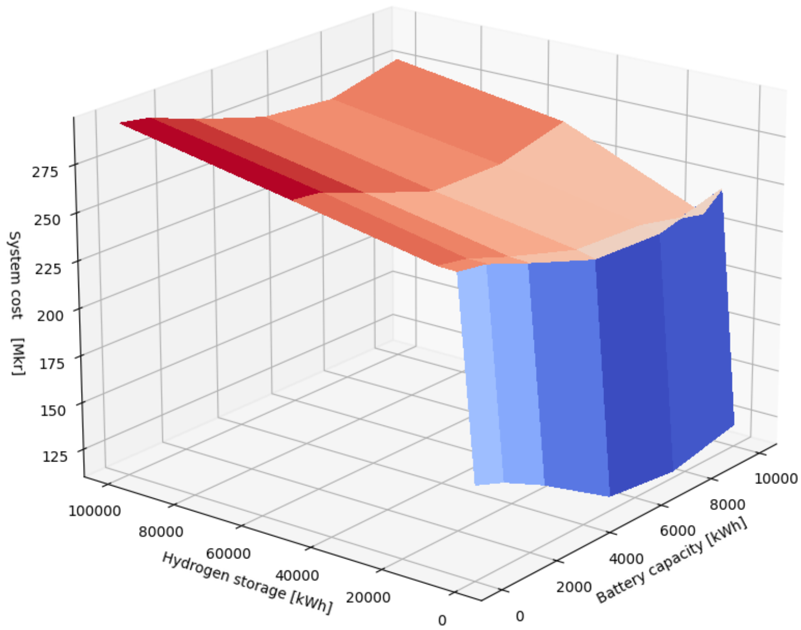

Figure 28: System cost analysis of storage combinations in Ekeröd with 0.5 hectare solar panels

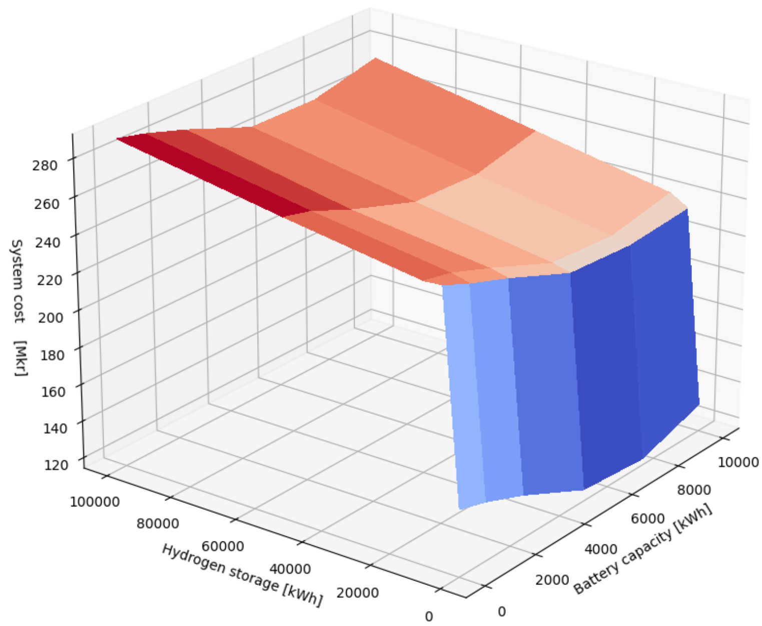

Figure 29: System cost analysis of storage combinations in Ekeröd with one hectare solar panels

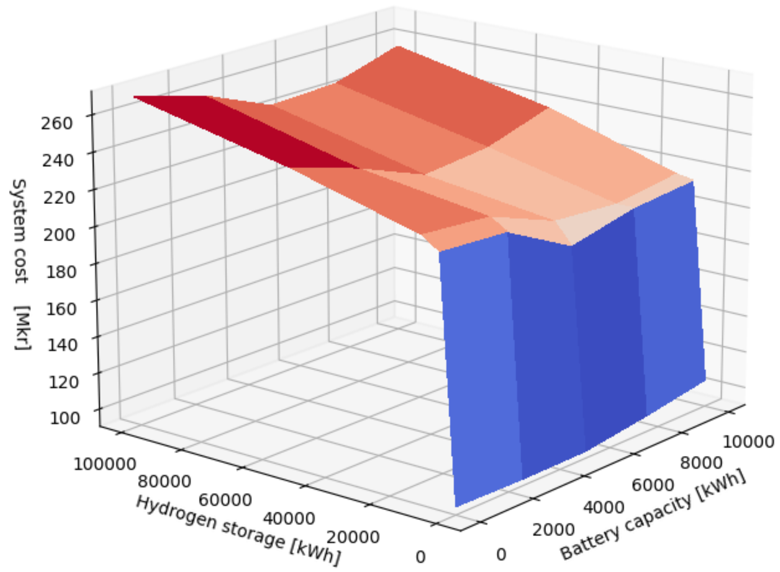

Figure 30: System cost analysis of storage combinations in Ekeröd with five hectare solar panels

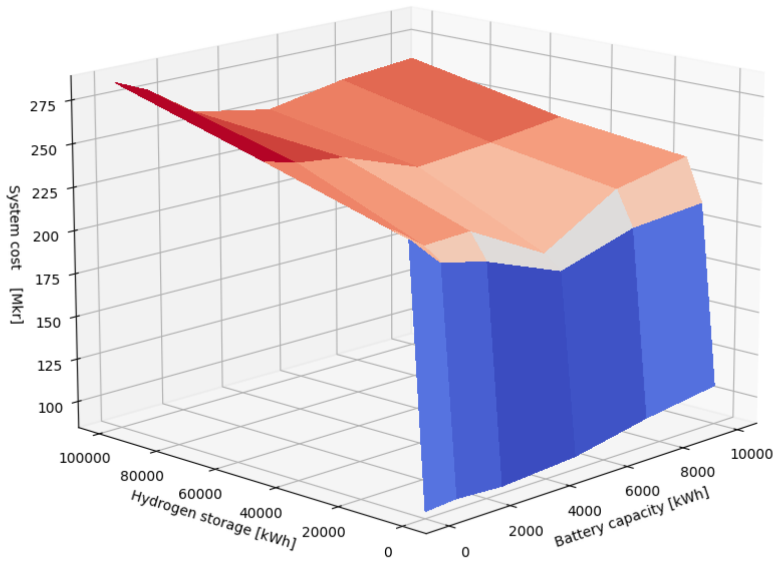

Figure 31: System cost of storage combinations in Ekeröd with ten hectare solar panels

It is worth repeating that there is a limit of 1 MW power allowed to be sold to the grid. With these results, table 15 can be created with optimal values in Ekeröd.

Table 15: Optimized values for each solar panel area over a 25 year period

Solar area [hectare]	Optimal battery and hydrogen storage	
	Ekeröd	**System cost**
0.5	Battery: 7.5 MWh, Hydrogen: 0 MWh	113.84 Mkr
1	Battery: 7.5 MWh, Hydrogen: 0 MWh	117.73Mkr
5	Battery: 2.5 MWh, Hydrogen: 0 MWh	93.96 Mkr
10	Battery: 0 MWh, Hydrogen: 0 MWh	88.59 Mkr

From the results, it is possible to determine that hydrogen is not economically profitable in any of the simulated cases. Another conclusion is that an increase in solar panel area is profitable for the selected plane areas, when assuming a 25 year solar panel lifetime. At the same time batteries become less cost effective the larger the solar panel area that is used. It should be noted that the batteries have a lifetime of 15 years, meaning that during 25 years there is a cost for a replacement of the batteries. What if the simulations instead are done over 15 years, meaning that the batteries are used over a full lifetime? Considering how profitable the solar panels seem to be, they might be profitable already before reaching their lifetime. Thereby an analysis of a system with only battery storage is done to see which configuration results in the lowest system cost. However in figure 32, 33 and 34 both solar panel and battery lifetime is set to 15 years. Optimal setup of installed power and number of charging spots for the future case with 30 km between charging stations is used, which is shown in table 10 in section 5.1.

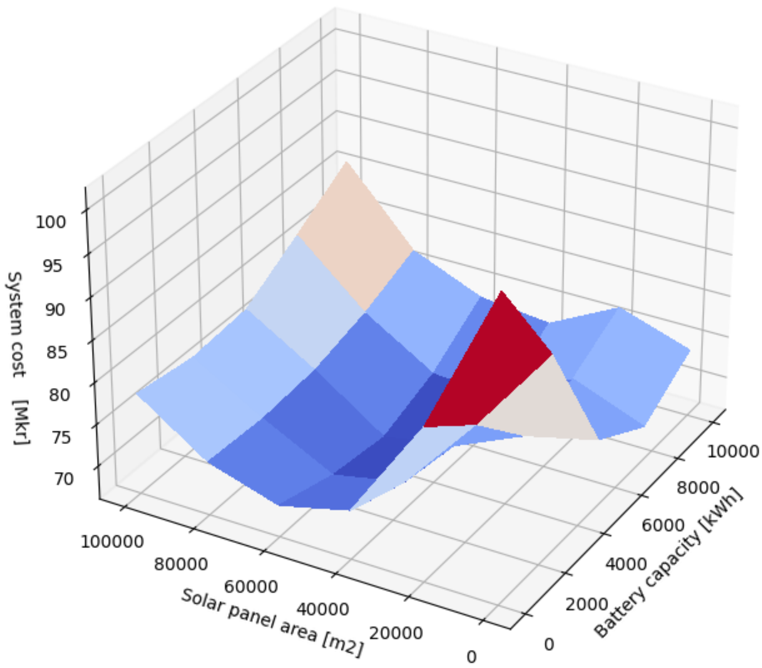

Figure 32: System cost analysis of battery and solar panel combinations in Ekeröd

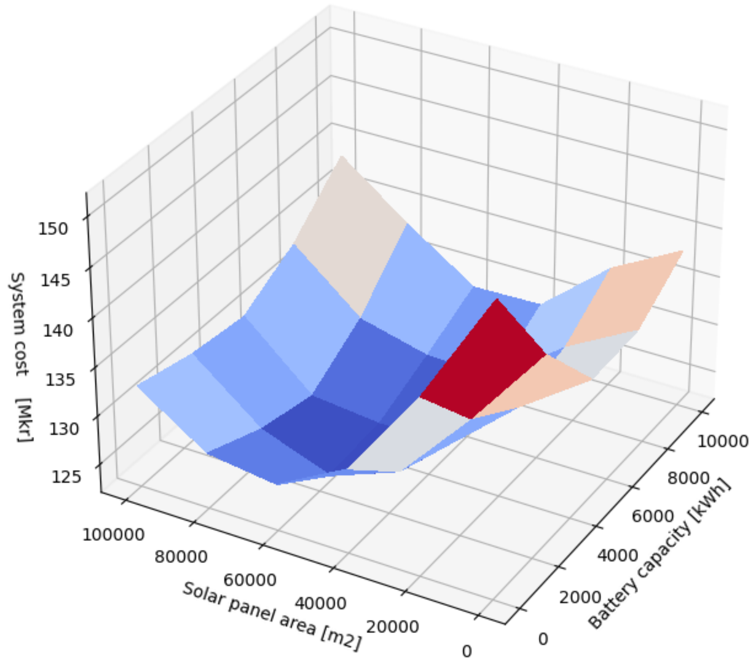

Figure 33: System cost analysis of battery and solar panel combinations in Ödeshög

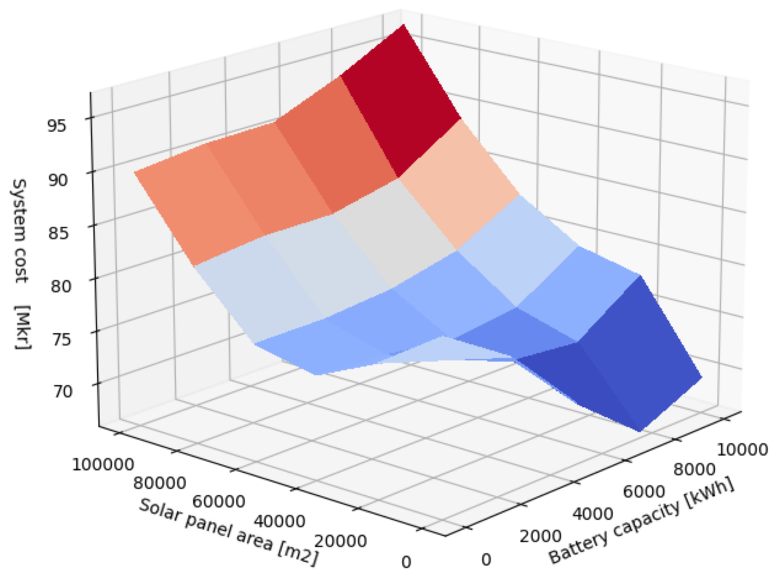

Figure 34: System cost analysis of battery and solar panel combinations in Norrfjärden

The minimum system cost for each location together with the optimal solar panel area and battery capacity is displayed in table 15.

Table 15: Optimal solar panel area and battery capacity for each location over a 15 year period

Location	**Solar panel area**	**Battery storage capacity**	**System cost**
Ekeröd	6 hectare	5 MWh	66.71 Mkr
Ödeshög	6 hectare	2.5 MWh	122.67 Mkr
Norrfjärden	0 hectare	7.5 MWh	66.49 Mkr

In the following simulations these values are used unless specified otherwise.

5.2.1 Wind turbines effect on the system

In figure 35 the power output of a 2 MWp solar system is combined with a 2 MW wind turbine in Ekeröd. The output is put to 2MWp since that is the average rated power of a common wind turbine discussed in section 2.2.2. Since the focus is put on the comparison between solar and wind turbines, the rated power of both should be the same and thereby the solar panel system is given the same rated power. In table 16 the setup of the system in Ekeröd is shown based on optimal values for installed power, number of charging spots and battery capacity.

Table 16: Setup in Ekeröd location in future case with 30 km between stations

Installed power	Car charging spots	Truck charging spots	Battery capacity	Solar panel system power	Wind turbine power
2.2 MW	21	3	5 MWh	2 MWp	2 MW

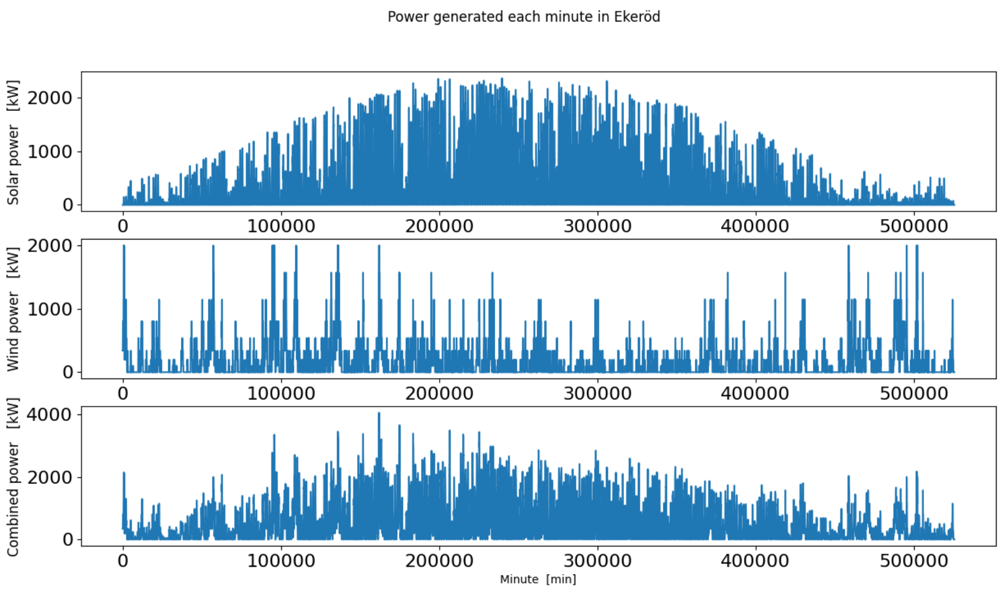

Figure 35: Solar and wind power generation compared and combined in Ekeröd

The same simulation is conducted in Norrfjärden seen in figure 36, to get a comparison between possible energy production depending on location. Notable is also that Norrfjärden is located near the coast while Ekeröd is located inland. In table 16 the setup for the Norrfjärden simulations is displayed.

Table 16: Setup in Norrfjärden location in future case with 30 km between stations

Installed power	Car charging spots	Truck charging spots	Battery capacity	Solar panel system power	Wind turbine power
3.2 MW	20	3	7.5 MWh	2 MWp	2 MW

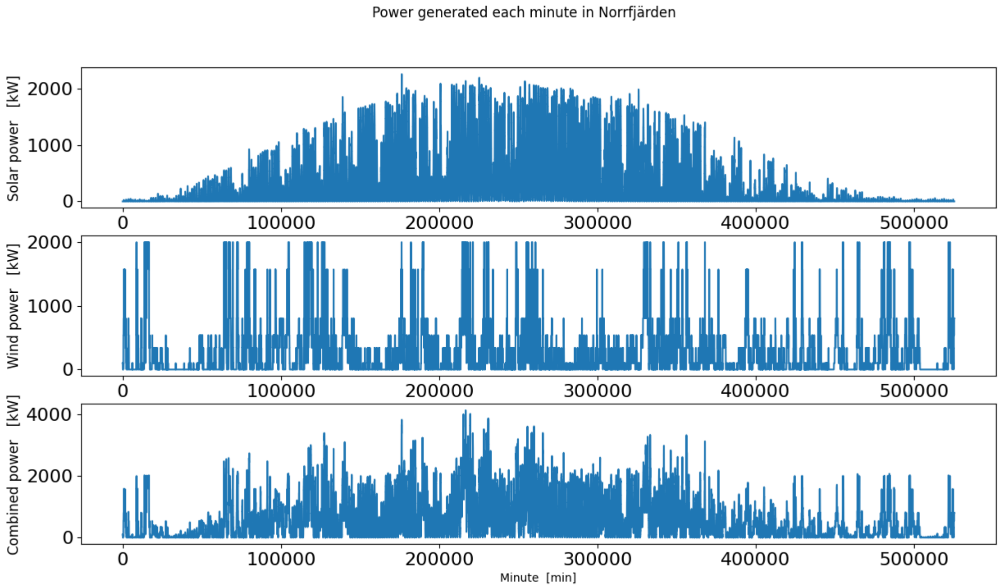

Figure 36: Solar and wind power generation compared and combined in Norrfjärden

To illustrate the effect 2 MW rated power for both energy sources can have on the overall grid demand, figure 37 displays the grid load from simulations using no local generation, 2 MW wind turbine or 2 MWp solar panels. The blue curve represents grid load used, while the green is power sold to the grid.

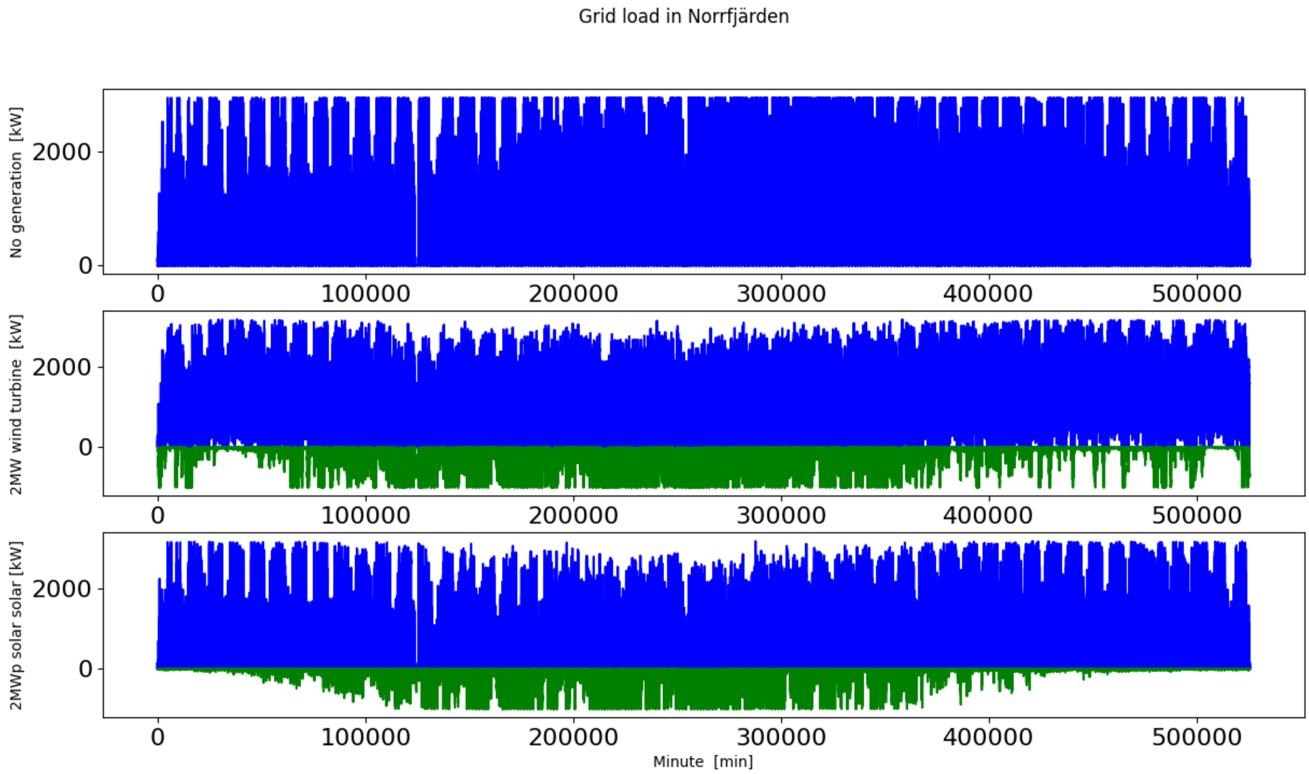

Figure 37: Wind turbines effect on the needed grid load in Norrfjärden

From figure 37, it can be seen that solar power in Norrfjärden provides very seasonal based power support compared with wind power.

5.3 Visualization of the simulation process

This section focuses on illustrating the operation of the energy node. Doing so gives a deeper understanding of the effects each subsystem has on the energy node and the rules it follows become clearer. It is also a great tool for searching for unwanted behaviors either prompted by errors in the model or inefficient rules. Table 16 summarizes the inputs for all locations considered optimal from previous results. Ekeröds values are used as a baseline for the simulations in this section.

Table 16: Summarization of optimal inputs

	Ekeröd	**Ödeshög**	**Norrfjärden**
Installed power	2.2 MW	3.2 MW	3.2 MW
Car charging spots	21	22	20
Truck charging spots	3	4	3
Solar panel area	6 hectare	6 hectare	0
Battery storage capacity	5 MWh	2.5 MWh	7.5 MWh
Hydrogen storage capacity	0 MWh	0 MWh	0 MWh

5.3.1 Simulation results from a day of the model illustrated

Results from the operation of the energy node during a 24 hour time span between 00.00-00.00 display how it reacts to the daily shifts in vehicle load, spot prices and local energy production. These variations vary depending on which weekday it is, which can be seen in the graphs in appendix 1. This section shows the simulation results from the first Thursday and Saturday of May after an optimal simulation. The reason for these two weekdays is that both weekday and weekend traffic flow is of interest, however the exact weekday is trivial and chosen without any more specific reason. The reason for May being chosen is the high solar energy production, while the traffic flow patterns are not affected by the summer vacations taken during June, July and August in Sweden. The minor ticks on the x-axis are located in 60 minute intervals to indicate hours. The first two figures, 38 and 39, display vehicle flow of both cars and trucks during the day.

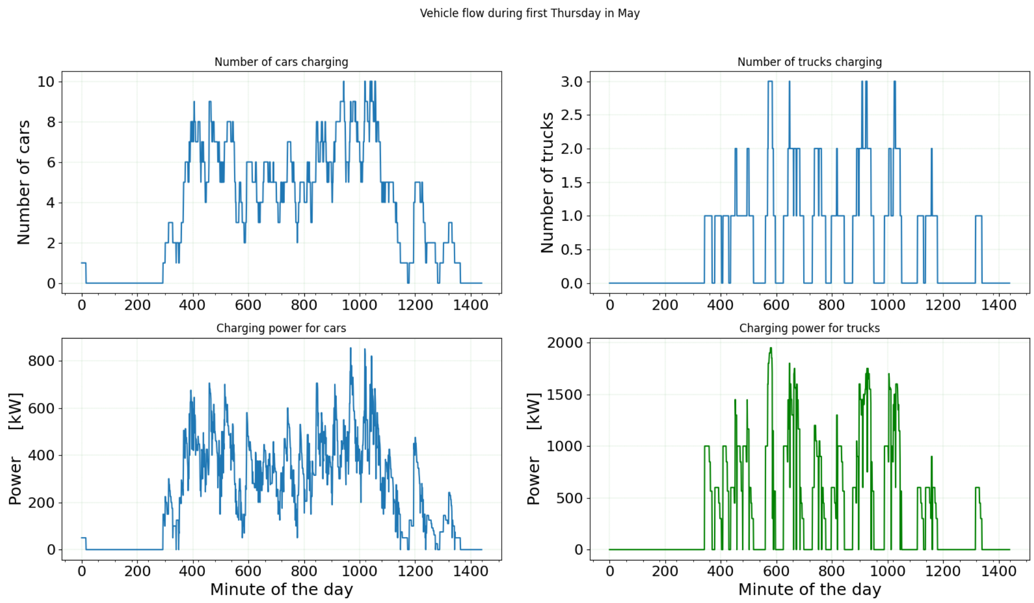

Figure 38: Simulated vehicle flow during the first Thursday in May 2021

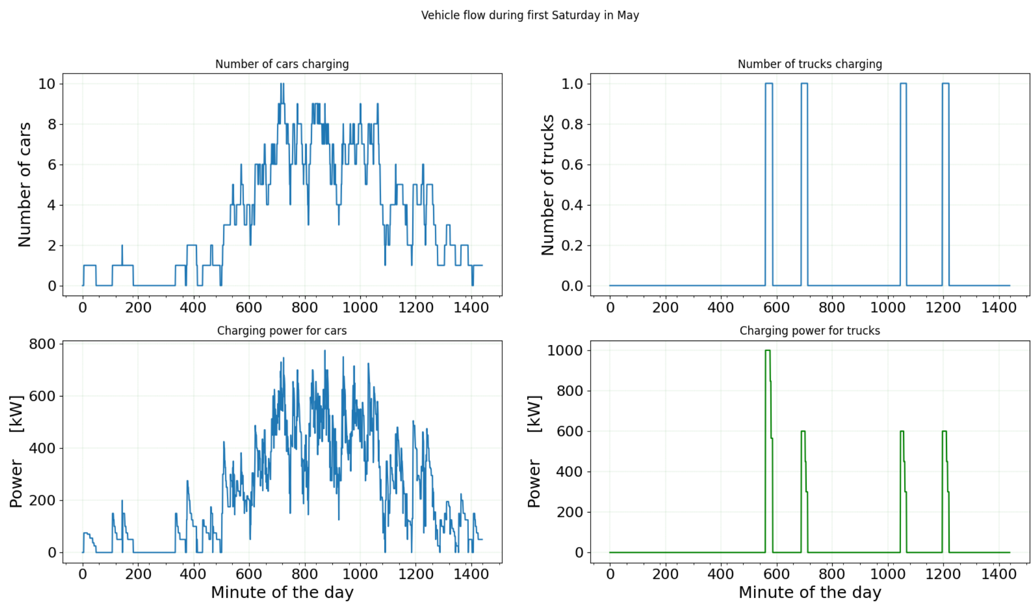

Figure 39: Simulated vehicle flow during the first Saturday in May 2021

Figures 40 and 41 display the energy flow during the days mentioned. The upper left graph shows the vehicle load (both cars and trucks) over the day in striped red and locally generated power (as hourly average values) in striped green. Of greater interest is if the locally generated energy is more or less than the needed energy to charge the vehicles, which is displayed in the same graph in blue. When the blue curve has a positive power value it means that the leftover generated energy needs to be stored or sold, while when it has a negative value there is not enough locally generated energy which means that energy is needed from either the storage or the grid.
The upper right graph displays the prices of each energy source over the day, to illustrate when each becomes profitable to use or store in. In the lower left graph, the total energy stored in the battery storage is displayed to give an overview of how it varies over the day as a function of its usage or charging. Finally the lower right curve displays the power flow of each energy source, to show how much power is required either to store or use the different storages and the grid.

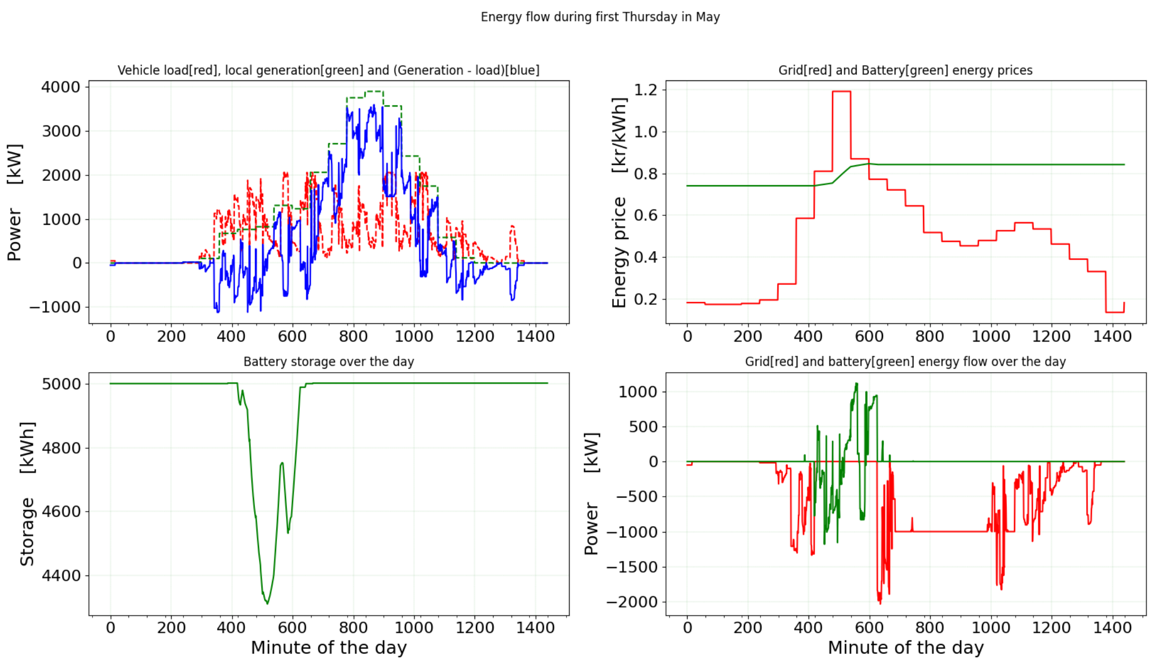

Figure 40: Simulated energy flow during the first Thursday in May 2021

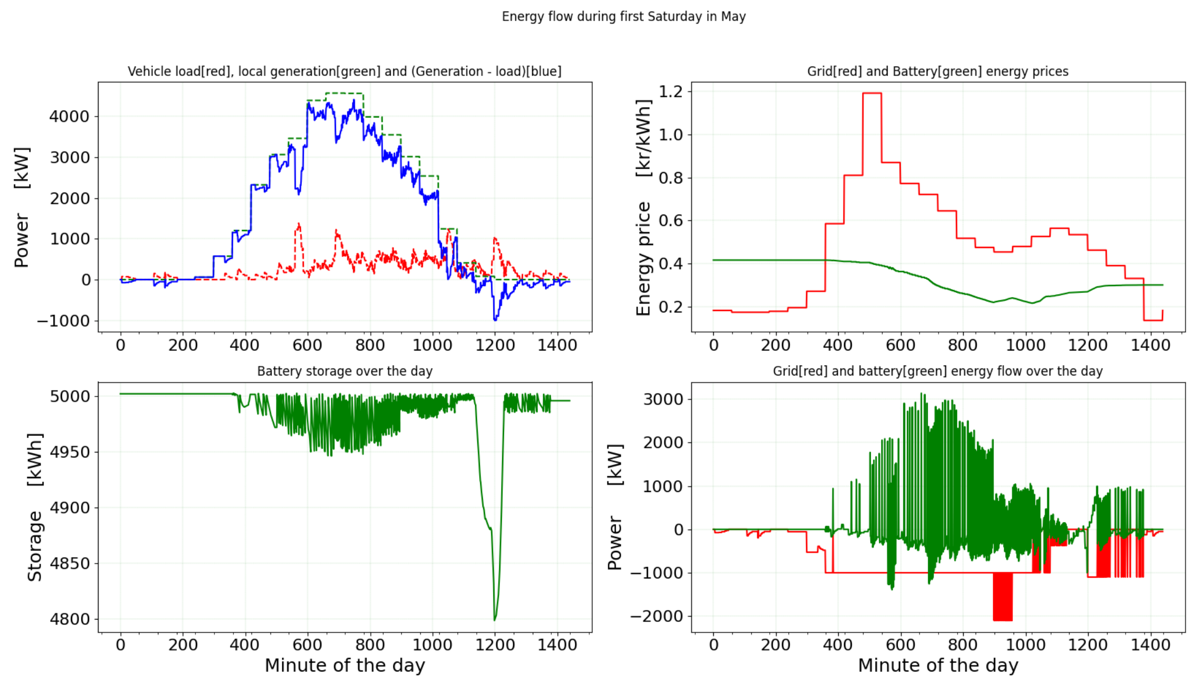

Figure 41: Simulated energy flow during the first Saturday in May 2021

In appendix 2, the first Thursday of January and November are also simulated to illustrate the difference between months in operation behavior.

5.3.2 Energy flow over the year of the model illustrated

The in and outflow of energy from the grid over the year is prone to volatility due to big variations in energy spot prices and local energy production. In figure 42 the price of energy over the year is displayed in the top left graph, energy in the local storage in the top right graph, local power generation subtracted by vehicle charging power in the bottom left and lastly grid power flow in bottom right corner.

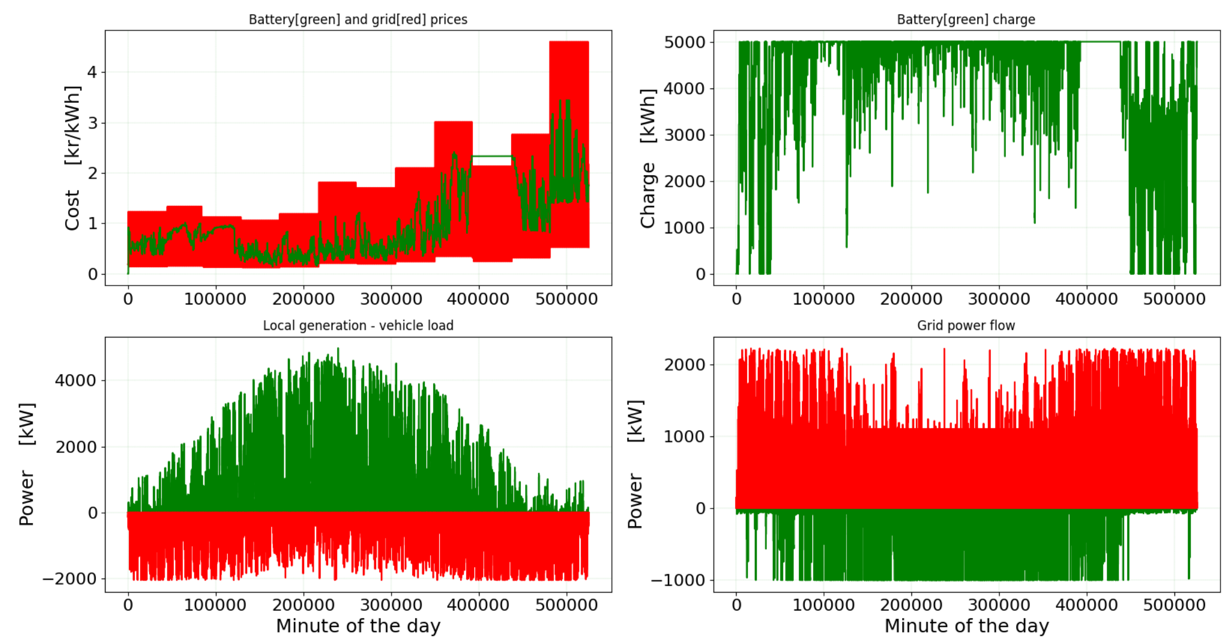

Figure 42: Cost analysis of battery and solar panel combinations in Ekeröd using 2021 data

From the data in appendix 1 it is clear that grid energy spot prices can be vastly different depending on the year. Thereby the same energy flow graphs are shown in figure 43, but using data from 2019 in the simulation.

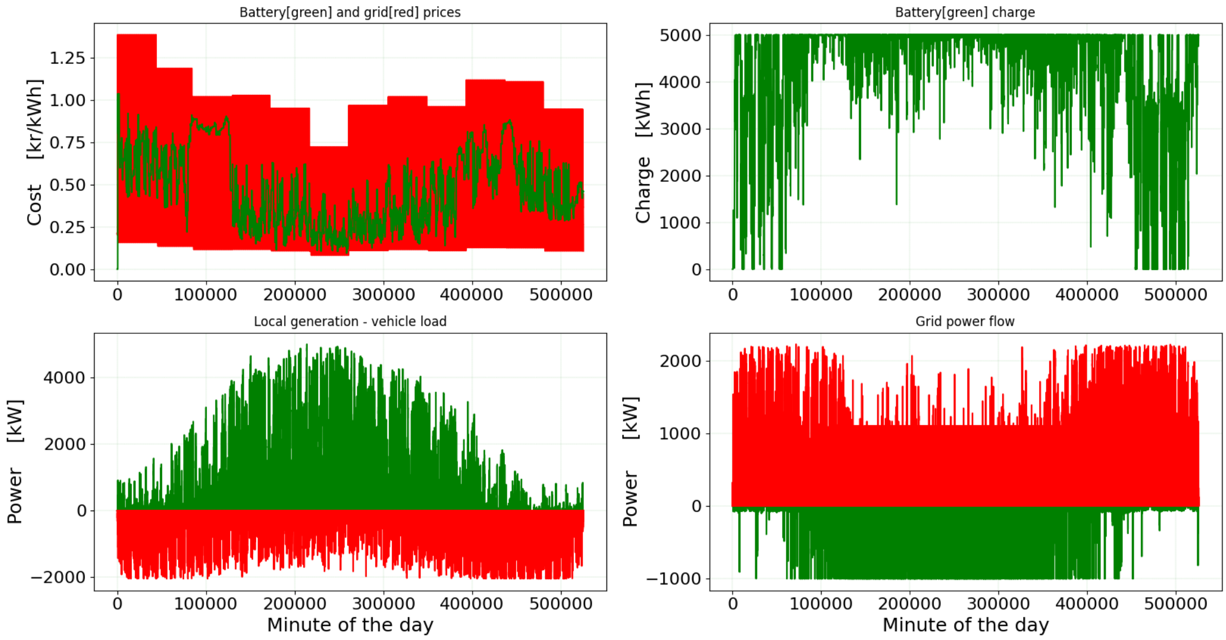

Figure 43: Cost analysis of battery and solar panel combinations in Ekeröd using 2019 data

5.4 No local generation or storage

Having no local generation or storage thereby relying on getting all the power from the grid, results in the grid loads displayed in figure 44, 45 and 46. In these cases the limit on the possible power demand from the grid is the installed power, which is optimized in section 5.1 to never result in a queue time of over 30 min for cars or trucks. In table 17 a repetition of the optimal parameters is given for each location.

Table 17: Setup for the following simulations in future case with 30 km between stations

	Ekeröd	**Ödeshög**	**Norrfjärden**
Installed power	2.2 MW	3.2 MW	3.2 MW
Car charging spots	21	22	20
Truck charging spots	3	4	3

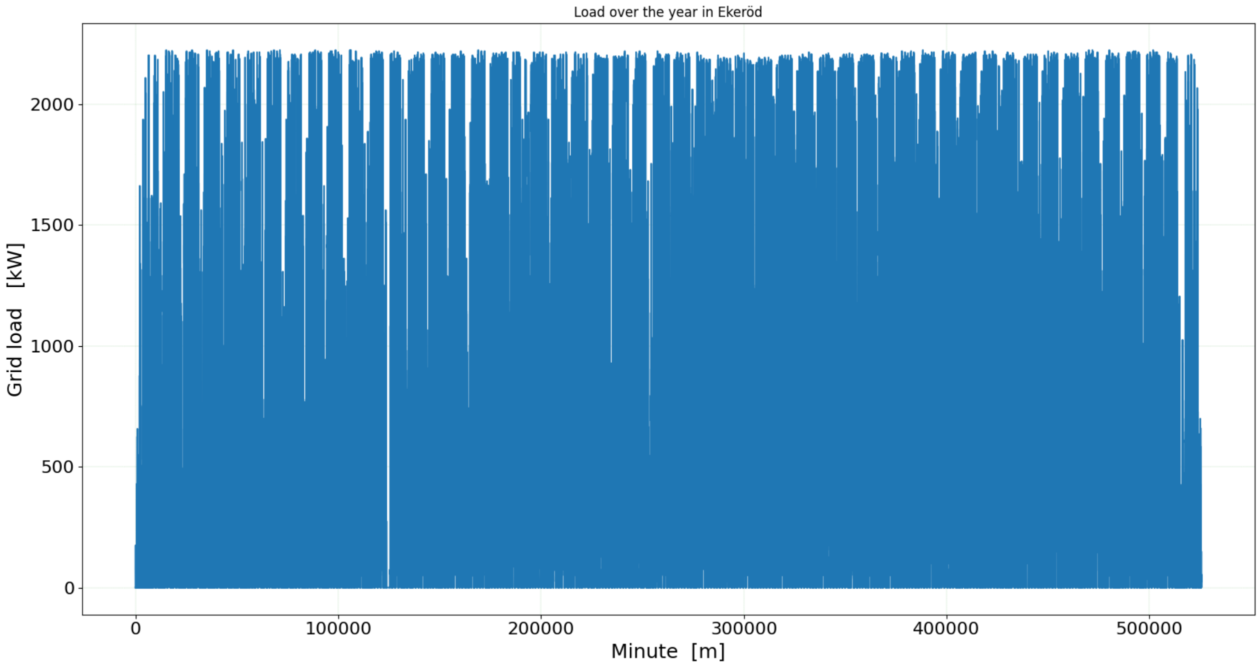

Figure 44: Grid load in Eketöd with no local generation or storage

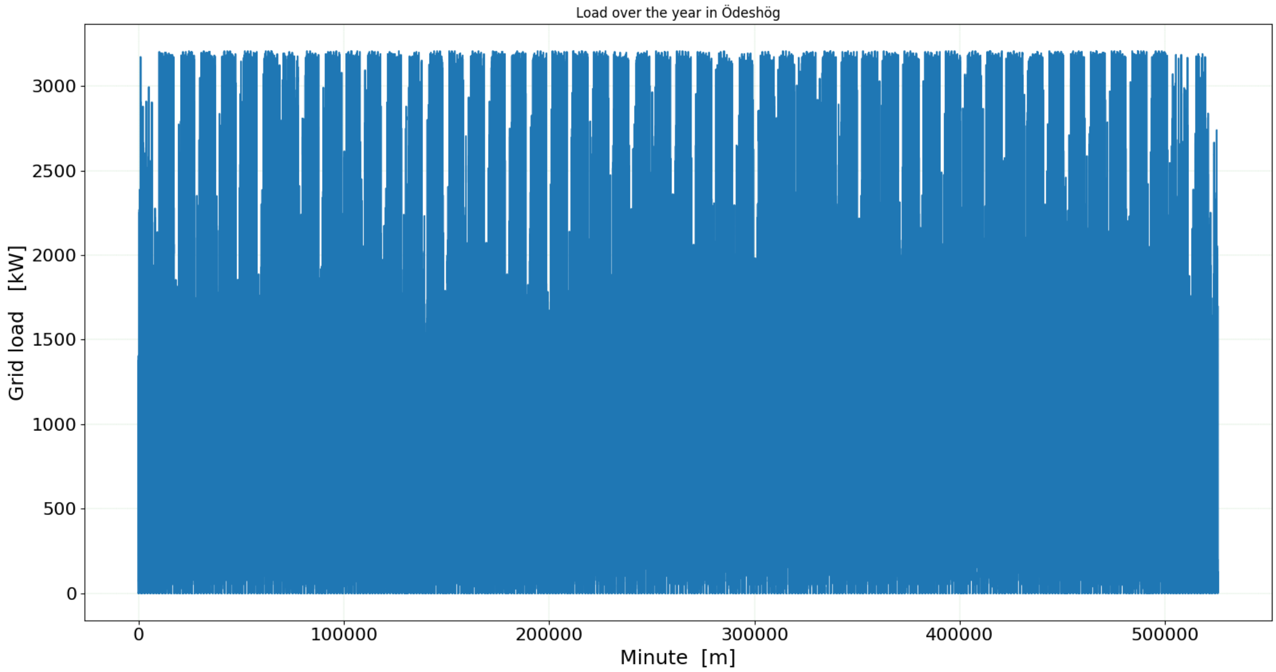

Figure 45: Grid load in Ödeshög with no local generation or storage

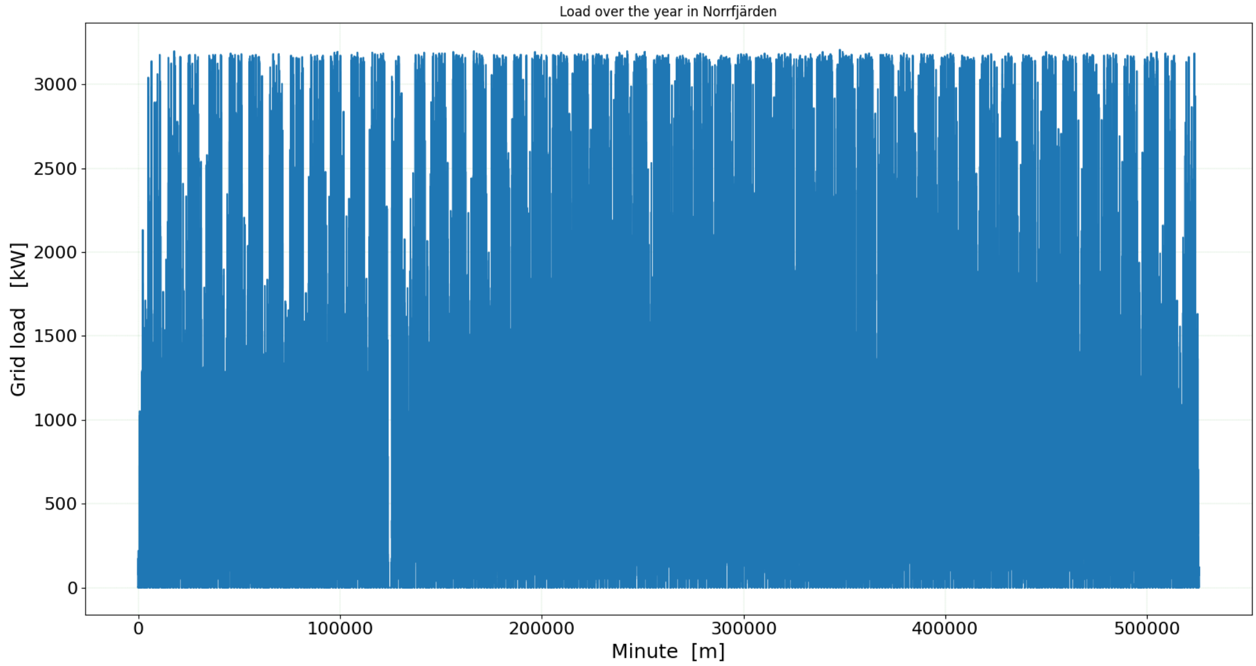

Figure 46: Grid load in Norrfjärden with no local generation or storage

5.5 Full lifetime cost rundown

Taking into account the lifespan of each major component of the energy node, a complete lifetime cost rundown is presented here. Each system is given the optimal setup that is showcased in section 5.3 table 16, with 25 years as the modeled lifetime. In table 18 the modeled lifetime cost rundown is provided

Table 18: Full cost rundown of the energy nodes major parts using optimal values

Cost in kr	Ekeröd	Ödeshög	Norrfjärden
Grid load	67.7 Mkr	88 Mkr	87.2 Mkr
50 kW converters	1.5 Mkr	2.2 Mkr	2.0 M
Solar panels	36.3 Mkr	36.3 Mkr	-
Battery pack	16.4 Mkr	8.2 Mkr	24.7 Mkr
Total cost	121.9 Mkr	134.7 Mkr	113.9 Mkr
Profit from energy sold to grid	32 Mkr	35.6 Mkr	-
Final cost	89.9 Mkr	99.1 Mkr	113.9 Mkr

The major hydrogen components are not included in table 18 since they are not part of any of the optimal cases.

5.6 Optimal parameters applied without being able to predict the future

Since the optimization is based on iterative simulations, the future has always been at hands to better optimize the parameters in question. However in the real world all the used data can vary, and is often not possible to predict with certain accuracy. To put the model's optimized system design (in terms of solar cell installation area, energy storage size, number of charging spots etc) to the test, the 2021 optimized parameters are used for data from 2019 and 2020. Tabel 18 shows the results.

Table 19: Iteratively optimized values from 2021 data used for 2019 and 2020 data for a years simulation

	2019	2020	2021
Cost of grid load	1.1 Mkr	0.7 Mkr	2.3 Mkr
Longest car queue time	13 min	4 min	18 min
Longest truck queue time	19 min	21 min	20 min
Average wait cars	0.004 min	0.001 min	0.035 min
Average wait trucks	0.015 min	0.021 min	0.042 min
Profit from charging with local generation instead of buying from grid	1.7 Mkr	1 Mkr	3.3 Mkr
Profit from charging with battery storage instead of buying from grid	1.4 Mkr	0.8 Mkr	2.6 Mkr
Profit from sold energy to the grid	0.8 Mkr	0.6 Mkr	1.4 Mkr

6 Discussion and conclusion

6.1 Flaws

By definition, a simulation is the act of representing something close enough to the real operation while being as simple as possible. Therefore for every part that varies from the subject that is being simulated, a possible flaw occurs with the model. The importance is to acknowledge all possible flaws of the simulation but also try and estimate their impact on the results. When it comes to simulating an energy node which includes elements of human actions, the flaws can easily be many. The following subsection of the thesis goes over some of the major possible flaws in the model and how they could affect the results and ultimately how they could be prevented with more time and research.

6.1.1 The evolution of electrical vehicles

The main user of the energy node is the electrical vehicles that need charging. While accurate data is available for electrical cars used in the beginning of the 2020 decade, the same can not be said for electric trucks. As of 2021 it is estimated to be only 69 597 electric trucks world wide [56], with data like charging curves hard to come by. Thereby approximations are made based on the C-rate charging curves of average trucks, which are then used on the truck models attending the energy node. When it comes to the future scenario of 50% electric vehicles on the roads, estimations based on projections are made for both cars and trucks. These possible flaws in assumptions can have an impact on the amount of cars that need to be charged each minute, how long it takes to charge and what need they have in power when loading. To improve the model, further research into projections from different sources needs to be made when it comes to future vehicle specifications.

6.1.2 Data accuracy

When deciding which location to simulate, the quality of data available in terms of vehicles entering the system, wind speeds, solar irradiance and temperature varies greatly.

Considering the data on the amount of vehicles on the road which “Trafikverket” provides, not every road in Sweden is equally studied. For most locations the data gathered is from a spot further down the road, which should not be too big of a problem unless there are major exits or entries to the road between the energy node and the data point. In locations like the one in Ödeshög, the hourly data over the year is not possible to get close enough to the energy node. Which resulted in the need to simulate the possible hourly data over the year with only one day's variation as a starting data point. This can result in inaccuracies in the amount of vehicles entering the system.

When performing the simulation of the energy node, the data of Ödeshög did not show any strange values when compared to simulations in Ekeröd and Norrfjärden. It should however always be taken into account when trying to analyze and study different simulations made on the Ödeshög station.

Much like the vehicle data, the meteorological data needed for each energy node location varies depending on the closeness of the station giving them. These distances should be acknowledged when looking at the results, with greater distances contributing to more inaccuracy when it comes to solar and wind power generated. Table 20 displays the closest stations for each type of meteorological data and their distance to the energy node:

Table 20: Distances to the different data gathering stations for each location

	Ekeröd	Ödeshög	Norrfjärden
Temperature (C)	Hörby, 7 km	Jönköping-Axamos Flygplats, 64 km	Luleå-Kallax Flygplats, 45 km
Solar irradiance (W/m^2)	Lund, 42 km	Norrköping, 104 km	Luleå, 45 km
Wind (m/s)	Hörby, 7 km	Malexander, 70 km	Luleå-Kallax Flygplats, 45 km

When it comes to data collection accuracy, it becomes a problem if there are no close data gathering points. In such a case the most optimal solution would be for the user of the model to gather the data over a year at the specified location on their own. If that is not a possibility the second option is to instead choose the location of the simulated energy node, based on the availability of close data points for all the needed parameters.

In the simulated values of spot prices shown in section 3.7 and in appendix 1, the monthly averages are used as a basis. However these averages have big differences between them, causing unrealistic increases and decreases between the last day of one month and the first of the next month. To get more realistic values, the spot prices should decrease and increase at a steady rate between months.

6.1.3 Efficiency losses

With a system containing many subsystems, there needs to be a line drawn of what systems to include. Depending on the amount of systems disregarded, the final outcome of the simulation can vary. In the model created for this thesis the following subsystems effect on the efficiency of the energy node are disregarded:

- Cable losses for all subsystems
- Internal electrical components like resistors, inductors, capacitors, transistors and more in all subsystems
- Maintenance costs for all subsystems

6.1.4 Randomization

Most systems and especially systems which include human behavior have uncertainty in them. This is illustrated by allowing randomization to occur in the model with both which type of model the vehicles coming in each minute, but also which state of charge the vehicles have between 10% to 30%. Resulting in the chance of unexpected outcomes from the simulation due to a bottleneck effect being created if the “worst” vehicle at the lowest state of charge keeps entering the energy node at the “wrong” time due to randomness. Thereby the model's simulations become more and more accurate the more simulations under the same initial conditions are made. The initial conditions are however not the same each year when it comes to the data. By using Gaussian distribution on the data that gives the number of vehicles entering the system each hour, it is possible to create a model that takes into account randomness and can be optimized with it in mind.

6.1.5 The COVID pandemic

Starting in the end of 2019, the outbreak of the Covid pandemic occurred. Which in large increased the amount of people working and studying from home. This has its effect on the traffic data gathered from 2019, 2020 and 2021. Since traffic flow has a big effect on the vehicle load on the energy node, any potential flaws in the data have a large effect on the results.

6.2 Discussion of the simulation results

The optimization of installed power and number of charging spots in section 5.1 in table 10 show how there is a difference in installed power needed depending on where the power node is located. However these differences are not very large and a baseline can easily be made from the results of around which values of installed power and number of charging spots an energy node that is located by a well trafficked highway should have. When it comes to location, it is important to take into account that it does not only change the amount of vehicle entering the energy node, but each location also has its own patterns in the traffic flow variations over the year, which is further visualized by looking at the figures over traffic flow at each location in appendix 1. As could be expected the increase in percentage of vehicles being electrical resulted in an increase in the needed installed power and number of charging spots. It is also clear that the distance to the closest energy nodes has a great impact on the results. Table 11 in section 5.1 shows that when allowing three hour waiting times, the amount of installed power and charging spots did not decrease drastically. Which begs the question if allowing longer queues is worth what is saved from the decrease.

Even if the waiting time is low for most vehicles in the optimal setup used for figure 22 in section 5.1, below one minute in many cases, there are also a lot of waiting times in the order of 10's of minutes. The psychological effect this may have on people's willingness to own and use electric vehicles is beyond the scope of this thesis to evaluate. This can be seen as positive, but it can also indicate that there is a possibility for cost savings by decreasing the installed power or number of charging spots. A decision should be made on what is more important, keeping the queue time for most vehicles at a reasonable number while some might have high queue times. Or making sure that no vehicle reaches unreasonable queue times.

The increase or decrease in the number of charging spots in section 5.1.1 show differences between car and truck queue sensitivity to changes. Changes to the number of car charging spots do not cause extreme growth in queue times, instead just resulting in more vehicles having higher queue times with only one reaching the limit. Using this in consideration, the optimal values could be adapted to accept a selected number of vehicles exceeding the limit queue time over the year, resulting in financial savings while not resulting in major queue time changes. When focusing on the changes to the number of truck charging spots, a higher volatility can be seen. This together with the results from 5.1.2 that show the potential financial impact of low number of truck charging spots, illustrates how complex it can be to select the number of truck charging spots needed. Figure 27 in section 5.1.1 contains the biggest effect on queue times, illustrating how outside factors like the distances to closest charging stations have a significant influence on how the energy node needs to be optimized. From table 12 in the same section it can be seen that the average queue time for both trucks and cars is below one minute in the 30 km cases.

When it comes to optimization of the local generation and storage, it is clear from the simulation results that having hydrogen as energy storage for an energy node is very costly. The high amount of energy lost due to the round trip efficiency and high cost of components, do not make up for the long time storage gained. The problem of seasonal storage in hydrogen is further amplified by the uncertain nature of the energy spot prices, with high dependance of political situations. In section 5.3.2 this is illustrated in figures 44 and 45, where the electricity spot price from the grid displays two very different patterns over the year when comparing 2019 with 2021. This uncertainty makes it hard to know when seasonal storage energy is worth buying from the grid to store in hydrogen without it resulting in a loss. While hydrogen storage might not have a place in providing power to battery driven vehicles in the power node, it is worth considering the potential increase in fuel cell driven trucks in the future mentioned in section 2.3.2 and have a hydrogen storage to provide for fuel cell driven vehicles.

When looking at the optimized cases for each location, solar panels are more cost efficient in the locations where grid spot prices are higher. While battery storage follows the same trend without the dependance on weather.

Wind turbines show potential when it comes to power nodes located near the coast of Sweden, with high power production during periods that the solar panels lack displayed in section 5.2.1. A conclusion could be drawn for the perfect power node location to be near the coast in the south of Sweden. High energy spot prices could be omitted by the effective usage of wind and solar power. Even a possibility of the extreme case of no grid connection could be considered at such locations. One consideration that would also be worth mentioning is the possibility of adapting the energy node to an already existing wind turbine and bypassing many of the mentioned pre-development disadvantages in section 2.2.2.

The main goal of the thesis is to create a functioning model which can simulate how an energy node operates. The visualization of the simulation results displayed in section 5.3 provide an insight into if the goal is met. Certain system behaviors are expected when taking into account the theory from section 2 and model building from section 3. From figure 40 and 41 in section 5.3.1 it can be seen that cars follow an expected pattern of high number of cars and load during the hours when people drive to and from work during a weekday.

During Saturday, the number of cars are more congested, with people less likely to be out driving during the early hours of the day. Another example is looking at figure 44 in section 5.3.2, which displays the energy flow over the year. During the month of October it can be seen that the battery energy prices are higher than the grid energy prices during the whole month. Consequently the battery energy is not used during the whole month, which can be seen in the same figure. This is an expected behavior since the cheapest energy source should always be prioritized.

In section 5.4 it can be seen that most of the year the grid demand reaches its highest at a constant rate at each location, if there is no local generation or storage. The energy node has basically become a simple charging station with a connection to the grid. When considering all the charging stations needed all over Sweden in the future and that most could have the same grid load pattern as in section 5.4, the expected constant grid demand over the year will become high without energy nodes created with local generation and storage.

The location effect on the system is displayed in section 5.5, where the cost rundown is displayed. Here it is possible to see what system costs can be expected over a lifetime of an energy node located at the different locations.

Table 19 in section 5.6 displays promising results for the optimization results being adaptable to data variations depending on which year the data came from. This is very important since traffic and grid spot price data is very dependent on global, regional and local politics that can be affected by various unpredictable events happening each year. The different traffic flow and grid spot price graphs displayed in appendix 1, show how big the variation from year to year can be when it both comes to variation patterns during the year and also the magnitude of the data. The focus should be on the difference in results, especially negative differences between the data year 2021 and the two other years (2019 and 2020).

As a conclusion to the goals mentioned in section 1.2, a model that can simulate the operation of an energy node is achieved with this master thesis. While it still needs improvements, it gives results that are expected based on the theory from section 2. When it comes to how an energy node should be best optimized, this is achieved for three locations in Sweden. The optimization results varied for each location, showing how there is not one final answer to how an energy node should be best constructed. But it is instead very dependent on the location of the energy node. The final summation of the thesis is that optimizing an energy node, which has many subsystems working together, is complicated and hard to predict. Many variables affect the final result. Further improvements of the model are needed when it comes to reducing the possible flaws mentioned in section 6.1.

6.3 Future research

There is a large variety of possible further research which can improve the energy node model.

In section 5.1.2 the cost for truck companies are simulated for different number of truck charging spots. By doing a deeper study on the exact cost of a charging spot, it would be possible to compare the profit/cost of having more or less charging spots. This would then be able to be compared to the economic loss for truck companies over the year. Looking at the result from these it would be possible to notice where the cost for truck companies becomes larger than the profit from having less charging spots.

A complementary social science study could also be of interest, where the behavior of car and truck drivers is measured. Focus is on how long drivers are willing to wait in queue before making a note of avoiding this energy node in the future. By doing this the queue time limit of 30 minutes used in this thesis could be replaced by a more scientifically based one and more accurate optimisation of installed power and charging spots can be made.

The system created for deciding which energy to use and where to store it has potential for further research. By incorporating modifiers that adapt the energy price of the energy stored based on the state of charge of the battery, it would be possible to create a healthier usage of the battery storage. Same incorporation could be made for the hydrogen storage. The limit on selling power to the grid at 1 MW power should also be further researched. Looking into the possibility of increasing/decreasing the limit at a cost, while at the same time looking at the economic effect this would have on the energy node.
The electricity spot price is based on variations during a day and also variations between months. However this results in variations between days being missed. Better data needs to be gathered, preferably with hourly variation over a whole year like the traffic data.

Wind turbines are mentioned in the thesis, but not given the same focus as the solar panels. A deeper economic analysis of including wind turbines in the energy node could be of interest.

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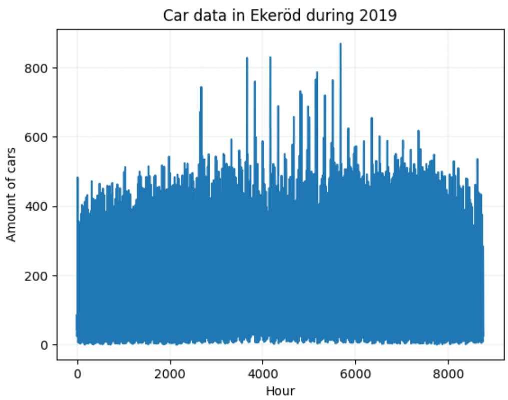
Appendices

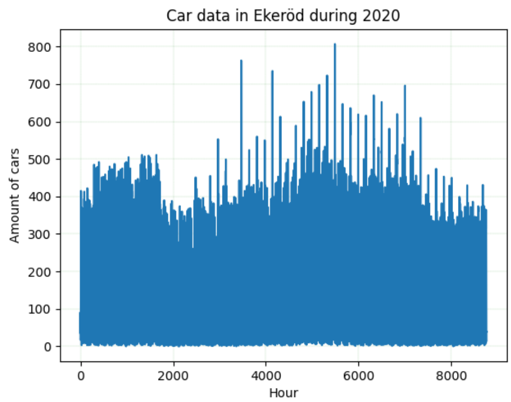
Appendix 1: Data

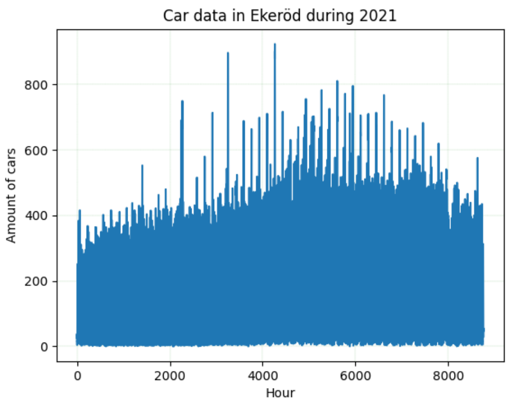
This appendix contains all the possible data gathered for each location, that is then used as the basis for the simulations.

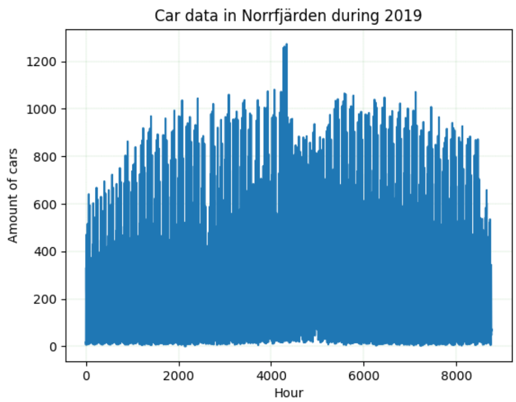
First the vehicle flow at each location is represented. It is important to note that this is total flow, which means that it contains both electrical, hydrogen and combustion vehicles. This data is then modified in section 3.3 to represent the amount of vehicles that enter the node each hour needing charging.

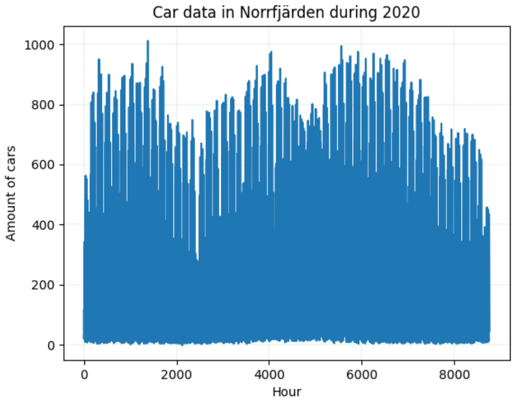
Car data:

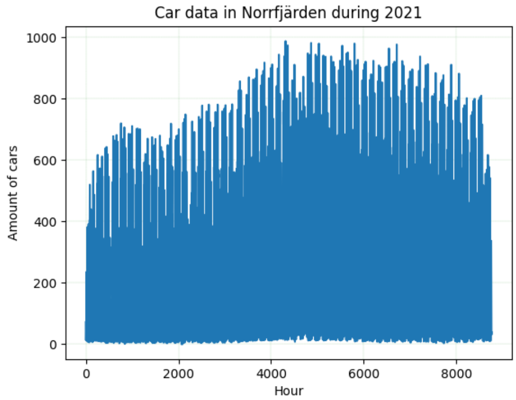




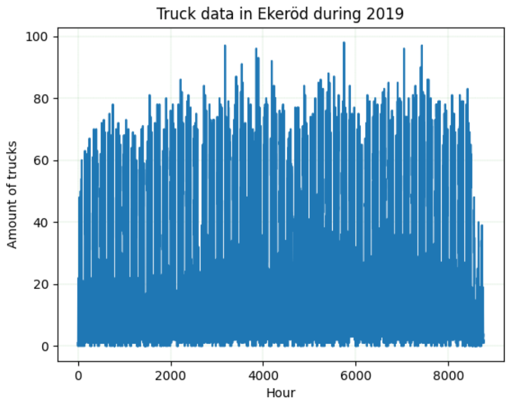


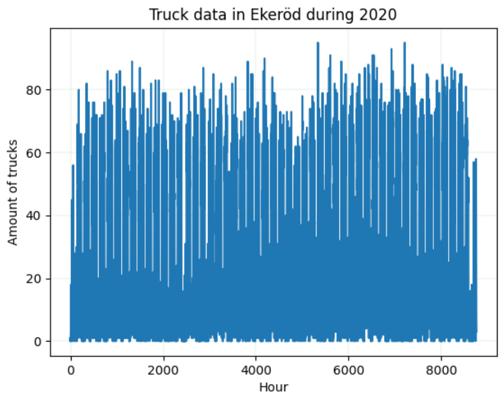


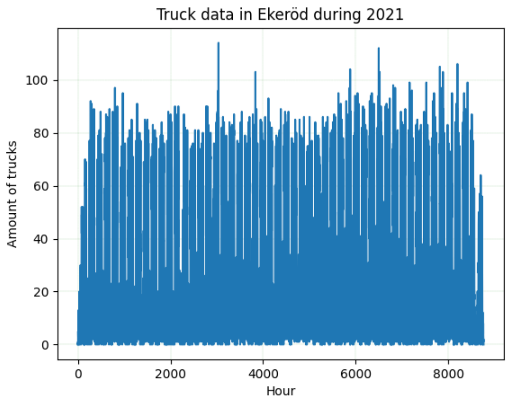

Car data in Norrfjärden during 2020
Amount of cars
Hour

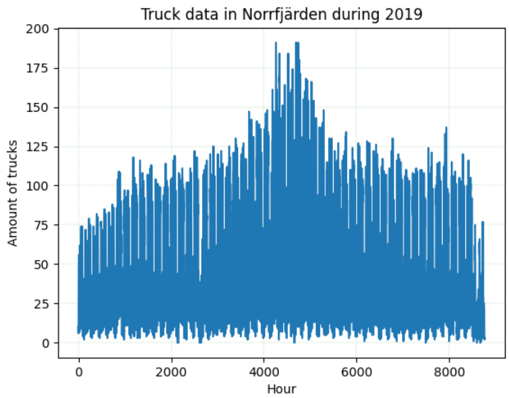

Car data in Norrfjärden during 2021
Amount of cars
Hour

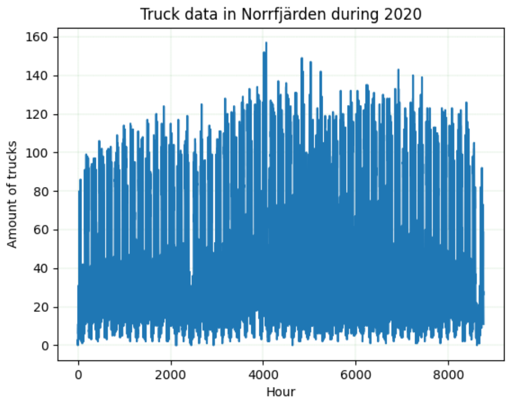
Truck data:

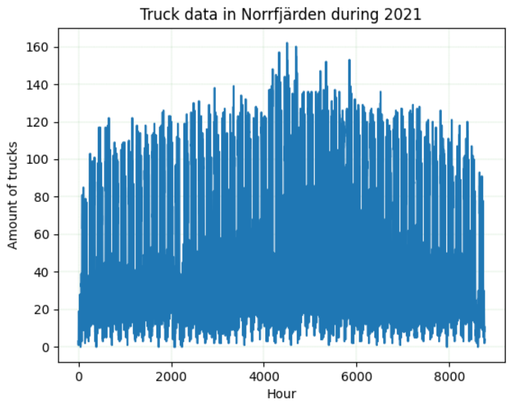

Truck data in Ekeröd during 2019
Amount of trucks
Hour


Truck data in Ekeröd during 2020
Amount of trucks
Hour


Truck data in Ekeröd during 2021
Amount of trucks
Hour

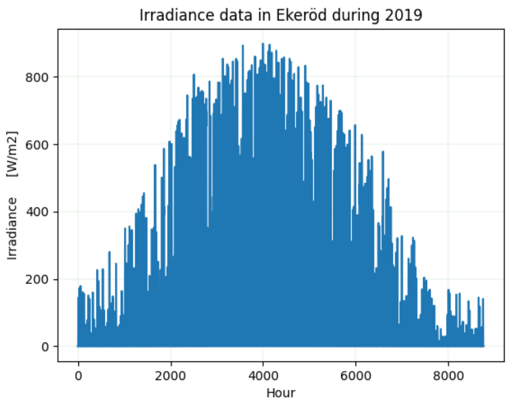

Truck data in Norrfjärden during 2019
Amount of trucks
Hour

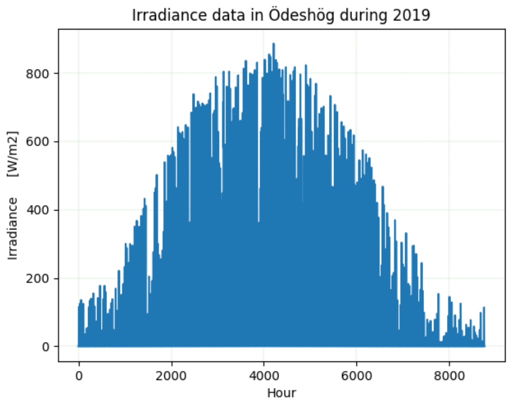


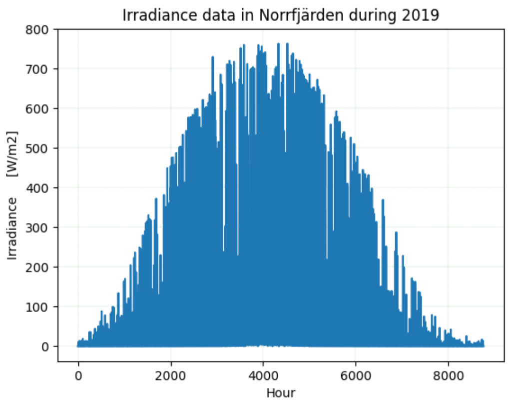


The following figures represent the weather data used in section 3.4 to get the power generated for both solar and wind at each location.

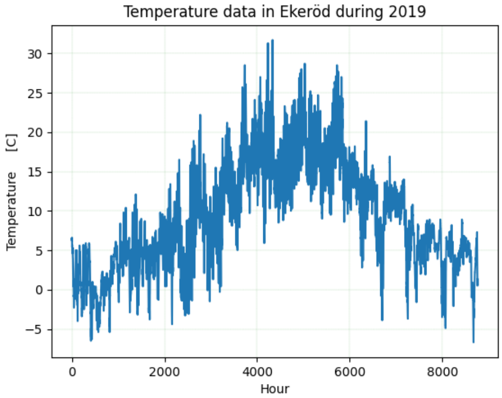
Solar irradiation data:

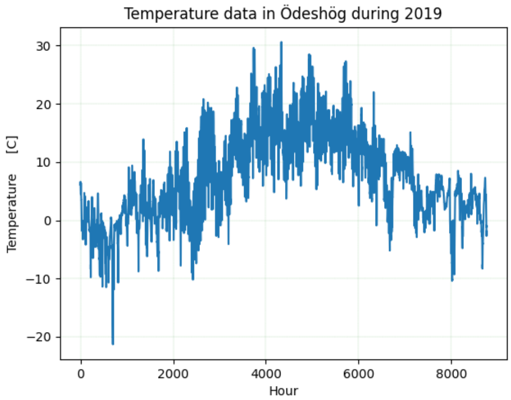


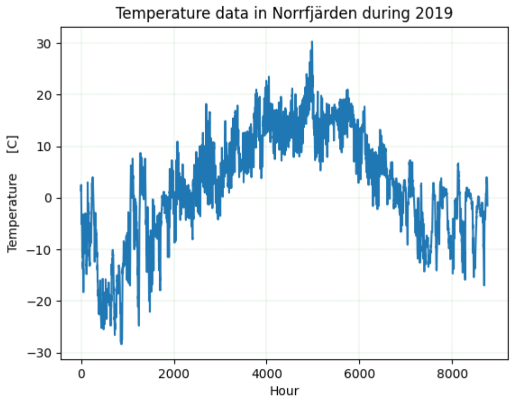




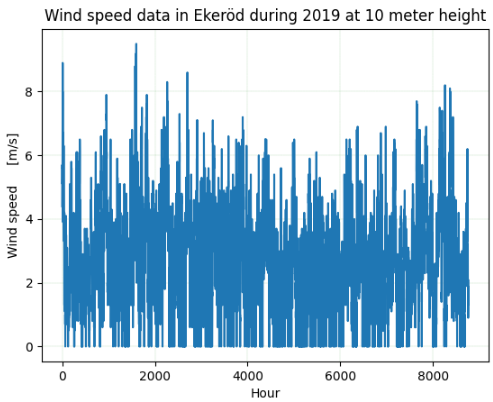
Temperature data:

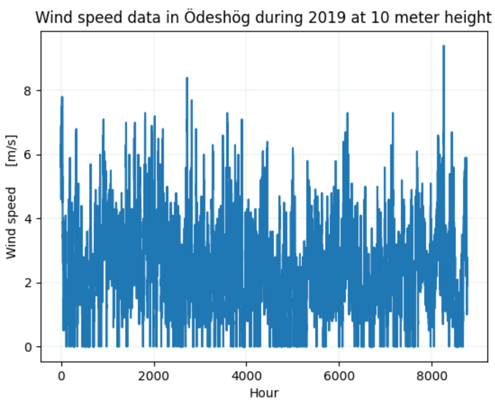


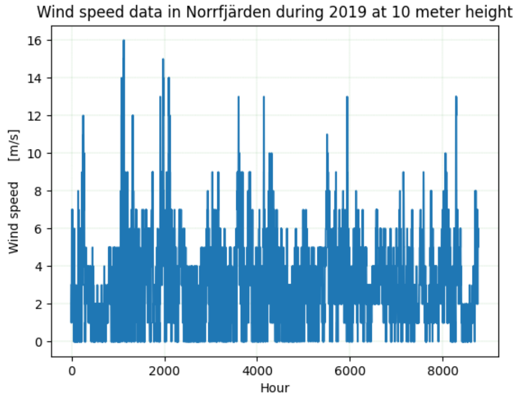




Wind speed data:



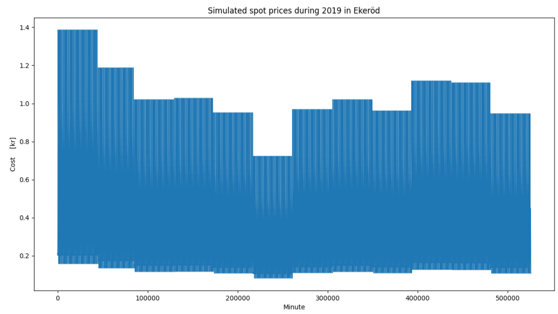


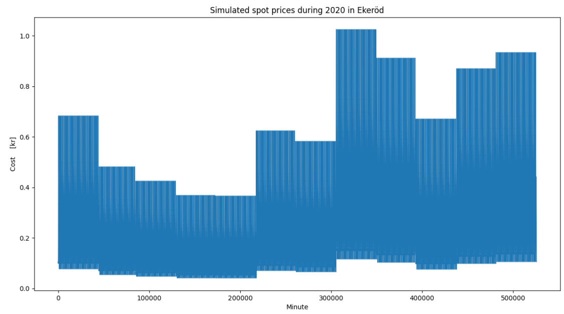


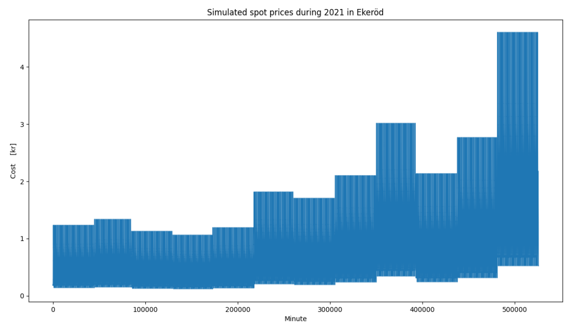
Lastly the following figures display the grid spot price variations over each year and location. It is important to consider that these are modified as described in section 3.7.

Data over grid spot prices:

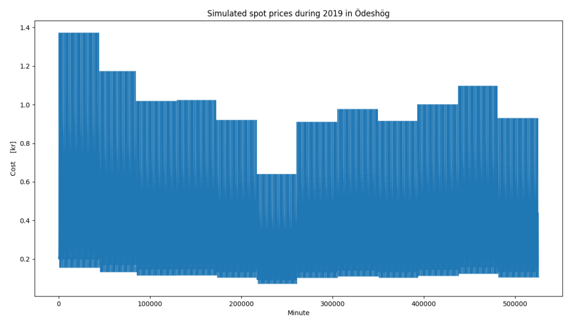
Ekeröd 2019, 2020 and 2021

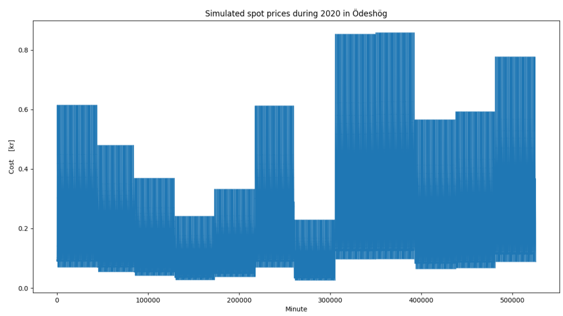


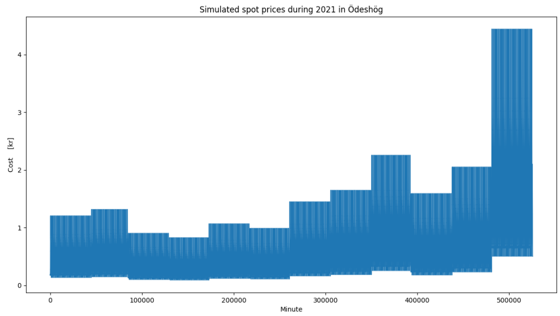




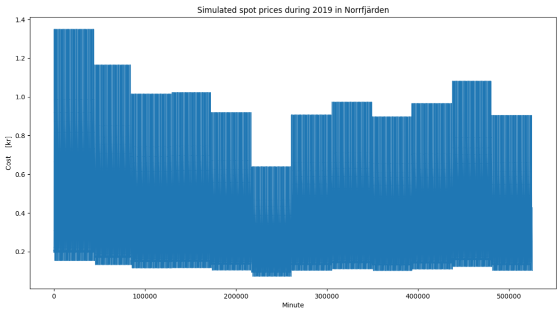
Ödeshög 2019, 2020 and 2021

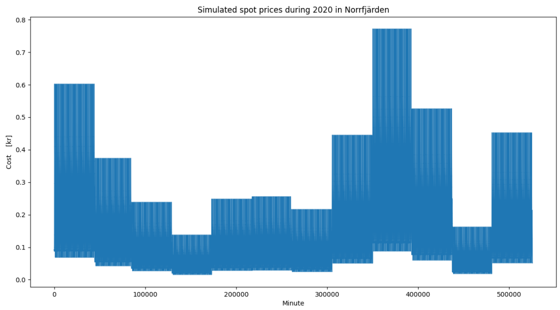






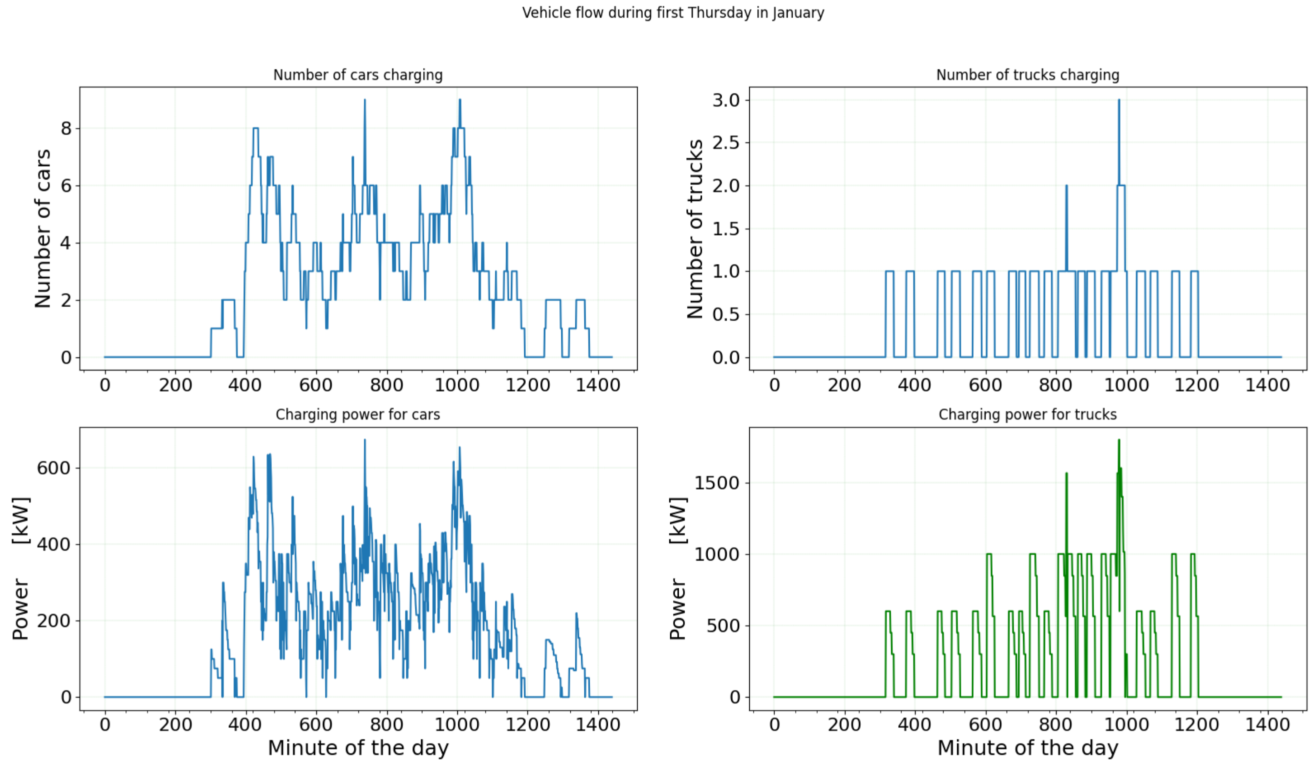
Norrfjärden 2019 and 2020

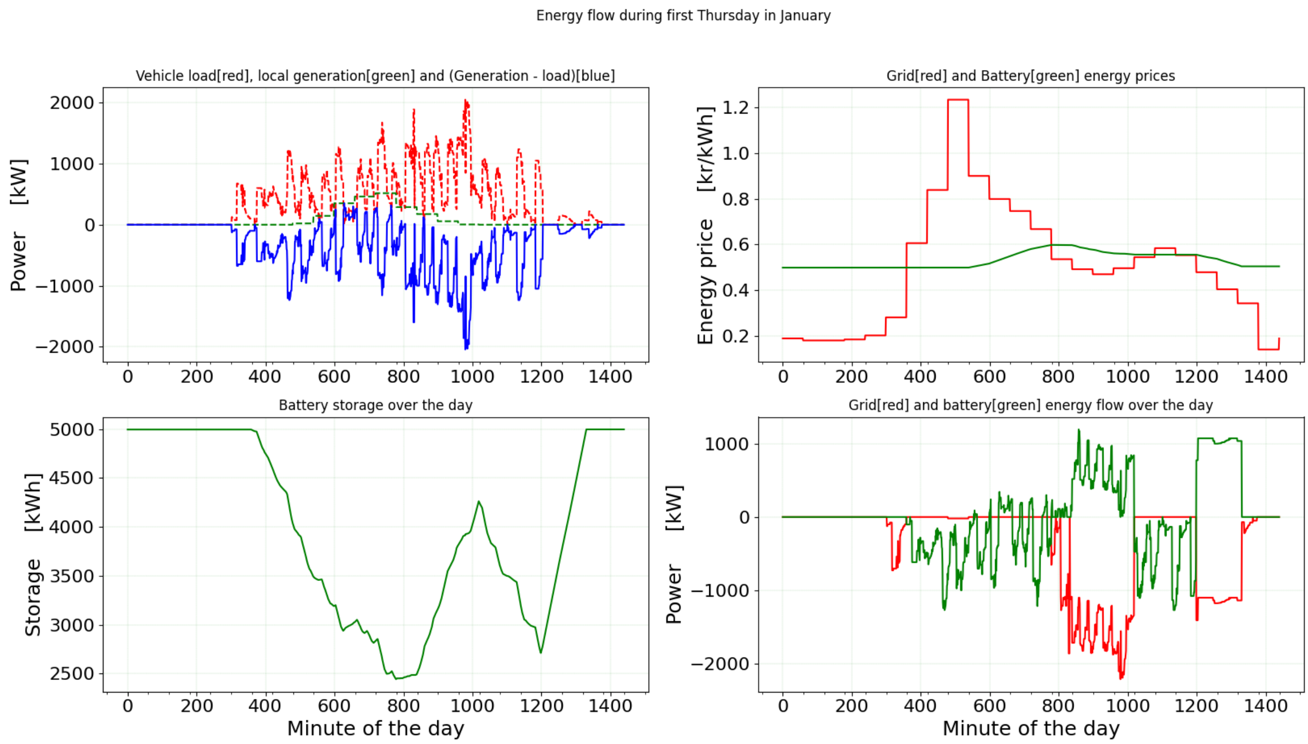


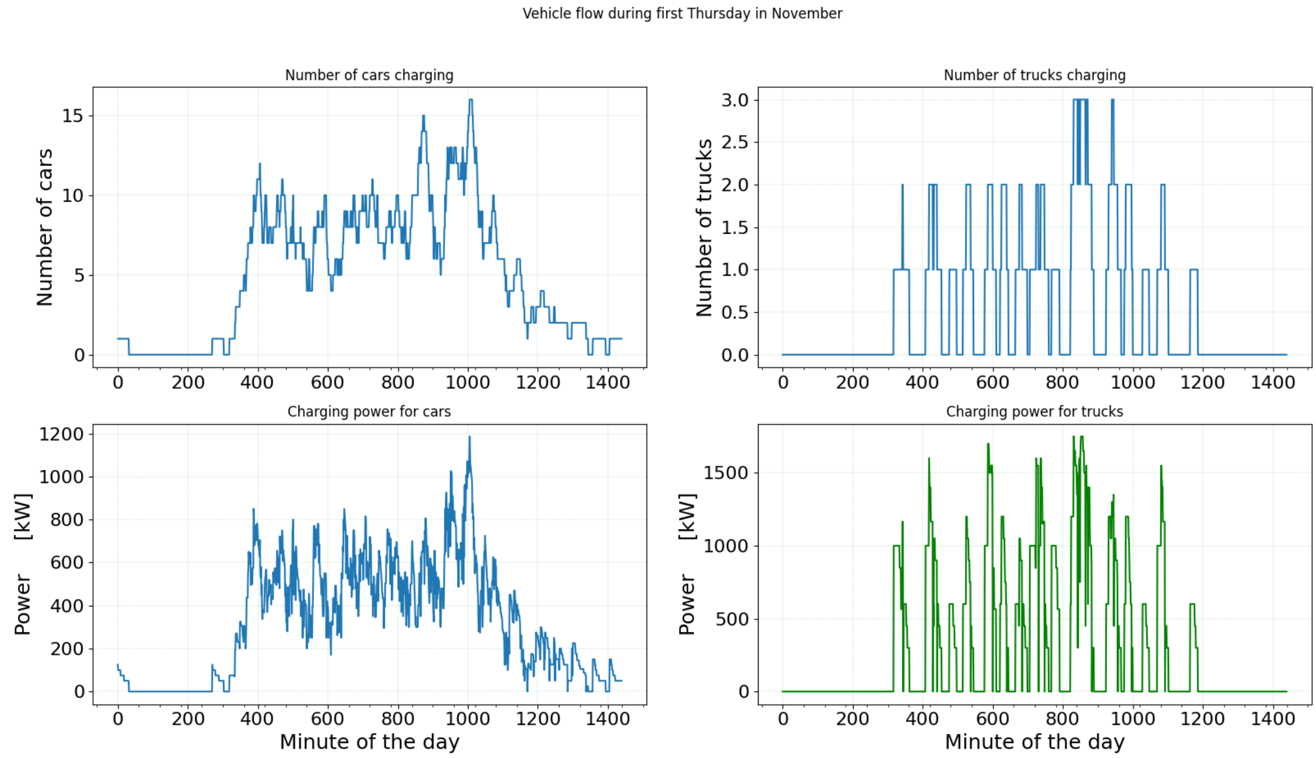


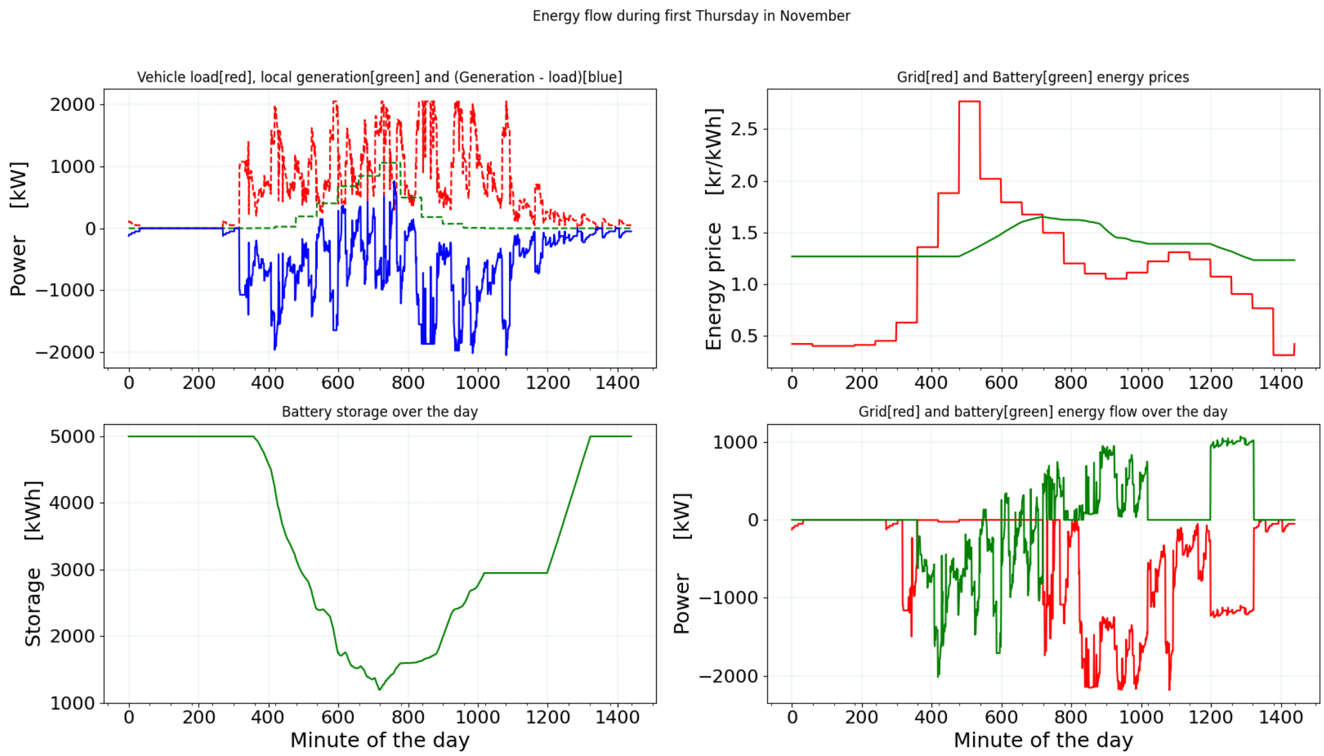
Appendix 2: Illustrations over day operation

The figures in appendix 2 show a further look into how the simulations operate during a day, but now in January and November to get an insight of possible seasonal differences compared to the weekly differences explored in section 5.3.






Vehicle flow during first Thursday in November
Number of cars charging
Number of cars
Number of trucks charging
Number of trucks
Charging power for cars
Power [kW]
Minute of the day
Charging power for trucks
Power [kW]
Minute of the day


Energy flow during first Thursday in November
Vehicle load[red], local generation[green] and (Generation - load)[blue]
Power [kW]
Grid[red] and Battery[green] energy prices
Energy price [kr/kWh]
Battery storage over the day
Storage [kWh]
Minute of the day
Grid[red] and battery[green] energy flow over the day
Power [kW]
Minute of the day

Appendix 3: In- and outputs of the model

The inputs needed to simulate the model are the following.
Inputs:

- Which location is simulated
- Which case is simulated: now, future or extended future
- Which year the data is coming from
- Distance between charging stations [km]
- Installed power [MW]
- Area of the solar panels [m^2]
- Hydrogen storage capacity [kWh]
- Battery storage capacity [kWh]
- Number of charging spots for electrical cars
- Number of charging spots for electrical trucks
- Power of the converters [kW]
- Limit on power sold to the grid [kW]

After a simulation the following outputs are given as mostly lists. These are the results of the simulation which change depending on the inputs chosen. It is then possible to optimize the system, by changing the inputs until acceptable outputs are given.

Outputs:

- List over the load on the grid each minute during the year [kW]
- List over the cost of the load from the grid each minute during the year [kr]
- List over number of cars charging each minute
- List over number of trucks charging each minute
- List over the load from cars charging each minute [kW]
- List over the load from trucks charging each minute [kW]
- List over car queue length each minute
- List over truck queue length each minute
- List over the queue time for all the cars that went through the system [min]
- List over the queue time for all the trucks that went through the system [min]
- Number of converters in the loading system
- List over energy stored in the hydrogen storage each minute during the year [kWh]
- List over hydrogen gained from local generation each minute [kWh]
- Total number of cars charged
- Total number of trucks charged
- Total battery capacity [kWh]
- List over the charge in the battery pack each minute [kWh]
- List over solar power generated during the year [kW]
- List over local generation over the year, which in the case that includes the wind turbine becomes relevant. It is included in the solar power based simulation to be able to have the same outputs for both systems. [kW]
- List over cost of charging vehicles avoided by local generation each minute [kr]

- List over cost of charging vehicles avoided by hydrogen storage each minute [kr]

- List over minutes each truck is in system, from first to last [min]
- Money lost for each truck driver by being over 45 min in the system [kr]
- List over power sold to grid each minute [kW]
- List over profit from power sold to grid each minute [kr]
- Number of solar panels that fit into the selected solar panel area
- List over cost of charging vehicles avoided by battery storage each minute [kr]
- List over battery storage state of charge each minute [%]
- List over the price of the energy stored in the battery each minute [kr/kWh]
- List over the price of the energy stored in the hydrogen storage each minute [kr/kWh]
- List over the spot price of grid energy each minute [kr/kWh]
- List over power wasted each minute [kW]
- List over the power usage of the battery [kW]
- List over the power usage of the hydrogen storage [kW]