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Energy Storage Combined with Solar PVs for Large Facilities

A linear optimization and evaluation based on case studies

Master's thesis in Sustainable Energy Systems and Product Development

HANNA BÄHR

MARIA SVENSSON

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT

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HANNA BÄHR
MARIA SVENSSON



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Division of Energy Technology
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HANNA BÄHR
MARIA SVENSSON

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Supervisor: Fanny Malmgren & Caroline Hammar, Triathlon Group
Examiner: Maria Taljegård, Space, Earth and Environment

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Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Abstract

As part of the fight against the ongoing climate change, there has been a strong emphasis on implementing fossil-free energy sources. This has resulted in an increased demand for renewable energy sources, which in turn has put pressure on the development of such technologies. One renewable energy technique that has gained popularity, even in Sweden, is solar photovoltaic (PV). Solar power is intermittent, thus combining it with energy storage systems is beneficial in order to mitigate the intermittency and to overcome the mismatch between production and load.

This master thesis investigates the suitability of investing in solar PV's and combining them with either battery storage and hydrogen storage, the two most popular storage technologies to combine with PV's. The scope includes commercial facilities located in the SE3 region of Sweden, and three electricity demands have been addressed in order to give the results a realistic foundation. Each demand pertains to a different facility type with varying yearly electricity demands: an office building, a production site, and a warehouse facility. Additionally, four different models were created in the study, using the linear optimization program GAMS, General Algebraic Modeling System, to address different cases. Two reference models were created for comparison of the results, one with no investments in neither PV's nor storage system, referring to a "business as usual" scenario, and one with the possibility to only invest in PV's. Furthermore, two models also enabled the possibility to invest in solar PV's with or without the combination with either battery storage or hydrogen storage. In each model, three different optimization scenarios were tested, one only minimizing the total system cost, one minimizing the system cost with the goal of also increasing the self-sufficiency rate, and the third only testing the feasibility of becoming 100% self-sufficient.

The findings suggest that achieving complete self-sufficiency with solar PV's and energy storage within reasonable limits is not feasible, considering the typical electricity demand profiles of commercial buildings. In the situations where a storage system could be suitable, it was shown that battery storage outperforms hydrogen storage based on current data and input parameters. How much economical benefits a storage system can bring was proven to be highly dependent on the amount of excess electricity that the facility had, being more favourable when the excess rate was higher. It also shows that the incentive of investing in solar PV's is higher when the electricity prices are high, and when it thereby is a potential profit created by electricity trading. Sensitivity analyses have also been carried out, assessing the results dependency on current values on taxes, component costs, etc. Investment costs are the most influential factor for improving system cost. Overall, these findings provide a framework for companies interested in exploring the business potential of energy storage investments.

Keywords: solar PV's, energy storage, battery, hydrogen, self-sufficiency, cost, optimization.

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Hanna Bähr & Maria Svensson, Gothenburg, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CAPEX	Capital expenditure
CCS	Carbon Capture and Storage EV
Electrical vehicle	
GD	Grid to Demand
GG	Grid to Grid
GH	Grid to Hydrogen system
GWh	Giga Watt hour
HD	Hydrgen system to Demand
HG	Hydrogen system to Grid
H ₂	Hydrogen
kW	kilo Watt
kWh	kilo Watt hour
NG	Natural Gas
O&M	Operation and Maintenance
OPEX	Operational expenditure
PV	Photovoltaic
PVD	PV to Demand
PVG	PV to Grid
PVH	PV to Hydrogen system
PEM	Proton Exchange Membrane
SE3	An electricity region in south of Sweden

Contents

List of Acronyms	ix
List of Figures	xv
List of Tables	xvii
1 Introduction	1
1.1 Contextual background	1
1.2 Thesis aim	2
1.3 Scope	2
1.4 Literature study	2
2 Theory	5
2.1 Solar PV	5
2.1.1 The technology	5
2.1.2 Electricity supply pattern	6
2.2 Batteries	6
2.2.1 Lithium-ion battery	6
2.2.2 Sodium-Nickel-Chloride Battery	7
2.2.3 Sodium-sulfur battery	7
2.2.4 Comparison of battery technologies	8
2.3 Hydrogen	8
2.3.1 Storage of hydrogen	9
2.3.2 Electrolyzers	10
2.3.3 Fuel cell technology	10
2.3.4 Markets for hydrogen	10
2.3.5 Risk management for hydrogen systems	11
2.3.6 Future of hydrogen	11
2.4 Electricity market	13
2.4.1 Electricity grid operators	14
2.4.2 Electricity trading companies	14
2.4.3 Tax obligations	15
2.4.4 Selling electricity to the grid	15
3 Methodology	19
3.1 Reference models	21
3.2 Battery model	22
3.3 Hydrogen model	24
3.4 The mathematical structure of the models	25

3.5	Future scenarios	28
3.5.1	Future of hydrogen	28
3.5.1.1	Hydrogen model: electricity-H ₂ -use	28
3.5.2	Changes in taxes, tariffs and subsidies	29
4	Data	31
4.1	Electricity prices	31
4.2	Data related to the Solar PV's	31
4.3	Electricity demand profiles	32
4.4	Taxes and tariffs	36
4.5	Technical data	36
4.6	Technical limitations of components	37
5	Results and analysis	39
5.1	Overview of the results	39
5.2	Results for the three demand profiles	46
5.2.1	Demand profile 1 - Office facility	46
5.2.2	Demand profile 2 - Production facility	49
5.2.3	Demand profile 3 - Warehouse facility	51
5.2.4	Comparison of cost structures	52
5.3	Model behaviour	53
5.3.1	Excess electricity	53
5.3.2	Dependency on the grid	53
5.3.3	Supply pattern	54
5.3.4	Cost reductions enabled by the battery	55
5.3.5	Remove the possibility to trade electricity with the grid	56
5.4	Future scenarios	59
5.4.1	Changes in taxes and tariffs	59
6	Discussion	61
6.1	Scope	61
6.2	The foundation of the models	61
6.3	Flexibility services	62
6.4	Area for solar PV installation	62
6.5	Ratio solar PV/demand	62
6.6	Cable capacity	63
6.7	Sensitivity analysis	63
6.7.1	Future of hydrogen	63
6.7.2	Taxes and tariffs	64
6.7.3	Electricity prices in the future	64
6.8	Investment model	65
6.9	Island mode	65
7	Conclusion	67
	References	69
A	Appendix A - Figures	I
B	Appendix B - The Hydrogen Model	III

C Appendix C - Sizes of components in the hydrogen system	VII
--	------------

List of Figures

2.1	General pattern of a normalized solar irradiation curve for six days	6
2.2	Electricity to hydrogen to electricity	8
2.3	Electricity to hydrogen to usage	9
2.4	Predicted price development of green, blue and grey hydrogen [57]	12
2.5	Electricity bidding zones in Sweden [62]	13
2.6	Illustration of how taxes, tariffs and compensations are flowing through the system.	17
3.1	An overview of all of the 72 cases created	20
3.2	Explanation of the used icons	21
3.3	Reference model 1	21
3.4	Reference model 2	22
3.5	Visualization of the battery model with numbered electricity flows	22
3.6	Hydrogen model with numbered electricity flows	24
3.7	Hydrogen model, el-H ₂ -use, with numbered electricity and hydrogen flows	28
4.1	Electricity prices for 2018 and 2022 [84]	31
4.2	Solar irradiation profile [86]	32
4.3	Plot of all demand profiles, measured in kW over the period of one year	33
4.4	Plot of all demand profiles, measured in kW over a three-week period	35
4.5	Example photo of a battery container	38
5.1	A visualization overview of the outputs from the models with marking of the cases that were either eliminated (red) or gave the same results (orange and yellow).	40
5.2	System cost for office demand and electricity prices from 2018 with different models and optimization goal. Values from Table 5.1.	46
5.3	System cost for office demand and electricity prices from 2022 with different models and optimization goal. Values from Table 5.2.	47
5.4	Staple diagram of shares in costs and revenues related to the battery model, office case, with 70% self-sufficiency	48
5.5	Staple diagram of shares in costs and revenues related to the battery model, production case, with 10% self-sufficiency	50
5.6	Staple diagram of shares in costs and revenues related to the battery model, warehouse case, with 30% self-sufficiency	51
5.7	Staple diagram of shares in costs and revenues, comparing the reference models with the battery model with the office demand and electricity prices of 2022 as input	52

5.8	Supply of electricity from the solar PV's plotted together with the three demands during a week in May	53
5.9	Bought electricity from the grid during one year for the case: Office, battery model, 2022, 70% self-sufficiency	54
5.10	Supply and demand behavior for the office	55
5.11	How the battery can be used in order to reduce costs	56
5.12	Cost comparison between the reference model 2 Only PV and the battery model for three optimization scenarios (minimize cost, 40% and 70% self-sufficiency) when the grid to grid charging of the battery was removed. The office demand and electricity prices from 2022 were used.	58
5.13	No grid tariff compensation and removing tax on electricity from the PV to demand compared to the original case for office, battery model, 70% self-sufficient and electricity prices from 2022. Changes outlined with red.	59
A.1	Electricity grid operators in SE3 region of Sweden [66].	I

List of Tables

2.1	Table of costs and performance properties related to batteries	8
2.2	Color coding of hydrogen [36]	9
2.3	Table of compensations and fees for trading electricity within the area of Gothenburg [69]	15
3.1	Costs and revenue streams related to the electricity flows. # refers to the electricity flows numbered in Figure 3.5.	23
3.2	Costs and revenue streams connected to the electricity flows. # refers to the electricity flows numbered in Figure 3.6	24
4.1	Values of the parameters related to the solar PV's	32
4.2	Summary of the electricity demands	36
4.3	Values of the parameters related to taxes and tariffs	36
4.4	Values of the parameters related to the battery	37
4.5	Values of the parameters related to the hydrogen system	37
5.1	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2018 and the Office demand	42
5.2	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2022 and the Office demand	43
5.3	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2018 and the Production demand	43
5.4	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2022 and the Production demand	44
5.5	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2018 and the Warehouse demand	44
5.6	Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from 2022 and the Warehouse demand	45
6.1	Changes that would be needed for the Island mode to be feasible, for the office demand. Area reference is the area needed in number of football fields. Battery size reference is in number of 40ft containers that would be required.	65
C.1	Sizes of elektroyzer, H ₂ storage and fuel cell in the four cases where a hydrogen system was invested in	VII

1

Introduction

This chapter aims to cover relevant background information that is necessary for understanding the thesis and its purpose. The introduction will also include thesis aims and chosen scope.

1.1 Contextual background

The world today is facing big challenges in adapting to the ongoing climate change. According to the Paris Agreement, 197 countries have agreed on ambitious goals regarding sustainable development. Within the agreement, the goal of limiting global warming to well below 2°C by 2050 [1] is included. The Swedish government is one of the nations that have signed the agreement, and several national strategies have been established. Some of them handle emission regulations and some include incentives for private actors as well as companies to become more sustainable. One reason for the emission problem is the CO₂ emissions related to energy supplies, and one of the Swedish goals, presented in energy politics, is to reach 100% renewable energy production by 2040 [2]. The result of the energy goals is an increased interest and need for making facilities more sustainable and energy efficient.

One way of working towards increased sustainability is through renewable energy sources, utilizing the weather, i.e., wind, hydro power and solar power. Solar PV's are becoming more common among both private and commercial facilities, enabling the production of clean and renewable electricity [3]. Through research done by the Swedish energy authority, it is clear that the amount of PV installations has increased a lot over the past years [4].

However, solar power is an intermittent electricity source that can not produce electricity directly on demand due to its dependency on unpredictable solar irradiation. The technology shift towards renewable energy sources directly implies a shift from reliable, demand-driven, CO₂-emitting energy sources to sources that in most cases are weather dependent and therefore intermittent and uncertain. Due to this, several benefits of combining these energy sources with energy storage systems have been identified [5]. Also, larger-scale solar PV installations can provide the facility owners or operators with a potential business opportunity. Therefore, combining solar PV with energy storage systems is becoming an interesting solution.

1.2 Thesis aim

This master thesis aims to deliver a framework that can be used in evaluation purposes of energy storage solutions for commercial facilities that are partially self-sufficient in producing electricity by solar PV's. The commercial facility types included in this thesis are office buildings, production sites, and warehouse facilities. The framework will consider different use cases including future changes in behavior, regulations, and business opportunities.

1.3 Scope

This master thesis limits its investigation of the potential of combining solar PVs with energy storage systems to the region SE3 in Sweden. This region and its present solar irradiation properties have been affecting data on electricity prices and fees. The electricity fees have been collected from the area of Gothenburg, located within the SE3 bidding area. Furthermore, two energy storage solutions have been investigated; battery systems and hydrogen systems, including electrolyzer, storage tanks with compressors, and a fuel cell. To broaden the applicability of the result, three electricity demands were investigated. The selection of electricity demand belongs to different businesses with different types of electricity demands and different tax obligations. The three demands included were

- Demand 1: Office facility
- Demand 2: Production facility
- Demand 3: Warehouse facility

1.4 Literature study

Since the urgency of implementing renewable energy sources is increasing every day, there are great incentives for executing studies regarding these matters. Renewable energy technologies are developing very fast which constantly changes the business models for investors, such as a property owner investing in solar PV [6]. Due to the technology shift towards more intermittent, uncertain, and unpredictable energy sources, there are great incentives for utilizing various techniques for storing energy [7]. Hence, a lot of previous research has dealt with questions regarding how renewable energy sources can be combined with energy storage systems [8] [9] [10] [11].

In previous literature, various alternatives of energy storage systems have been investigated [7] [12] [13]. Which alternatives to investigate have to some extent be dependent on where the storage system is located globally [14]. This is partly due to differences in national laws and political guidelines, but also a result of different climate conditions [12].

In the existing literature, two of the most commonly addressed storage systems are in general electro-chemical systems and hydrogen systems [15]. There is documented research of comparisons of the systems as well as research about combinations of them [14] [15] [16] [17]. Zhang, E., et al. [17] execute a comparison of the two energy storage alternatives in combination with solar PV's, referring to a case in which data from residential facilities in Sweden are being used. The analysis was executed in 2016, and the outcome of the comparison concluded that there were more identified economic incentives in battery storage systems, since the battery system performed better than the hydrogen storage in terms of efficiency and usability. The battery system was also proven of being more ben-

eficial in terms of self-sufficiency rates. With the current prices for components included in the hydrogen storage system, it was also concluded that the prices must decrease to 25% before such systems can be profitable [17]. However, the comparison between the storage systems being executed in this research was using dynamic programming, Pareto font, which differs from the methodology within this master thesis.

There is other research addressing the residential building case regarding solar PV's in combination with energy storage systems. In recent research, Mansin, I. et al. [18] present the results from the comparison between a battery system and a hydrogen system. The comparison has been executed using TRNSYS software. The electricity demand profile refers to a residential building located in Iran, where the solar irradiation in general is higher than in Sweden [19], and the demand consist of heating, cooling, hot water and the overall electricity supply demand. The conclusions show, as most other articles, that the battery system is much efficient, especially from the cost point of view. Though, the hydrogen storage system was proven of being more feasible at higher loads and at higher size units since the battery costs scale relatively linear in comparison to the hydrogen storage in which it is the electrolyzer and the fuel cell that is the most expensive components [18].

Furthermore, Castañeda et al. [16] address comparisons of the storage systems, with a slightly different approach [16]. Through a dynamic model, implemented in MATLAB-Simulink environment, an investigation is executed. The investigation is regarding which energy management, including sizing and control strategies, that are suitable for a stand-alone energy storage system connected to solar PV's. The geographical area of this research was Málaga, located in Spain. The new approach in the reasearch of Castañeda et al. [16] is that the systems are addressed both as separate systems alone, as well as a hybrid system combining them both. The results that are presented from the study is, aligned with Zhang's and Mansin's research, showing that the battery system is more economically beneficial compared to the hydrogen storage alone. Though, this study shows that the hybrid system could bring valuable benefits such as reliability to the electricity supply. However, such system would not be economically reasonable due to the multiple component investment with high component costs [18]. Castañeda suggests that further research within the hydrogen development must be conducted in order to lower the investment costs before such solution could be worth considering. Although this research was conducted 2013, more recent studies show the same conclusions [20] [21].

In summary, there are articles that covers comparisons of hydrogen systems and battery systems [17] [19] [18] [21], especially regarding what type of value creation the energy storage is aiming for. This master thesis include different use cases that can differentiate the requirements and needs for a energy storage system, and also uses the linear optimization program GAMS that have not been used in previous research regarding this kind of comparison.

2

Theory

This section contains theory about the solar PV, followed by the two storage alternatives; batteries and hydrogen storage systems. Lastly, the theory about the electricity market in Sweden is presented.

2.1 Solar PV

Solar photovoltaics, also known as solar PV's, is one of the renewable energy techniques that is growing rapidly [22]. The technique has its foundation in converting sunlight into electrical energy. They can be installed on buildings or in open-ground areas. Since they are dependent on sunlight, they are more beneficial to install in regions that are exposed to more sun hours per day.

2.1.1 The technology

The purpose of solar panels is to generate DC electricity fed by an inverter in order to convert it into AC electricity [23]. Sunlight is a set of particles that contain solar energy, also known as photons. The amount of energy that these photons contain can differ and corresponds to what wavelength that specific solar spectrum has [24].

The technology behind solar PV's is converting these photons into electricity. This is obtained by having small cells absorb the sunlight. Each individual cell can individually produce around 1 to 2 W of power. The cells are made of semiconducting materials that enable them to absorb the light's energy. Once the energy is absorbed, it can be transferred into negatively charged electrons. This creates an electrical current flow that subsequently can be extracted through conductive metal contacts [25].

How efficient solar PV's can be is dependent on several aspects. In order to achieve more electricity, PV cells are connected in chains. These chains create panels that can be adjusted to the current electricity demand, and the available size of the operational use area. The efficiency is also dependent on the intensity and wavelength of the sunlight. At this moment, panels that are built using high-cost IBC (Interdigitated Back Contact) cells are the most efficient ones. They provide an efficiency of 20-23% [26], and the general efficiency ranges around 15-21%.

Furthermore, the solar panels can be put into mounting structures that point the cells toward the sun at an optimal angle in order to increase efficiency. The mounting structures that are mounted on the ground can also be equipped with tracking mechanisms that continuously and automatically allow the panels to move according to how the sunlight changes angle and direction. Even though this is an effective way of utilizing the photons' full potential, it requires maintenance and is thereby costly to operate [24].

2.1.2 Electricity supply pattern

The amount of electricity produced by solar PV's is directly correlated to solar irradiation. An example of a normalized solar irradiation curve is plotted for six days in Figure 2.1. It is possible to generate electricity from roughly 08-16, i.e., when the sun is shining. On the fourth day in Figure 2.1, the radiation is lower due to cloudy weather which affects the output from the PV's. The amount of electricity generated from solar PV's always follows this pattern, with some variance due to seasonal weather changes and geographical location.

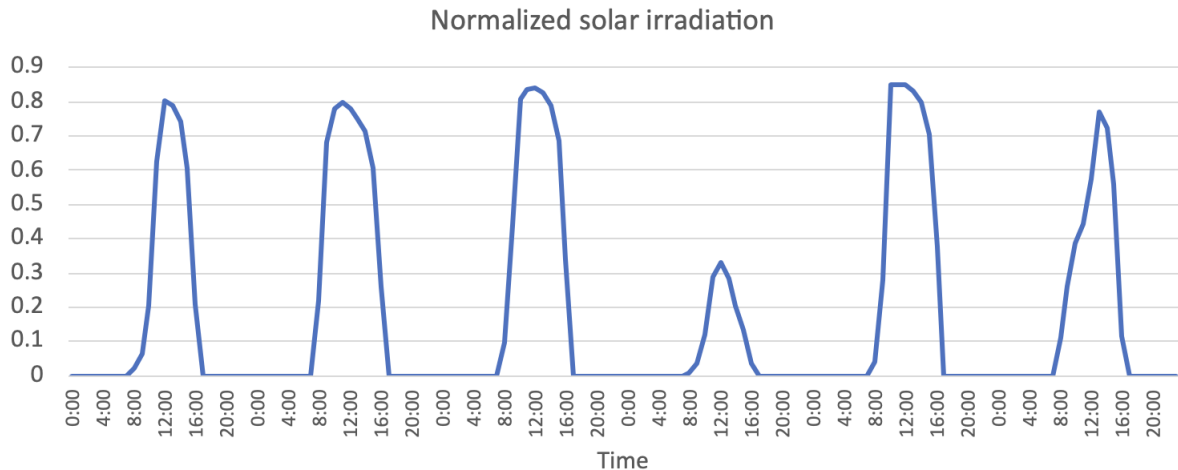


Figure 2.1: General pattern of a normalized solar irradiation curve for six days

2.2 Batteries

In today's society, there is a wide range of use areas for electrochemical batteries. They are used in smartphones, laptops, and in most electrical devices that are being used on a daily basis. The technology behind batteries is chemical reactions that cause them to charge and discharge when the battery is exposed to electrical loads. This process creates a current that can flow through the battery as a result of the voltage caused by the charged electrons. C-rating is a measurement of how fast the battery is charged and discharged. A C-rate of 1C refers to that a fully charged battery should be able to be fully uncharged for one hour [?].

There are several types of batteries that can be used for different tasks. The needed battery capacity, the electricity demand pattern as well as how the electricity is consumed are examples of factors that result in different optimal battery types [27]. This thesis focuses on large scale PV installations, and therefore suitable battery types for such use cases will be further addressed and compared.

2.2.1 Lithium-ion battery

Lithium-ion batteries are commonly used today, especially in products such as cellphones and laptops. The technology has been considered to have good development potentials, and therefore it has recently gotten an increased interest. This is partly due to the batteries light weight, high energy density and recharge ability [28].

The lithium-ion battery consist of, as all batteries, one anode and one cathode. Positively charged lithium ions, coming from an electrolyte, can pass through the separator between them, going from the anode with positively charged lithium ions to the negatively charged cathode. This movement releases free electrons in the anode which creates a positive charge in the current collector. This current can flow through a connected device to the negative current collector, providing the device with power. When the battery is being charged, the opposite occurs, meaning that lithium ions are released by the cathode and received by the anode [28]. Lithium-ion batteries can use several materials as electrodes, but the most commonly used material combination for the cathode and the anode is cobalt oxide and graphite.

The round-trip efficiency of lithium-ion batteries can be up to 95%. This refers to the measurement of how well the battery and inverter can convert and store electricity. The round-trip efficiency can be relevant to consider since there are often losses associated with all electrical processes which implies that the efficiency will most likely not be 100% in any cases. The losses occur mostly when inverting the DC to AC current, as well as when the battery is charged and discharged [29]. As for the life cycle, the amount is most often between 2000-3000 cycles, which can be equalized to a life span of 15 years, depending on the use of the battery. When it comes to energy capacity, the average lithium-ion battery can reach a capacity of 50 MW [30].

There are other use areas for Lithium-ion batteries than personal electronic devices. For instance, they can be used for storing solar energy generated by solar panels. They are especially suitable for this due to their fast charging abilities. Compared to other battery types, they are also lighter and more compact which can enable a higher amount of energy which provides the suitability for small personal electronic devices. Considering these advantages, there is a high chance of increased demand for these types of batteries in the future. Though, there are also some environmental issues that have been identified with lithium-ion batteries. The mining of lithium and the end-of-life treatment of the batteries are two problematic processes that often result in damage to ecosystems and humans [31].

2.2.2 Sodium-Nickel-Chloride Battery

Sodium-nickel-chloride batteries are electrochemical energy storage systems that are based on charging and discharging reactions that occur between cathodes and anodes. The anode material is typically sodium and the anode that consist of nickel and sodium-chloride. It can be classified as a high temperature battery, operating at temperatures between 270°C and 350°C.

With a round-trip efficiency of 85-95%, it is suitable for several use areas. A few of these use areas are energy storage in residential homes, distribution grids, transmission grids and for energy storage for electricity produced by solar PV's [32].

2.2.3 Sodium-sulfur battery

Sodium-sulfur batteries are a high-temperature battery that operates in temperatures ranging between 300 to 350°C. A drawback with this battery is its dependency on a heat source to operate, using a part of the battery's energy resulting in a decreased round-trip efficiency [33]. Even though this decreases the efficiency, it still reaches 75-90%.

The technology behind a sodium-sulfur battery is, alike lithium-ion batteries, built upon charging and discharging reactions between the positive and the negative electrodes. The positive cathode mainly consist of nickel and sodium chloride as the anode most often is made out of sodium [33].

Other characteristics of a sodium-sulfur battery is the life cycle that measures around 2500 and 4500 cycles. Additionally, it is advantageous with its quick charging characteristics, low maintenance, and good scale potential for future needs. Today, sodium-sulfur batteries can reach a capacity rating of 34 MW [30].

2.2.4 Comparison of battery technologies

The Danish Energy Agency discuss different ways of storing electric energy using technologies, such as batteries [34]. In their reports, they compare the most common batteries regarding different characteristics that can be beneficial to consider when designing a suitable storage system. When comparing battery types, their costs are also an aspect that is worth considering. Table 2.1 displays all costs that are associated with purchase, installation, maintenance, operation etc, according to the Danish Energy Agency [34] and Nilsson Energy [35].

Table 2.1: Table of costs and performance properties related to batteries

	Lithium-Ion	Sodium-Nickel-Chloride	Sodium-sulfur
CAPEX	580 €/kWh [35]	370 €/kWh [34]	420 €/kWh [34]
OPEX	0.002 €/kWh [34]	0.0018 €/kWh [34]	0.0006 €/kWh [34]
Efficiency	95% [34]	83% [34]	87% [34]
Lifetime	15 years [34]	19 years [34]	17 years [34]

2.3 Hydrogen

Another available energy storage solution is a hydrogen system. There are mainly two ways of using hydrogen in this context:

1. Electricity-hydrogen-electricity: Use the surplus electricity in an electrolyzer to produce hydrogen, store the hydrogen and then use a fuel cell to get electricity again.

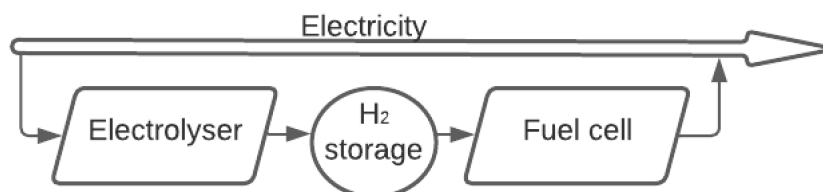


Figure 2.2: Electricity to hydrogen to electricity

2. Electricity-hydrogen-use: Use the surplus electricity in an electrolyzer to produce hydrogen, store the hydrogen and use the hydrogen itself.

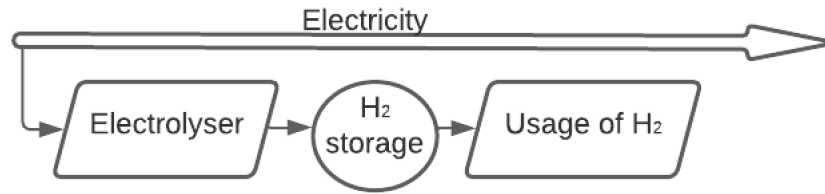


Figure 2.3: Electricity to hydrogen to usage

Depending on how the hydrogen is produced, it often gets a color code [36]. The most common color codes together with their primary energy source and production process are summarized in Table 2.2 below.

Table 2.2: Color coding of hydrogen [36]

Color code	Primary energy source	Production process
Brown	Coal	Gasification
Grey	Natural gas	Steam reforming
Blue	Any fossil fuel	Combined with CCS
Turquoise	Natural gas	Pyrolysis
Pink	Nuclear power	Electrolysis
Green	Renewable electricity	Electrolysis

2.3.1 Storage of hydrogen

There are different ways of storing hydrogen, the three most common ones are pressurized tanks, tanks with hydrogen in liquid form and geological storage [37]. The storage technologies have different cost structures, and technical benefits as well as drawbacks.

Hydrogen can be pressurized to about 200-700 bars and stored as a gas in tanks. This storage option is often used in hydrogen fueled vehicle since the tanks are relatively light weight [38] and fueling the tanks is quite fast, about 10 minutes [39]. A drawback with pressurized tanks is the low energy content per weight and volume of gaseous hydrogen [40].

Hydrogen can also be stored as a liquid in tanks at -253°C . A drawback with this method is the energy intense conversion from gas to liquid, estimates are of about 12.5-15.0 kWh/kg for liquefaction compared to compression to 700 bar which is about 6.0 kWh/kg [41]. Both the investment cost and operation cost for the cryogenic hydrogen tanks are expensive, and storage of liquid hydrogen is therefore economical at large production rates and at long storage periods [42]. The temperature difference in the tank compared to the surrounding air causes boil-off gas, but the energy content is higher when hydrogen is stored as liquid compared to gas [40]. The density of liquid hydrogen is near twice the gaseous at 700 bar [39], which makes this alternative more space efficient.

Geological storage of hydrogen is another option. Hydrogen can be stored in underground formations like aquifers, depleted natural gas caverns and salt caverns. Aquifers are made of layers of permeable sand or rock, located between layers of impermeable rock. When the hydrogen is compressed and pumped down in the aquifers, it stays below the impermeable rock. Depleted natural gas caverns contain porous rocks and works similar as aquifers. Salt caverns are created when fresh water is pumped down into the salt dome which dissolves the salt [42]. Advantages of geological storage are

- Safety: more safe since the storage is located underground and is less sensitive to fire, terrorist attacks or military actions,
- Space management: less space on ground is needed compared to tanks,
- Economic aspect: geological storage is cheaper than other options with a comparable capacity [43].

Some disadvantages with geological storage are that they can not be placed anywhere due to their dependency on the landscape. If its geological structure is unknown, and time-consuming exploration is needed, potential gas leaks and the presence of hydrocarbon residues in oil fields can reduce the hydrogen cleanliness [44].

2.3.2 Electrolyzers

There exists several electrolyzer technologies that splits water with electricity into hydrogen and oxygen. Three of the most common ones [45] will be presented in this section.

Proton exchange membrane (PEM) is an electrolyzer that is promising. It provides high current density, high energy efficiency, less problem with gas crossover between the anode and cathode, and can efficiently adapt to renewable energy intermittency. It works at a temperature between 20-80°C. The downsides of PEM is the high cost of the catalyst and the proton exchange membrane, the need for the scarce metal platinum as the catalyst, and the problematic degradation of the catalysts under acidic environment [46].

The alkaline electrolyzer is a well known technology, and as a contrary to the PEM electrolyzer, it does not need any noble catalyst [47]. It also has a lower investment and operational cost and works at a temperature between 30-90°C. Disadvantages with the alkaline electrolyzer are the lower current density, lower efficiency and higher risk for gas crossover which, in a worst case scenario, can lead to an explosion [46].

The solid oxide electrolyzer is another promising electrolysis technology with high efficiency as its main advantage. Since the electrolysis is done with water as steam, it needs to operate at a high temperature, between 500-850°C. This is an energy consuming process and as a result of this, the catalyst degrades fast which makes it problematic to maintain a long lifetime of this electrolyzer [46].

2.3.3 Fuel cell technology

One of the most frequently used fuel cell technologies are the PEM fuel cell. Some of its advantages are delivering high power density at low weight and volume in comparison to other fuel cell technologies. In order to operate, it only needs hydrogen, water and air (oxygen) and can operate at relatively low temperatures, around 80°C [48].

2.3.4 Markets for hydrogen

The total efficiency of the process electricity-hydrogen-electricity is only about 35% [49]. Instead of turning the hydrogen into electricity again, selling the hydrogen to other industries can therefore be of interest. There are mainly four markets for hydrogen (excluding hydrogen to electricity) which are listed below, without any specific order:

1. Mobility: the market for hydrogen fueled vehicles is growing [50] and naturally, so does the demand for hydrogen.

2. Chemical industry: hydrogen is used as a component or catalyst in ammonia production, oil refining and methanol production [51].
3. Natural-gas (NG) grid: it is possible to integrate hydrogen in the NG grid up to a concentration of 5-15% [49] before becoming problematic. This alternative is attractive since integrating hydrogen in the NG grid will lower the climate impact from the grid by reducing the CO₂ emissions [52].
4. Steel industry: hydrogen will play an essential role in making the steel industry fossil free. By replacing the fossil fueled furnace with hydrogen and renewable based electricity, the CO₂ emissions from the steel industry will drop dramatically [53].

2.3.5 Risk management for hydrogen systems

Before installing a hydrogen system a building and environmental permit from the municipality is often required alongside with a permission from the local rescue service. Getting this permission can take time which is why this is something to consider when planning on investing in a hydrogen system. Also, performing risk analysis of the hydrogen system is essential in order to ensure a safe installation. HAZOP (Hazard and Operability Study) and HAZID (Hazard Identification) risk analysis are often used [35].

2.3.6 Future of hydrogen

In order to reach the climate goals for the nearest future, Sweden has, as well as other countries in the European Union, established political climate goals and strategies to work towards. Among these, strategies of green hydrogen plays an important role.

Most hydrogen being produced today comes from processes that use fossil fuel, mainly originating from the steam reforming of natural gas and coal gasification. Analyses from 2021 show that only 0.2% of the total hydrogen that was produced this year came from green sources [54]. The result of this is high CO₂ emissions which have increased due to the higher demand for hydrogen, and the lack of change in its production technologies [54]. By following the strategy of the Net Zero Scenario, the emissions related to hydrogen will decrease [54].

In order to reach this goal, the demand for green hydrogen will increase significantly. If the produced amount of green hydrogen is increased in the future, great potentials have been identified with such scenarios. For instance, it has been proven to be beneficial to convert electricity into hydrogen and store it in tanks, in order to use it as a source for balancing the electricity grid. Furthermore, according to the International Energy Agency, the current state of the hydrogen development is showing great potential in reducing CO₂ emissions. This by becoming a substitute in the industrial sector involving chemicals, iron and steel, and decarbonise the long-haul transport sector [55]. In Sweden, most of the fossil emissions originate from the industry and transport sector. Green hydrogen is therefore considered as one of the most important solutions in the work towards decreasing emissions [56].

In Sweden, a national strategy has been implemented, aiming to help reach the target of reduced CO₂ emission by using green hydrogen production as a tool. The initial goal is to, by 2030, create a capacity of 5 GW with electrolyzers, and by 2045 reach a capacity of additionally 10 GW. The direct result from this will be a higher electricity demand, ranging between 60 to 126 TWh per year. A higher use of green hydrogen creating green

electricity can reduce the carbon dioxide emissions by 1,5-3 million, respectively 7-15 million tons per year. This would imply that the total amount of Sweden's emissions would be reduced by up to 6% by 2030, respective up to 15% by 2045 [56]. In order to make the strategy implementable, several financial incentives have been proposed. These incentives do for instance include governmental financial supports, national and international partnerships and collaborations as well as credit guarantees [56]. Additionally, the proposal in the national strategy that has been presented by the Swedish government includes changes and development suggestions on standards, laws and permitting processes related to the value chain of the fossil free hydrogen.

Worth considering when addressing the future of hydrogen is also the price development of the maturing technology. Today, it is more expensive to produce green hydrogen, mainly because the fossil alternatives manage to evade environmental compensation expenses, combined with the high prices of the technologies needed for producing green hydrogen. The gap between these costs are one of the biggest global challenges in the transition of implementing more green hydrogen [56]. According to a study executed by McKinsey and Co., the prices of both installing hydrogen systems as well as producing the hydrogen will decrease rapidly over the upcoming years. Figure 2.4 shows the price development from now until 2050.

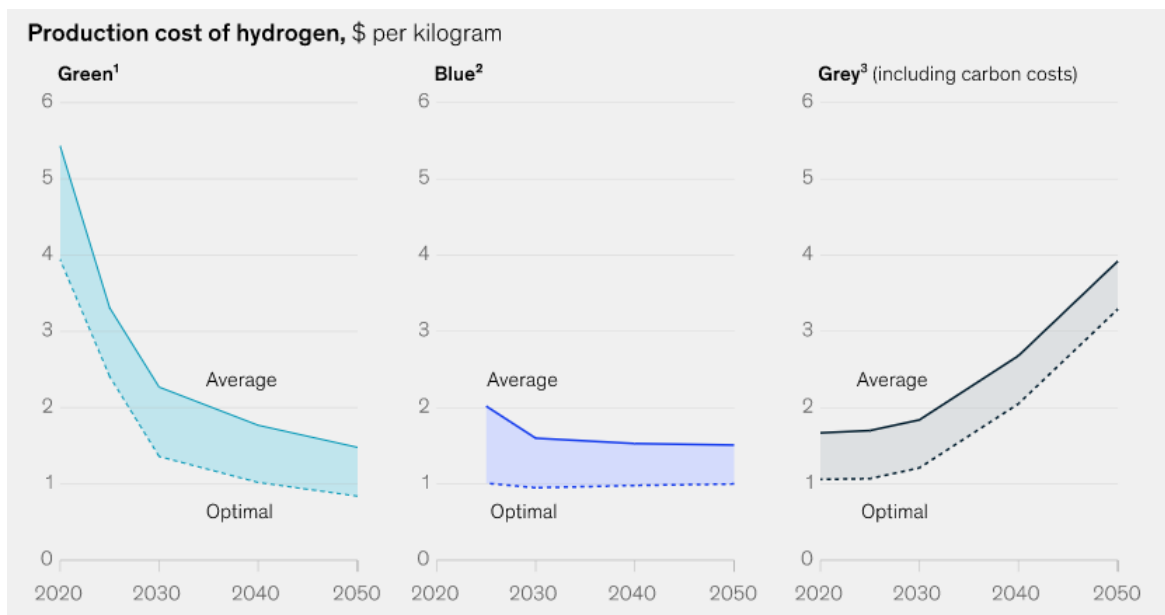


Figure 2.4: Predicted price development of green, blue and grey hydrogen [57]

If the prices follow this predicted pattern, it would bring additional benefits of implementing green hydrogen production to a higher extent [57]. There is more research that support this foresight, and according to PWC the production costs of hydrogen are estimated of being halved by 2030 [58]. Regarding the costs related to the hydrogen technology, the market price of hydrogen might also change with the increased demand. The market price in Sweden is estimated to decrease to 5.5€/kg [58] from 9€/kg, that is the current market price [59].

2.4 Electricity market

In Sweden, the electricity trade is deregulated and all electricity distribution is done via a monopoly, regulated by the Swedish Energy Markets Inspectorate [60]. However, the actual purchasing of the electricity is completely competitive, and customers have around 120 suppliers that they can choose from. The available electricity is produced both domestically and abroad. The electricity is transported through a national grid network, through entire Sweden.

Since 2015, there are regulations established within the European Union that cover the capacity allocation and congestion management. This regulation describes which commitments that are required if a company wants to apply as a power supplier within the European Union, and its core content cover the following categories:

- Optimal definition of bidding zones
- Calculation of capacities between bidding zones
- Allocation of cross-zonal capacities with market coupling
- Management of residual congestions with remedial actions [61].

Bidding zones cover all geographic areas in which physical electricity exchange is present. These simplify the trading of electricity, and to make the exchange as efficient as possible. In Sweden, there are four bidding zones, called SE1, SE2, SE3, and SE4, illustrated in Figure 2.5.



Figure 2.5: Electricity bidding zones in Sweden [62]

To provide good quality of the electricity that is being approved in Sweden, EI, The Swedish Energy Markets Inspectorate, is working with four areas of quality assurance. These include:

- Continuity of supply
- Voltage quality
- Technical requirements, functional requirements and protection against falling trees
- Risk analysis, and action plans [63].

Since the electricity network market in Sweden is not driven by any competition, it is dependent on several national regulations. These are politically controlled by the Swedish Energy Agency. One of the main tasks of the Swedish Energy Agency is to monitor the fees by inspecting the total revenue of every electricity grid operator [64]. Every facility connected to the electricity grid in Sweden must have at least two agreements. One with the local electricity grid operator, and one with an electricity trading company.

2.4.1 Electricity grid operators

In Sweden, the power grid is divided into different power grid zones. Each power grid zone is owned by a electricity grid operator who is responsible for providing its customers with electricity. As a customer, you can not choose which electricity supplier company that you want to provide the electricity since this is dependant on the owner of the power grid zone that you belong to. This also implies that the customer has no mandate to make deals regarding the agreements and prices are regulated by the national electricity monopoly [65]. There are approximately 170 electricity grid operating companies in Sweden. The operating zones in SE3 are presented in Appendix A.

The fee that customers are obliged to pay the power grid companies is called power grid fee. These fees include costs such as fixed tariffs that cover the cost of having access to the electricity grid as well as a variable energy tax and an electricity transmission fee. The latter are dependent on both the amount of electricity that are actually being transferred from the grid [67].

In the area of Gothenburg, Göteborg Energi is one of the biggest electricity grid operators. The company is owned and operated by the city of Gothenburg [68]. For larger facilities that are both producing and consuming electricity, there is a high voltage limit that work as classifier for what fees that must be paid to the grid operator. In order to be classified as a large scale electricity producer, the total amount of installed capacity must reach above 1500 kW. Furthermore, the high voltage limits are at 10 kV and 130 kV and refers to which scale of connection the company has to the high voltage grid.

Table 2.3 shows the fees that are valid for voltage limits in the area of Gothenburg where the electricity grid operator Göteborg Energi is operative. The grid tariff compensation work as incentive for electricity producers to sell electricity to the grid. This is further described in Section 2.4.4. The subscription fee is a fixed fee that the electricity producer is obliged to pay in order to be connected to the grid. However, if the electricity producer is not only producing electricity, but also consuming it on site, the subscription fee is removed. Measuring fees are also referring to fixed fees that contain a yearly cost that are split up and paid on a monthly basis. This fee is only for electricity producers that are also consuming electricity in the same facility. Power fees refer to the fees that are dependent on the amount of electricity that are being sold on a monthly basis. The reactive power fee is an addition to the power fee that occur if the sold reactive power (measured in kVAr) exceeds the permitted amount. The permitted amount is 15% for 130 kV and 50% for 10 kV [69].

2.4.2 Electricity trading companies

What distinguishes electricity trading companies from the electricity grid operators is, first of all, that the customer can decide upon which company to conclude an agreement

Table 2.3: Table of compensations and fees for trading electricity within the area of Gothenburg [69]

Compensation	High voltage 10 kV	High voltage 130 kV
Grid tariff compensation	5,85 öre/kWh	5,7 - 8,7 öre/kWh

Fees	High voltage 10 kV	High voltage 130 kV
Subscription fee	0 SEK (8 400 SEK/year)	0 SEK (482 400 SEK/year)
Measuring fee	2 700 SEK/year	2 700 SEK/year
Power fee	1,84 SEK/kW, month	1,23 SEK/kW, month
Reactive power fee	7,00 SEK/kVAr, month	3,5 SEK/kVAr, month

with, independent of which power grid zone the facility is located in [67]. The agreement that is being signed covers the actual cost of the electricity that you, as a customer, are consuming on a monthly basis. This agreement can either be fixed or variable [70]. The pricing of the electricity is decided by the Nordic power market Nord Pool and is mainly dependent on supply and demand. The electricity trading companies are buying the electricity from Nord Pool and are then selling it to their customers which can either be citizens or companies.

2.4.3 Tax obligations

All electricity consumed in Sweden is taxable. Electricity that is self-produced and sold back to the grid is not taxable by the producer themselves, meaning that it is always the consumer of the electricity that is responsible to pay the tax [72]. In 2023, the energy tax rose from 36 to 39.2 öre/kWh, for companies that are VAT exempted [73]. However, this tax can be reduced to 0.6 öre/kWh if the facility fulfills certain incentives such as type of business or if the business is located in the northern parts of Sweden [74]. The industries that are covered by this dispensation are presented below.

- Farming and cultivating
- Forestry
- Agriculture
- Aquaculture
- Industrial operations
- Computer halls
- Over seas industries [74].

If a facility invests in solar PV's, the installed capacity in kW decides if they are obliged to pay energy tax on the self-produced electricity that is consumed on site. Companies that have a lower installed capacity of solar PV's than 500 kW is not obliged to pay any tax for the self-produced electricity that is being consumed by the company themselves. Companies that on the other hand exceeds 500 kW is obliged to pay energy tax [75].

2.4.4 Selling electricity to the grid

The Swedish government supports self-produced electricity, and want to benefit those who contribute to the national power grid. Therefore, politicians have decided to establish incentives such as the compensations that are addressed below.

Grid tariff compensation

When an electricity producer is selling excess electricity, they are contributing to the national electricity supply grid. This implies that the producer is unburdening the grid, enabling the electricity grid operators to use the electricity more efficient by offering locally produced electricity to a higher extent. By providing the grid with this benefit, the electricity producer will receive an economic compensation called a grid tariff compensation [76]. The compensation should by law correspond to the reduction in energy losses that is prevented through the shorter transmission ways, and the cost reductions associated with the same activity [77]. The exact value of the compensation depend on what electricity grid operator you have. It is also varying over the year, depending on whether the ongoing season is classified as a high load season or not. The Swedish high load period is between 1st of November to 31st of Mars, during the hours 06-22, with a few exceptions such as holidays. During the high load seasons, the compensation is slightly higher with a typical rise of one öre [78]. Usually, the electricity grid operators pay between 2-8 öre per sold kWh [79].

Certificate of origin

Electricity producers that are selling excess electricity that origins from renewable resources to the grid are entitled compensation for being environmental friendly. The purpose of the certificate is to communicate how the electricity was produced, i.e., what renewable energy source that has been utilized. Hence, the producer gains a certificate for each MWh that has been produced and sold. This compensation is called certificate of origin and is in itself not a profit, but they can be sold which enables revenue [80]. There are no fixed prices for the certificates which implies that the price is settled between buyer and seller at each transaction. Hence, the partners that are affected by these certificates are the electricity producers and the electricity trading companies. Certificates of origin can be interesting for industries that want to brand themselves as a "green industry" [81].

Flexibility services

Flexibility within the electricity grid refers to the grid's ability to answer to alterations that might affect the balance between the input and output energy. Hence, it is the ability to adjust the electricity demand [82].

A resource that can be classified as a flexibility resource is something that can adjust its energy consumption as well as electricity disposal and thereby deliver a service of flexibility. Heat pumps, EV's and other energy storage systems can be used as such resources. Energy storage systems for instance, can enable a postponement of the energy demand directly from the grid. The electricity producers can be compensated for collaborating and offering their flexibility to the grid. The electricity grid operators can place bids on flexible capacity, enables a revenue covering the time that the electricity producer is offering to postpone the electricity demand. It is not only the postponed time that are being paid for, but for the entire standby period. The postponement is usually regarding shorter periods, rather a few minutes than hours [83].

All of the taxes and tariffs that are mentioned in Section 2.4 are illustrated in Figure 2.6. For further descriptions of the figures used in the illustration, see Figure 3.2.

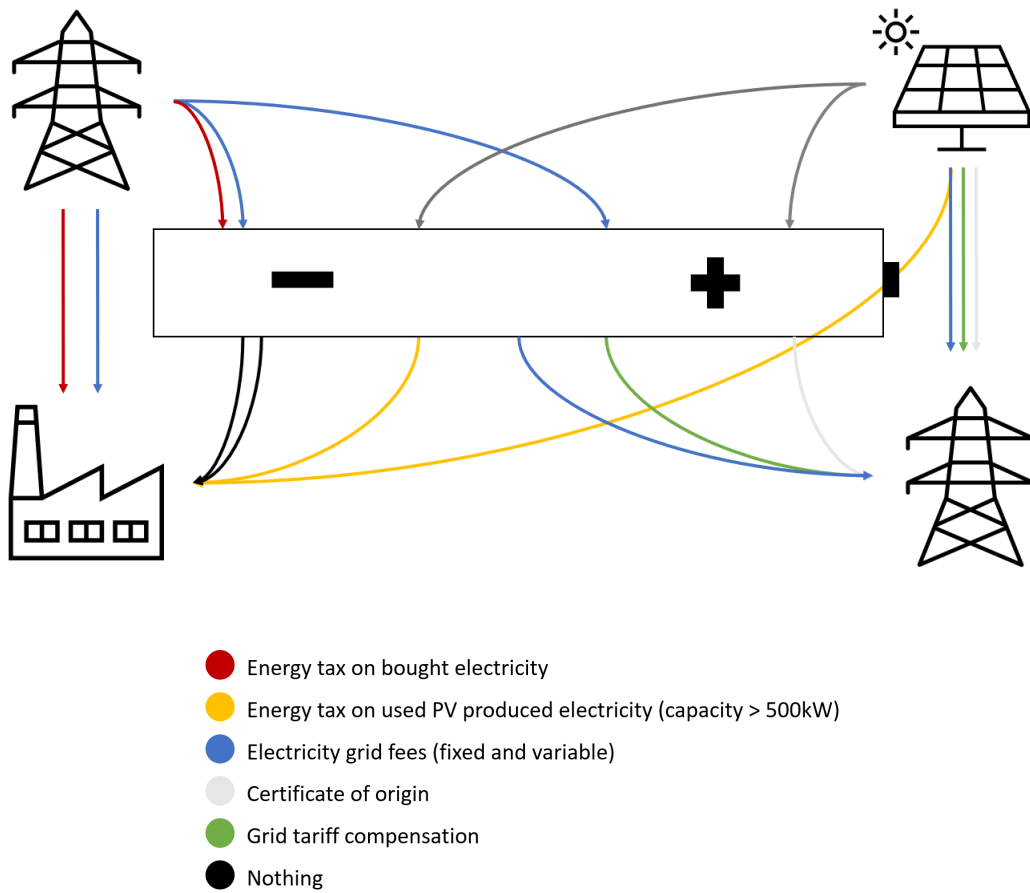


Figure 2.6: Illustration of how taxes, tariffs and compensations are flowing through the system.

3

Methodology

Explanation of concepts:

- **Model** - GAMS code. Four models exist; Reference 1 Only grid, Reference 2 PV, PV + Battery and PV + Hydrogen.
- **Scenario** - There are three scenarios that the models were run based on. Firstly, the models only optimize by minimizing the total system costs. Secondly, the system cost is still minimized but a requirement on varying self-sufficiency degrees is applied. Lastly, the models are disconnected from the electricity grid, while still minimizing the total system cost.
- **System** - The system is what is being modelled. It consists of the facility operating with the grid and components such as solar PV's and energy storage components.
- **Case** - 72 cases were created in this thesis, including 4 models, 3 scenarios, 2 electricity prices and 3 different electricity demands.

Four linear cost minimization models were built in GAMS. Two of the models had the possibility to invest in energy storage solutions, one with the option to invest in battery storage and the other one in hydrogen storage (electricity to hydrogen to electricity) including an electrolyzer, a compressed hydrogen storage tank, and a fuel cell. Two reference models were built to compare if an energy storage could benefit the system or not. Reference model 1 could only fulfill its electricity demand with electricity bought from the grid, in other words, providing a business as usual scenario. Reference model 2 could invest in solar PV's, but no energy storage.

All models had an hourly resolution and optimized the system over a one-year period. The CAPEX and installation costs for the components were annualized to enable the model to give accurate results for the one-year period. Bidding zone SE3 was considered in all of the models which affected the cost parameters related to the electricity spot price, electricity grid fee, and the solar irradiation profile. These input parameters could however be changed and customized to fit other situations as well.

All models were optimized in three different scenarios:

1. Minimize the total cost of the system
2. Minimize the total cost of the system while increasing the self-sufficiency degree
3. Minimize the total cost of the system while the system is disconnected from the grid,

Island mode.

When the models were optimized in the first scenario, minimizing the total system cost, it was free to decide how it wanted to solve the problem as long as it fulfilled the demand and did not exceed any of the other constraints. In the scenario of also increasing the self-sufficiency degree, an ascending amount of electricity, either directly from the PV or via the energy storage to the demand, was set as a fixed value in the model. The self-sufficiency degrees went from 10% to 100%, or until infeasible, and the model was forced to be x% self-sufficient while still minimizing the system cost. In the Island mode, the grid was fully removed from the models.

In Figure 3.1, a visualization of all 72 cases that can be put together from the 4 models, 3 scenarios, 2 electricity prices, and 3 electricity demand profiles is presented. Hence, each case set-up is built up by one model, one scenario, one electricity price, and one electricity demand profile.

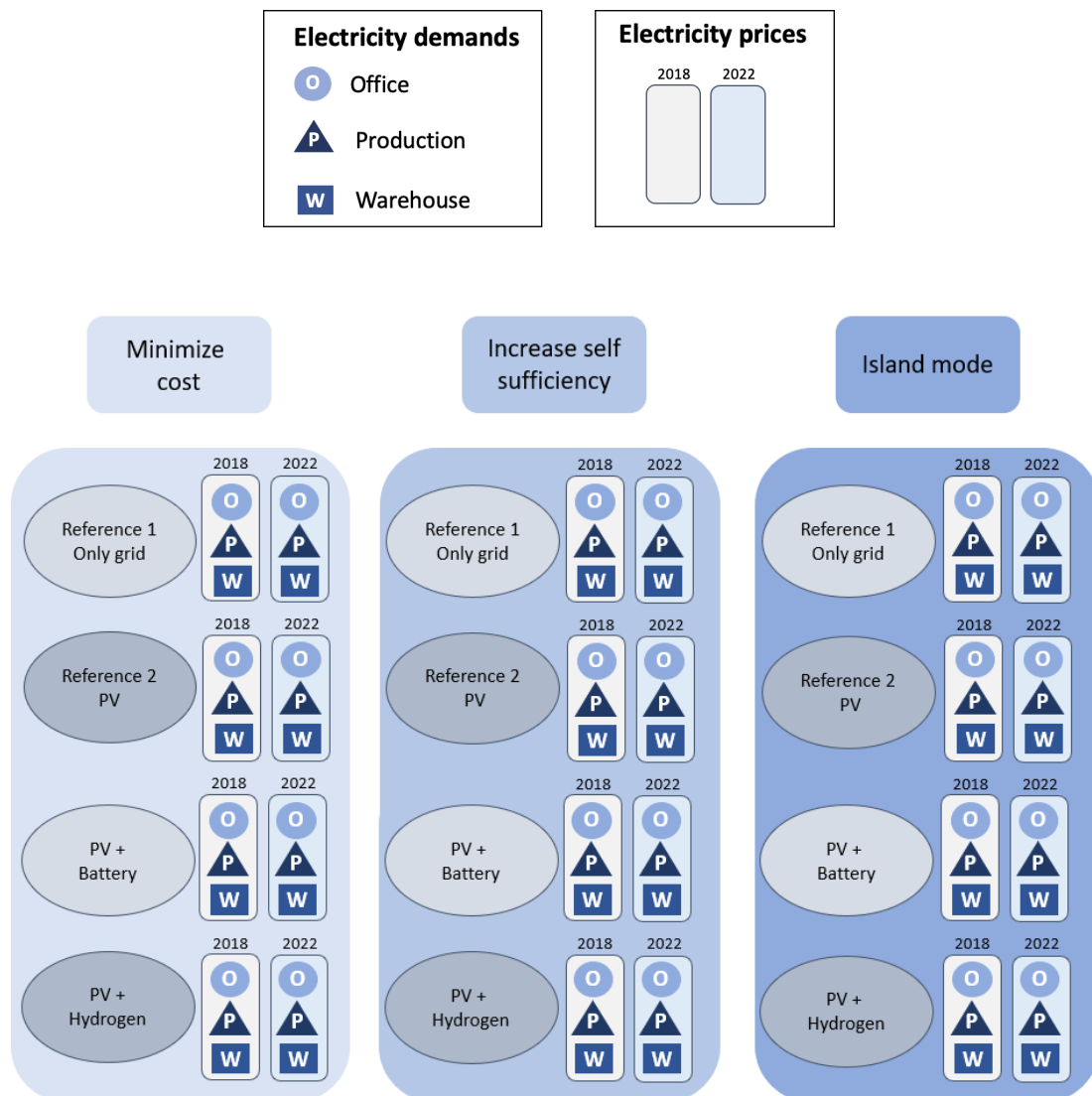


Figure 3.1: An overview of all of the 72 cases created

In Section 3.1, the reference models are explained shortly, likewise the battery model in Section 3.2, followed by the hydrogen model in Section 3.3. The GAMS-code for the battery model can be found in Section 3.4 and the hydrogen model in Appendix B.

The different icons used in the figures explaining the models in Section 3.1, 3.2, 3.3 and 3.5.1.1 are explained in Figure 3.2 below.

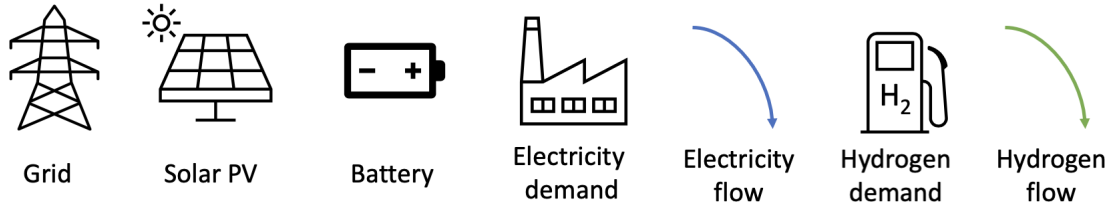


Figure 3.2: Explanation of the used icons

3.1 Reference models

The first reference model consisted of the grid and the electricity demand, see Figure 3.3. This would be the business as usual scenario of a system, fulfilling the electricity demand with electricity bought from the grid.



Figure 3.3: Reference model 1

The second reference model had the possibility to invest in solar PV's, making it possible to fulfill the electricity demand with both electricity bought from the grid, and from self-produced electricity originating from the solar PV's. The electricity produced from the solar PV's could also be sold directly to the grid. See Figure 3.4 for a schematic visualization of the model.

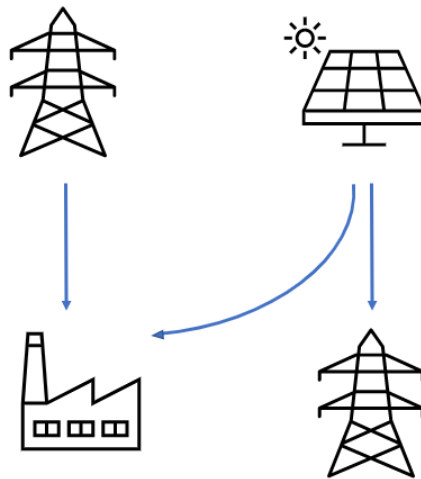


Figure 3.4: Reference model 2

3.2 Battery model

The battery model is visualized in Figure 3.5. The four smaller batteries were differentiated in the model, enabling a detailed analysis of the different electricity flows. In reality, it would only be one battery to invest in, which is represented by the illustrative larger battery containing the four smaller ones in the figure.

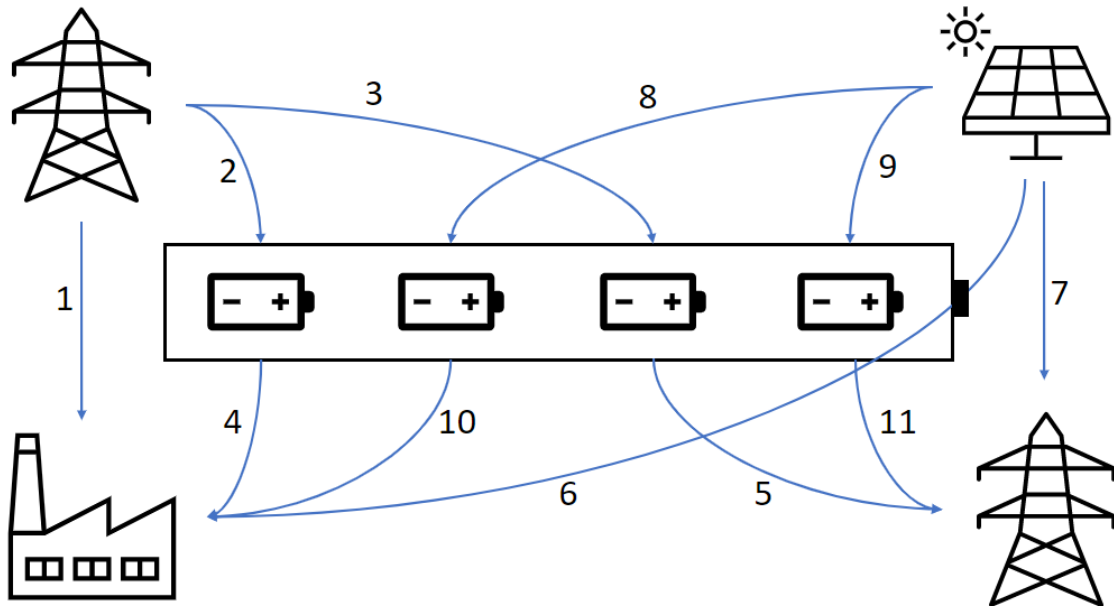


Figure 3.5: Visualization of the battery model with numbered electricity flows

The different electricity flows are related to different costs and revenues which are summarized in Table 3.1. In Figure 3.5, the numbers of the electricity flows from Table 3.1 are displayed. In addition to these costs, CAPEX, OPEX, installation costs, and fixed O&M costs related to the battery and solar PV's were added to the objective function, as well as electricity grid fees. The objective function, in linear optimization, is the function to

be minimized (or maximized) subject to the constraints.

Table 3.1: Costs and revenue streams related to the electricity flows. # refers to the electricity flows numbered in Figure 3.5.

#	Cost	Revenue
1	- Electricity spot price - Energy tax	-
2	- Electricity spot price - Energy tax	-
3	- Electricity spot price	-
4	-	-
5	-	- Grid tariff compensation - Electricity spot price
6	- Energy tax (if PV >500 kW)	-
7	-	- Certificate of origin - Grid tariff compensation - Electricity spot price
8	- Energy tax (if PV >500 kW)	-
9	-	-
10	-	-
11	-	- Certificate of origin - Grid tariff compensation - Electricity spot price

The return of investment for the battery was calculated for the highest possible self-sufficiency degree for all demands, with electricity prices from 2022. The annualized cost for the battery was removed in the yearly system cost

$$Total\ system\ cost\ [€/year] - Annualized\ battery\ cost\ [€/year] \quad (3.1)$$

and replaced by a single time investment cost, the battery capacity multiplied by the battery CAPEX.

$$Battery\ size\ [kWh] * Battery\ CAPEX\ [€/kWh] \quad (3.2)$$

The new yearly system cost was compared to the original system cost, originating from the first reference model. This comparison showed how much money that was saved each year

$$Total\ system\ cost\ ref.\ model\ 1\ [€/year] - New\ system\ cost\ battery\ model\ [€/year]. \quad (3.3)$$

The return of investment would therefore be

$$\frac{Single\ time\ investment\ cost\ battery\ [€]}{Money\ saved\ per\ year\ [€/year]} \quad (3.4)$$

The yearly OPEX and fixed O&M costs were excluded from this calculation, and would still occur each year. Though, they are considered of being very small relative to the CAPEX, and therefore they were neglected in these calculations.

3.3 Hydrogen model

The hydrogen model, in which energy is stored in hydrogen and then transformed back into electricity, is visualized in Figure 3.6. An electrolyzer splits water into hydrogen and oxygen with electricity. The hydrogen is then stored in pressurized tanks and after that transformed back into electricity in the fuel cells. The electricity output can either be used to fulfill the electricity demand, or be sold back to the grid.

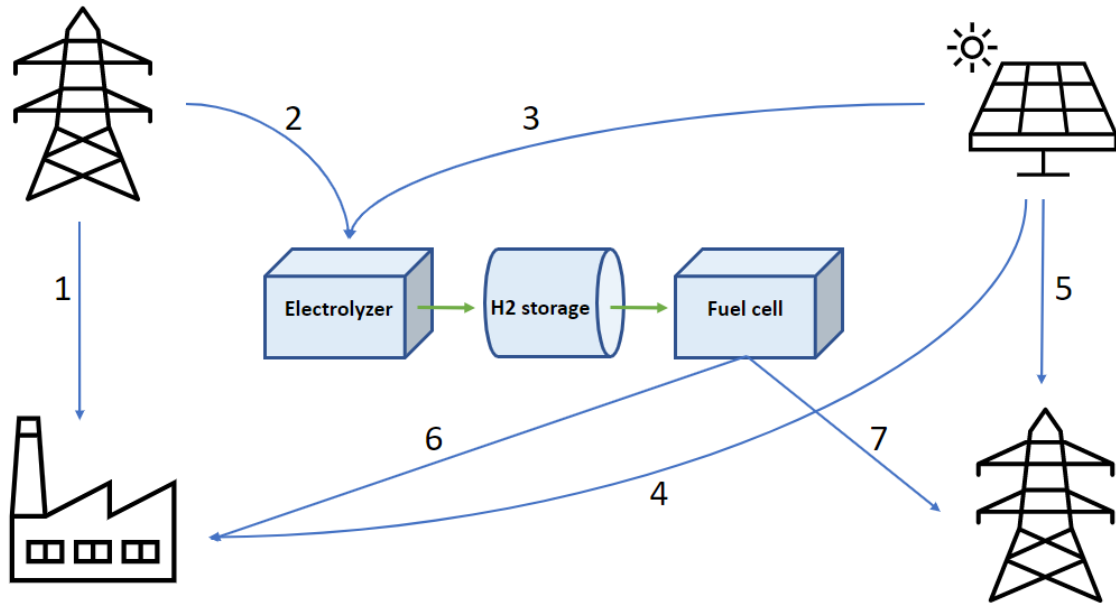


Figure 3.6: Hydrogen model with numbered electricity flows

The different electricity flows are related to different costs and revenues which are summarized in Table 3.2. In Figure 3.6, the numbers of the electricity flows from Table 3.2 are displayed. In addition to these costs, CAPEX, OPEX, installation costs and fixed O&M costs related to the electrolyzer, hydrogen storage, fuel cells and solar PV's were also added in the objective function, as well as electricity grid fees.

Table 3.2: Costs and revenue streams connected to the electricity flows. # refers to the electricity flows numbered in Figure 3.6

#	Cost	Revenue
1	- Electricity spot price - Energy tax	-
2	- Electricity spot price	-
3	-	-
4	- Energy tax (if PV >500 kW)	-
5	-	- Certificate of origin - Grid tariff compensation - Electricity spot price
6	- Energy tax	-
7	-	- Grid tariff compensation - Electricity spot price

3.4 The mathematical structure of the models

The models that have been created in GAMS are linear cost minimization models. In the following sections, indices, sets, parameters and variables used in the battery model are presented, see Appendix B for the hydrogen model which have a similar structure. These are later on used when describing the constraints as well as the objective function. The values of all parameters can be found in Chapter 4. Parameters and constraints that are labeled with a (*) was only used in the cases where the optimization goal was to increase the self-sufficiency.

Indices

t	Index for time step
i	Index for technologies
b	Index for flow directions

Sets

\mathcal{T}	Set of hours of one year: {1:8760}
\mathcal{I}	Set of technologies: {PV, battery}
\mathcal{B}	Set of flow directions: {GD, GG, PVD, PVG}

Parameters

PV_t	Solar irradiation profile in SE3 for every hour of the year
elp_t	Electricity price for every hour of the year
D_t	Electricity demand for every hour of the year
$areaPV$	Available area for solar PV installation
$instArea$	Installable area for solar PV installation [%]
p	Power-per-m ² for solar PV installation
tax	Electricity tax
gtc	Revenue from grid tariff compensation
u	Revenue from certificate of origin
$EgfB$	Electricity grid fee for bought electricity
PfB	Power fee for bought electricity
$EgfS$	Electricity grid fee for sold electricity
PfS	Power fee for sold electricity
$CAPEX_i$	CAPEX of technology i
$OPEX_i$	OPEX of technology i
ins_i	Installation cost of technology i
fix_i	Fixed O&M of technology i
l_i	Lifetime of technology i

r	Interest rate for annualization
a_i	Annuity factor of technology i
η_i	Efficiency of technology i
c	C-rate of the battery
$degSelf$	Degree of self-sufficiency*

Variables

$size_i$	Installed capacity of technology i
$SOC_{t,b}$	State of charge of the battery in time t
$charge_{t,b}$	Charging of the battery in time t
$discharge_{t,b}$	Discharging of the battery in time t
$supplyGD_t$	Supply of electricity from the grid to the demand in time t
$supplyPVD_t$	Supply of electricity from the PV's to the demand in time t
$soldPV_t$	Sold electricity from the PV's to the grid in time t
$highestSold$	The hour that the system sells the highest amount of electricity
$highestBought$	The hour that the system buys the highest amount of electricity
$cost$	Total cost of the system

Objective function

Minimize the total cost of the system.

$$\begin{aligned}
 minimize \ cost = & \sum_t \left(\left(supplyGD_t + \sum_{b=GD,PVD} charge_{t,b} + supplyPVD_t \right) * tax \right. \\
 & + \left(supplyGD_t + \sum_{b=GD,GG} charge_{t,b} \right) * elp_t \\
 & - \left(soldPV_t + \sum_{b=GG,PVG} discharge_{t,b} * \eta_{bat} \right) * \left(elp_t + gtc \right) \\
 & - \left(soldPV_t + discharge_{t,PVG} * \eta_{bat} \right) * u \\
 & + \sum_i size_i * \left(\left(CAPEX_i + ins_i \right) * a_i + OPEX_i + fix_i \right) \\
 & + EgfB + EgfS + PfB * highestBought + PfS * highestSold
 \end{aligned} \tag{3.5}$$

Constraints

Equation 3.6 balanced the electricity production from the solar PV's. What was produced each hour had to be distributed between the four electricity flows, leaving the solar PV's;

flow 6, 7, 8 and 9 in Figure 3.5.

$$size_{PV} * PV_t = supply_{PVD}_t + sold_{PV}_t + \sum_{b=\{PVG,PVD\}} charge_{t,b} \quad (3.6)$$

Equation 3.7 ensured that the demand was met at all timesteps.

$$supply_{GD}_t + supply_{PVD}_t + \sum_{b=\{GD,PVD\}} discharge_{t,b} * \eta_{bat} \geq D_t \quad (3.7)$$

Equation 3.8 is the state of charge balancing the four batteries. The state of charge at timestep $t+1$ is equal to the state of charge of the previous time step added by what is charged, multiplied by η , subtracted by what is discharged. Electricity that is charged comes either from the grid or from the solar PV's. Electricity that is discharged goes either to the facility (own electricity demand) or to the grid.

$$SOC_{t+1,b} = SOC_{t,b} + charge_{t,b} * \eta_{bat} - discharge_{t,b} \quad (3.8)$$

The charging and discharging rates were limited by the c-rate of the battery, presented in Equation 3.9 and 3.10,

$$charge_{t,b} \leq size_{bat,b} * c \quad (3.9)$$

$$discharge_{t,b} \leq size_{bat,b} * c \quad (3.10)$$

limiting the state of charge of the batteries to be smaller or equal to the capacity of the battery.

$$SOC_{t,b} \leq size_{bat,b} \quad (3.11)$$

Limiting the installed capacity of the solar PV's to be less or equal to the area available for solar PV installation, multiplied by the power-per-m² for solar PV, multiplied by the percentage of the available area that is installable. See also Equation 4.1 in Chapter 4 referring to the same constraint as Equation 3.12.

$$size_{PV} \leq area_{PV} * p * instArea \quad (3.12)$$

Finding the highest amount of electricity sold and bought from the grid in Equation 3.13 and 3.14. These values were used for calculating the power fee in the objective function.

$$highestSold \geq sold_{PV}_t + discharge_{t,GG} + discharge_{t,PVG} \quad (3.13)$$

$$highestBought \geq supply_{GD}_t + charge_{t,GD} + charge_{t,GG} \quad (3.14)$$

Deciding what percentage of the electricity produced from the solar PV's should be used in the demand, i.e., the self-sufficiency degree.

$$degSelf = \sum_t (supply_{PVD}_t + discharge_{t,PVD} * \eta_{bat}) / \sum_t D_t \quad * \quad (3.15)$$

The following equation prevented curtailment of electricity produced from the solar PV's, and made sure the self-sufficiency degree was correct. If the electricity supply, either directly from the solar PV's or via the battery, would be larger than the demand, electricity would have had to be curtailed. This would have looked like the model was more self-sufficient than it actually was. Therefore, equation 3.16 was needed.

$$supply_{PVD}_t + discharge_{t,PVD} * \eta_{bat} \leq D_t \quad * \quad (3.16)$$

3.5 Future scenarios

The GAMS models were extended in order to include future scenarios. The scenarios that were considered was regarding changes in taxes and tariffs. Additionally, research regarding a changed demand of hydrogen was executed.

3.5.1 Future of hydrogen

In order to investigate what the future of hydrogen might look like, research regarding future estimations have been conducted. As presented in Section 2.3.6, the production price of hydrogen is estimated to decrease by the same rate as the market price of hydrogen. Due to their correlative decrease, it was decided that no additional model was needed for this analysis. Instead, the result regarding the future scenario was based on literature studies.

3.5.1.1 Hydrogen model: electricity-H₂-use

If the future predictions becomes reality, it might be relevant to create a new model that answers to a new business case where the hydrogen is directly sold to a hydrogen demand after being stored in the compressed tank. The hydrogen model that was created in order to simulate such a future scenario, enabling a direct hydrogen use is visualized in Figure 3.7. An electrolyzer splits water into hydrogen and oxygen with electricity, exactly like the process in the other hydrogen model. Instead of transforming the hydrogen back to electricity through a fuel cell, the hydrogen is sold directly after storage. In this model, the electricity demand for the producing facility can only be fulfilled by electricity bought from the grid, or from electricity directly produced by the solar PV's. This imply that the energy storage can not supply the demand in this case.

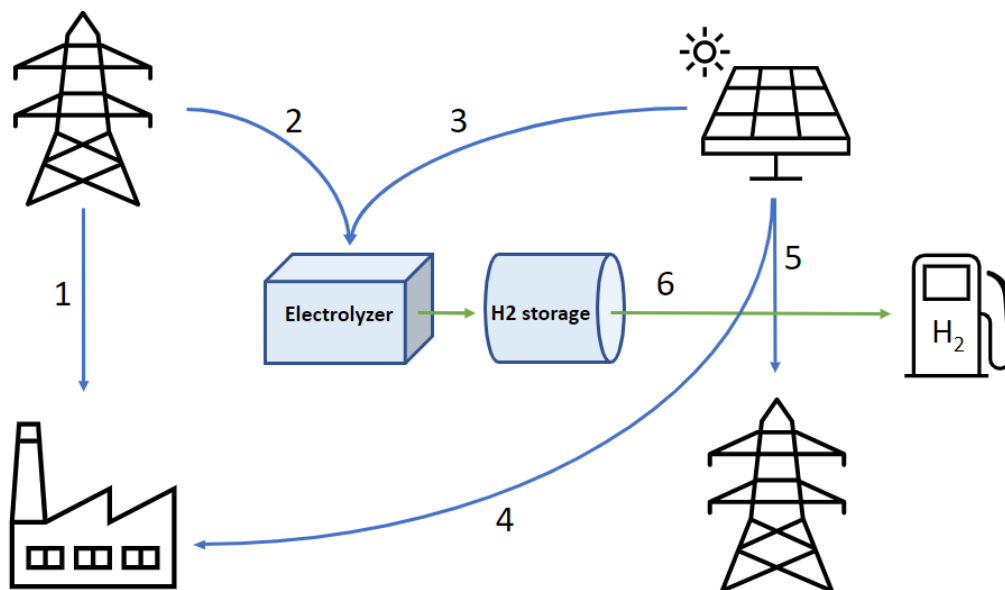


Figure 3.7: Hydrogen model, el-H₂-use, with numbered electricity and hydrogen flows

The different electricity and hydrogen flows are related to different costs and revenues,

similar to Table 3.2. Flow 6 generates a revenue from the sold hydrogen.

3.5.2 Changes in taxes, tariffs and subsidies

The current tax structure, tariffs, and subsidies implemented in Sweden are expected to undergo potential modifications in the future. Factors such as the emergence of a new government or policy shifts within the EU may contribute to these changes. Therefore, it was considered interesting to see what would happen if some of these input parameters would change.

The first potential change that was tested regarded the energy tax. If the installed capacity of solar PV's exceeds 500 kW you are, according to Swedish law, obliged to pay energy tax on the PV generated electricity that is used for own purpose. If the installed PV capacity on the other hand is below 500 kW, you are not liable for paying energy tax on any of the on-site produced electricity, i.e., neither the electricity you use yourself nor the one that you sell to the grid. Before the 1st of July 2021, this limit was 255 kW [75], and this development supports the reasoning of that the limit might be further raised in the future. To push this to the limit, the models were run entirely without the energy tax for self produced electricity in order to see what would happen if this limit was removed.

Apart from energy tax, another variable that could undergo changes in the future is the grid tariff compensation. If an increased amount of people were to invest in solar PV's, the volume of electricity sold back to the grid might also increase substantially. This could eventually lead to challenges in maintaining a stable energy balance within the grid. Consequently, an analysis was conducted to assess the potential implications of eliminating the grid tariff compensation for the sold electricity.

4

Data

This chapter presents the data that have been used as input data for the GAMS model.

4.1 Electricity prices

The result from this thesis is built on data regarding the electricity prices from 2018 and 2022. The reason for this is the extreme rise in the prices that has been present in the Northern electricity market recently. The data used for the electricity prices are shown in Figure 4.1. This data contain historic spot prices from Nord Pool, from the respective years in bidding zone SE3 in Sweden.

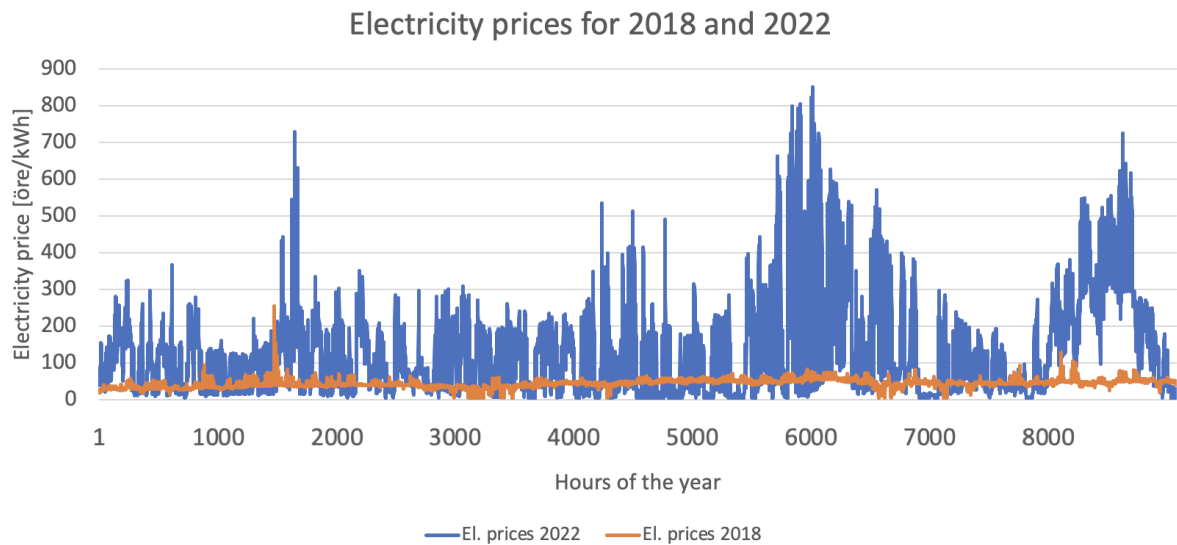


Figure 4.1: Electricity prices for 2018 and 2022 [84]

4.2 Data related to the Solar PV's

The area available for solar PV installation used in the GAMS model was chosen based on comparisons with already installed PV installations [85]. A normalized solar irradiation profile was used [86] which represented the average hourly production levels in the region SE3, and not specific for the locations of the facilities. The data used for the solar irradiation profile is plotted in Figure 4.2.

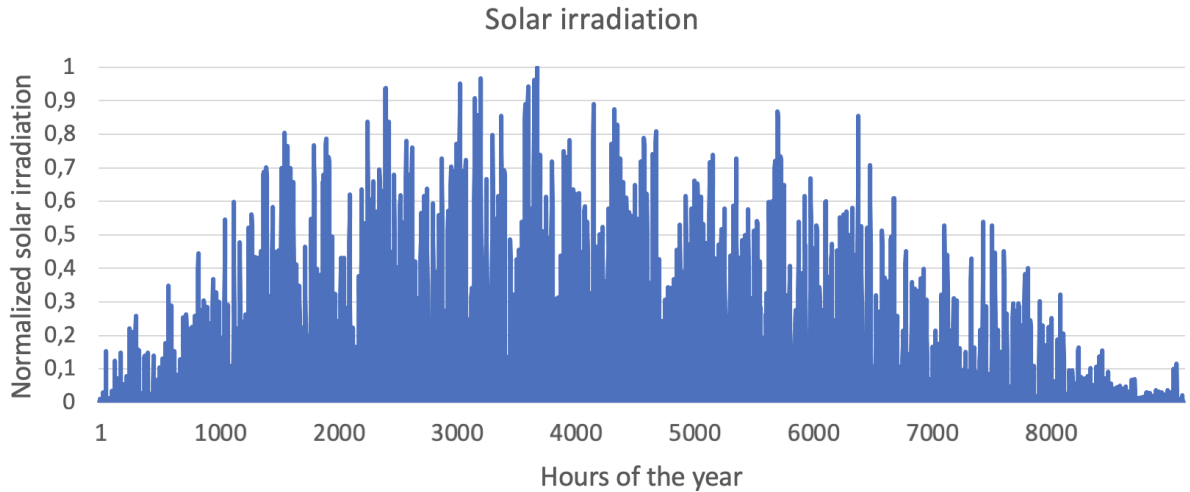


Figure 4.2: Solar irradiation profile [86]

Data for all parameters related to the solar PV's that were used in the GAMS models are listed in Table 4.1.

Table 4.1: Values of the parameters related to the solar PV's

	Value	Unit	Source
CAPEX	870	€/kW	[87]
OPEX	43.5	€/kW/year	5% of CAPEX
Fixed O&M	10.6	€/kW/year	[87]
Installation cost	87	€/kW	10% of CAPEX
Life time	35	years	[87]
Power-per-m ²	0.2	kW/m ²	[88]
Available area	30 000	m ²	[85]
Installable area	80	%	[89]

The area available for solar PV installation was 30 000 m². With the power-per-m² 0.2 kW/m² for solar PV's and the assumption that only 80% of the area could be used due to obstacles and space needed for the installers to work on, the maximum solar PV capacity could therefore be

$$30\,000\,m^2 * 0.2\,kW/m^2 * 80\% = 4\,800\,kW \quad (4.1)$$

The maximum yearly production of electricity from this size of solar PV's was 4.9 GWh, calculated by multiplying the maximum installed capacity 4 800 kW by the solar irradiation profile, and taking the sum of it.

4.3 Electricity demand profiles

In order to make the output of the model applicable in several use cases, different demand profiles regarding electricity use have been used. Gathering data from real-life buildings has been done in collaboration with external parties. The demand profiles that have been

gathered are the electricity consumption of three different facility types; an office building, a production site, and a warehouse facility. Hence, the extracted data comes from real-life scenarios. The demand profiles from the data are visualized in Figure 4.3.

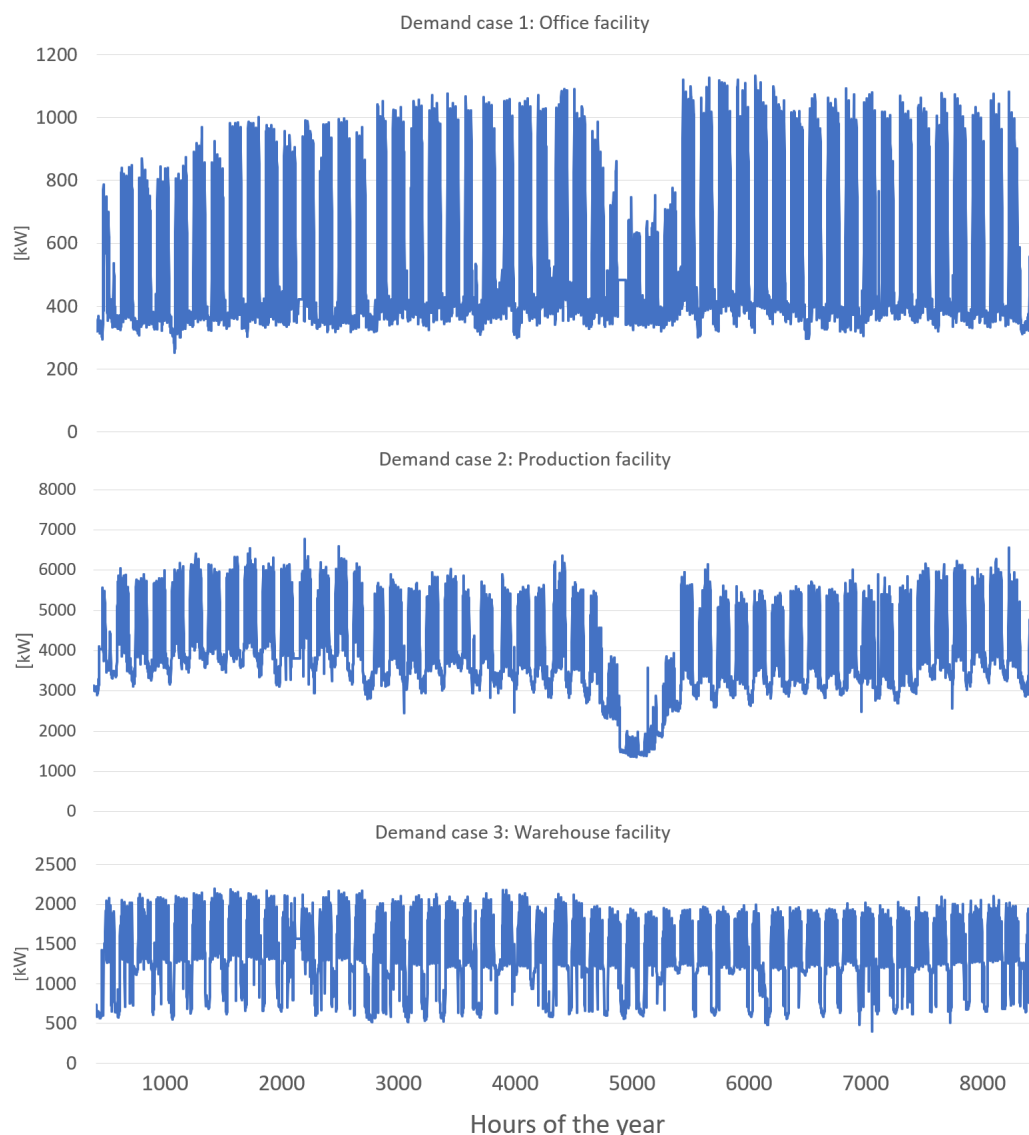


Figure 4.3: Plot of all demand profiles, measured in kW over the period of one year

The first demand case profile originated from an office facility. Here, the y-axis shows the total amount of used electricity and the x-axis shows all of the hours over one year. There is a constant base load of around 400 kW, present during all times of the week, nights and weekends included. The base load is mainly constituted by heating of the facility. The highest peak that the electricity demand reaches is approximately 1100 kW and is dependent on how many people are present on-site at the office each day and what operations they are running.

The data in demand case 2 has been extracted from a production site that is running a two-shift business. From this plot, one can tell that the base load of this facility is higher than for the office facility, ranging between 3000 to 5500. The base load is, like the first demand profile, mainly consisting of the electricity required for the heating of

the facility. The range of the base load is thereby dependent on seasonal differences in Sweden's climate, which implies that there is a higher base load during winter and slightly lower demand during summer. Even though the patterns share similarities, the total base load as well as the peak load is, however, reaching higher values in this case, which is distinguishing the cases from each other. The maximal peak load reaches approximately 6700 kW.

The data in demand case 3 has been extracted from the electricity demand of a warehouse facility. This facility is, as the production facility, running a two-shift business. Compared to the previously addressed demand profiles, the base load is in this profile around 1500 kW. The total electricity demand ranges between 500 to the peaks at 2200 kW. The base load consists of heating and the peaks are dependent on when the trucks in the warehouse are charged. To study the electricity use pattern in more detail, each of the three demand profiles was also plotted over a three-week period of time, see Figure 4.4.

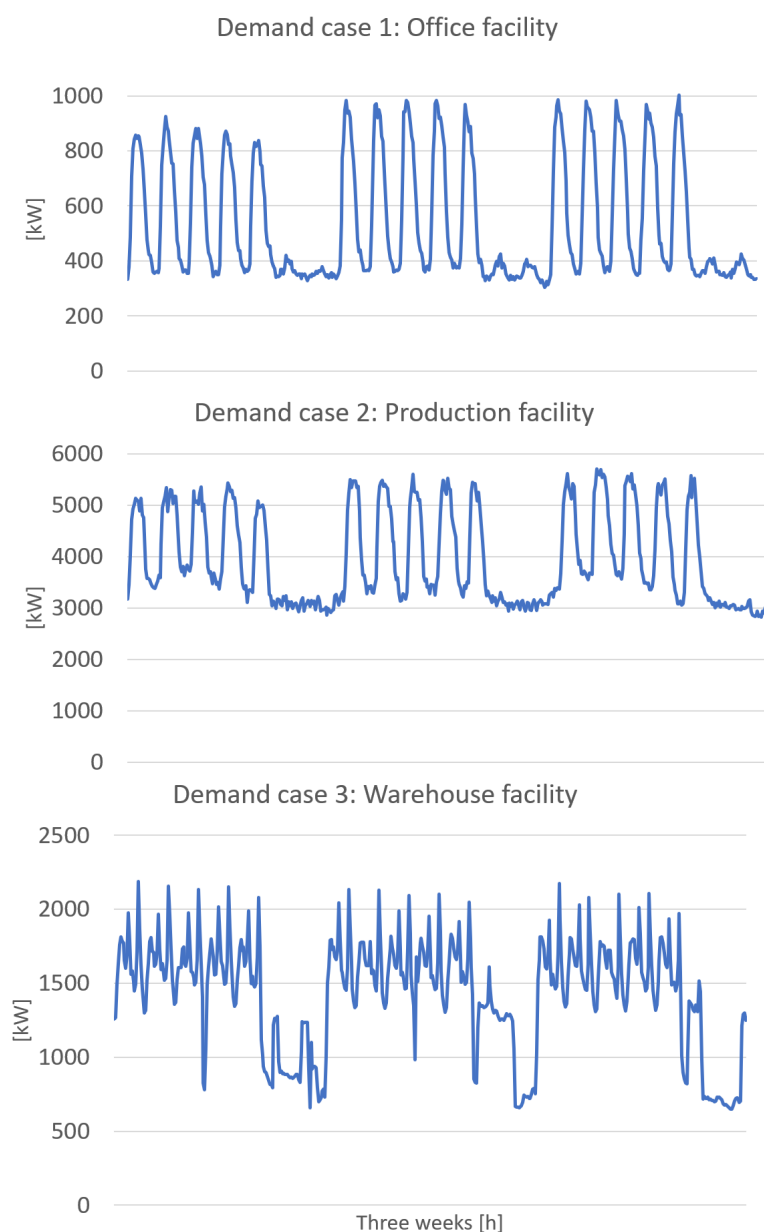


Figure 4.4: Plot of all demand profiles, measured in kW over a three-week period

By studying the weekly demand profiles it could be concluded that the office demand is following a frequent pattern over the weeks. The peaks each day are reached when there are people in the office, meaning that the peak is ranging from around 07:00 to 17:00. The production demand has similarities to the office case since they are both following a rhythmic pattern over the week. Even though the patterns share similarities, the total base load as well as the peak load is however reaching higher values in the production demand, which is distinguishing the cases from each other. However, the warehouse demand looks slightly different since it does not follow the same rhythmic pattern. Though, it shares the same weekly cycle over the weekdays and the weekends. The irregularities in case 3 are dependent on when the trucks are charged. In Table 4.2, the total yearly demands and largest peaks for the three demand profiles are summarized, as well as the ratio between the installed capacity of solar PV's and total demand.

Table 4.2: Summary of the electricity demands

	Largest peak	Total yearly demand	Solar PV/demand [GWh/GWh]
Office	1100 kW	5 GWh	0.98
Production	6700 kW	35 GWh	0.14
Warehouse	2200 kW	12 GWh	0.41

The ratio could be used in order to determine correlations between installed PV capacity and what storage system, as well as the size of it, that was a suitable investment. The ratio was calculated as follows:

$$\text{SolarPV/Demand} = \frac{\text{Total yearly PV produced electricity}}{\text{Total yearly demand}} \quad (4.2)$$

4.4 Taxes and tariffs

The data regarding taxes were extracted referring to a larger commercial facility with a higher installed capacity than 500 kW solar panels. As presented in Section 2.4.3, industrial operations are covered by a tax reduction in Sweden. Therefore, the demand profile 2: Production facility, was modeled with a reduced tax, and the other two demands were modeled with the standard energy tax. The grid tariff compensation and certificate of origin were chosen according to actual values used in the area of Gothenburg. The electricity grid fee and power fee were chosen according to what a facility with an energy demand of at least 5 GWh/year pays in the area of Gothenburg. Data for all parameters related to the taxes and tariffs that were used in the GAMS models are listed in Table 4.3. The numbers in the table have been recalculated from SEK to Euro by assuming 1 Euro equals 10 SEK.

Table 4.3: Values of the parameters related to taxes and tariffs

	Value	Unit	Source
Energy tax	0.0392	€/kWh	[90]
Reduced energy tax	0.0006	€/kWh	[90]
Grid tariff compensation	0.005	€/kWh	[79]
Certificate of origin	0.001	€/kWh	[91]
Electricity grid fee - bought el	1150	€/year	[92]
Power fee - bought el	25.9	€/kW/year	[92]
Electricity grid fee - sold el	270	€/year	[69]
Power fee - sold el	2.2	€/kW/year	[69]

4.5 Technical data

Data for all parameters related to the battery that were used in the GAMS model are compiled and listed in Table 4.4.

Table 4.4: Values of the parameters related to the battery

	Value	Unit	Source
CAPEX	580	€/kWh	[35]
OPEX	0.002	€/kWh/year	[93]
Fixed O&M	0.54	€/kW/year	[93]
Life time	15	years	[93]
Charging efficiency	98	%	[93]
Discharging efficiency	97	%	[93]
C-rate	0.5	1/h	[94]

Data for all parameters related to the hydrogen system that were used in the GAMS models are compiled and listed in Table 4.5.

Table 4.5: Values of the parameters related to the hydrogen system

	Value	Unit	Source	Value	Unit	Source	Value	Unit	Source
	Electrolyzer			H₂ storage & compressor			Fuel cell		
CAPEX	1000	€/kW	[35]	57	€/kWh	[93]	800	€/kW	[35]
OPEX	50	€/kW/year	[35]	0.6	€/kWh/year	[93]	40	€/kW/year	[35]
Fixed O&M	40	€/kW/year	[35]	0.6	€/kWh/year	[93]	32	€/kW/year	[35]
Installation cost	300	€/kW	[35]	9	€/kWh	[93]	240	€/kW	[35]
Life time	20	years	[35]	25	years	[93]	6	years	[35]
Efficiency	70	%	[95]	90	%	[93]	50	%	[95]

The annuity factor for all components were calculated as follows, where $r=5\%$ is the interest rate, and l is the life time of the component:

$$a = \frac{r}{1 - (1 - r)^l} \quad (4.3)$$

4.6 Technical limitations of components

Decisions had to be made regarding what batteries to use in the battery model. This was done according to the Danish Energy Agency's battery comparison that are presented in 2.2.4. From this, and from complimentary recommendations from people involved in the data-gathering process, the chosen battery type to include in the research was lithium-ion batteries.

The size of the battery storage was limited to 10 000 kWh. This was considered reasonable concerning the physical area sizes that the battery requires, which cannot be unlimited. A battery of the size of a full size, 40ft, container can store between 2 200 - 5 000 kWh [96] [97], depending on the quality of the batteries. Utilizing between two to four 40ft containers was therefore set as a suitable physical limit, resulting in a total storage capacity of 10 000 kWh. In Figure 4.5, a battery container is shown, representing what such a battery could look like.



Figure 4.5: Example photo of a battery container

Furthermore, the size of the hydrogen storage also had to be limited due to the same reason. Moreover, hydrogen storage must also answer to the Seveso requirements [98]. Here, the approved level has a maximum hydrogen storage limit of 5 ton. Transformed into energy (energy content of hydrogen is 33 kWh/kg [99]), 5 tons of hydrogen is

$$5 \text{ ton} * 33 \text{ kWh/kg} = 165 \text{ 000 kWh} \quad (4.4)$$

Additionally, all parameters related to the hydrogen storage, specifically the storage tank, refer to a 200 bar tank in which the hydrogen is stored as a gas. The pressure in the hydrogen tank was kept at this value, answering recommendations from professors in the field. Also, the parameters related to the electrolyzer is referring to a PEM electrolyzer, and the parameters related to the fuel cell is referring to a PEM fuel cell.

5

Results and analysis

This chapter starts off by giving an overview of the results of the 72 generated cases in Section 5.1. Thereafter, more specific results related to each demand is presented in Section 5.2, followed by results and analysis of the model behaviour in Section 5.3. Lastly, results from the future scenarios are presented in Section 5.4.

5.1 Overview of the results

From studying the 72 outputs, the first result to be identified was that all models optimized in the Island mode scenario were proven to be infeasible. These cases are marked with a red X in Figure 5.1. The reason for the infeasibility was the lacking size of area available for PV installations and the size (kWh) limitations on the energy storage. This implied that the area that was tested, together with the possibility of adding an energy storage, was not big enough to cover any of the electricity demands without additional help from the grid. The total yearly production from the solar PV's was 4.9 GWh (calculated in Section 4.5) and the smallest demand profile, office, had a yearly electricity demand of 5 GWh (from Table 4.2) which shows that Island mode was not possible. Due to the infeasibility, no results from the Island mode scenario could be presented.

Furthermore, other evident results from the first evaluations were that some of the models generated the same optimal solution, marked with either orange or yellow color in Figure 5.1. The orange color refers to cases where the result was the same as for the model *Reference 1 - No PV*, i.e., neither investment in PV nor energy storage was made. This result occurred in the minimize cost scenario using the electricity prices from 2018. The reason behind this was that the electricity prices during 2018 were very low, which led to the cheapest alternative simply being to fulfill the entire electricity demand with bought electricity from the grid.

The yellow color means that the optimal solution was the same as the results from model *Reference 2 - PV*, i.e., investment in PV was made but without energy storage. This result occurred in three states:

1. *Minimize cost - hydrogen - 2022 - all demands*: The investment costs of the components in the hydrogen system were too expensive, and minimizing the cost was made by only investing in solar PV's.
2. *Increase self-sufficiency - battery - 2018 - production demand*: The model could ensure the fixed percentage of self-sufficiency by only utilizing the PV's, and therefore no energy storage was needed to fulfill that requirement. Since the electricity prices this year were low, an investment in a battery would not result in any profit worth the investment cost.
3. *Increase self-sufficiency - hydrogen - 2018 and 2022 - production and warehouse*

demand: The model could fulfill the self-sufficiency requirement with only the PV's. The reason why the results look different in the hydrogen model compared with the battery model was the large efficiency losses that occurred in the hydrogen system. The battery model could reach a higher self-sufficiency degree due to the battery's higher efficiency.



Figure 5.1: A visualization overview of the outputs from the models with marking of the cases that were either eliminated (red) or gave the same results (orange and yellow).

In Table 5.1-5.6 the total system costs for all cases are presented, except Island mode, together with the sizes of solar PV's, battery storage and hydrogen storage. The orange and yellow colors correlate with the same colors as in Figure 5.1. The column to the left refers to what optimization scenario that is presented, where the percentage of self-sufficiency degree originates from the optimization scenario *Increase self-sufficiency*. Since the demand profiles (office, production and warehouse) have different total yearly demands of electricity, as presented in Table 4.2, and all systems have the same area of maximum possible solar PV installations, they can not reach the same amount of self-sufficiency. The battery model could reach the highest degree of self-sufficiency due to its higher efficiency,

and thus provided smaller losses in comparison to the hydrogen system. As a reference, the minimize cost models reached between 0-5% self-sufficiency. Sizes of all components in the hydrogen systems are presented in Appendix C.

Table 5.1: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2018** and the **Office** demand

Scenario	Total cost of reference model 1: 436 k€/year							
	Ref. model 2: PV		Battery model			Hydrogen model		
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage
Minimize cost	436 k€/year	0	436 k€/year	0	0	436 k€/year	0	0
10% self-sufficient	465 k€/year	469 kW	465 k€/year	469 kW	0	465 k€/year	469 kW	0
20% self-sufficient	498 k€/year	923 kW	498 k€/year	923 kW	0	498 k€/year	923 kW	0
30% self-sufficient	541 k€/year	1660 kW	541 k€/year	1660 kW	0	541 k€/year	1660 kW	0
40% self-sufficient	621 k€/year	2949 kW	616 k€/year	2697 kW	305 kWh	621 k€/year	2949 kW	0
50% self-sufficient	-	-	728 k€/year	3521 kW	1663 kWh	846 k€/year	4800 kW	1131 kWh
60% self-sufficient	-	-	857 k€/year	4371 kW	3176 kWh	1 250 k€/year	4800 kW	5292 kWh
70% self-sufficient	-	-	1 179 k€/year	4800 kW	8817 kWh	-	-	-
80% self-sufficient	-	-	-	-	-	-	-	-

Table 5.2: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2022** and the **Office** demand

Scenario	Total cost of reference model 1: 989 k€/year								
	Ref. model 2: PV		Battery model			Hydrogen model			
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage	
Minimize cost	753 k€/year	4800 kW	563 k€/year	4800 kW	10 000 kWh	753 k€/year	4800 kW	0	
10% self-sufficient	755 k€/year	4800 kW	563 k€/year	4800 kW	10 000 kWh	755 k€/year	4800 kW	0	
20% self-sufficient	757 k€/year	4800 kW	565 k€/year	4800 kW	10 000 kWh	757 k€/year	4800 kW	0	
30% self-sufficient	760 k€/year	4800 kW	568 k€/year	4800 kW	10 000 kWh	760 k€/year	4800 kW	0	
40% self-sufficient	763 k€/year	4800 kW	571 k€/year	4800 kW	10 000 kWh	763 k€/year	4800 kW	0	
50% self-sufficient	-	-	574 k€/year	4800 kW	10 000 kWh	915 k€/year	4800 kW	1454 kWh	
60% self-sufficient	-	-	595 k€/year	4800 kW	10 000 kWh	1 425k€/year	4800 kW	5841 kWh	
70% self-sufficient	-	-	714 k€/year	4800 kW	10 000 kWh	-	-	-	
80% self-sufficient	-	-	-	-	-	-	-	-	

Table 5.3: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2018** and the **Production** demand

Scenario	Cost of reference model 1: 1.74 M€/year								
	Ref. model 2: PV		Battery model			Hydrogen model			
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage	
Minimize cost	1.74 M€/year	0	1.74 M€/year	0	0	1.74 M€/year	0	0	
10% self-sufficient	1.96 M€/year	3414 kW	1.96 M€/year	3414 kW	0	1.96 M€/year	3414 kW	0	
20% self-sufficient	-	-	-	-	-	-	-	-	

Table 5.4: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2022** and the **Production** demand

Scenario	Cost of reference model 1: 5.44 M€/year							
	Ref. model 2: PV		Battery model			Hydrogen model		
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage
Minimize cost	5.20 M€/year	4800 kW	4.97 M€/year	4800 kW	10 000 kWh	5.20 M€/year	4800 kW	0
10% self-sufficient	5.21 M€/year	4800 kW	4.99M€/year	4800 kW	10 000 kWh	5.21 M€/year	4800 kW	0
20% self-sufficient	-	-	-	-	-	-	-	-

Table 5.5: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2018** and the **Warehouse** demand

Scenario	Cost of reference model 1: 1.04 M€/year							
	Ref. model 2: PV		Battery model			Hydrogen model		
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage
Minimize cost	1.04 M€/year	0	1.04 M€/year	0	0	1.04 M€/year	0	0
10% self-sufficient	1.11 M€/year	1152 kW	1.11 M€/year	1152 kW	0	1.11 M€/year	1152 kW	0
20% self-sufficient	1.20 M€/year	2475 kW	1.20 M€/year	2475 kW	0	1.20 M€/year	2475 kW	0
30% self-sufficient	-	-	1.34 k€/year	4701 kW	233 kWh	-	-	-
40% self-sufficient	-	-	-	-	-	-	-	-

Table 5.6: Total cost of the systems, size of PV, battery and hydrogen storage with electricity demand from **2022** and the **Warehouse** demand

Scenario	Cost of reference model 1: 2.23 M€/year							
	Ref. model 2: PV		Battery model			Hydrogen model		
	Total cost	Size PV	Total cost	Size PV	Size battery	Total cost	Size PV	Size H2 storage
Minimize cost	1.99 M€/year	4800 kW	1.80 M€/year	4800 kW	10 000 kWh	1.99 M€/year	4800 kW	0
10% self-sufficient	2.00 M€/year	4800 kW	1.80 M€/year	4800 kW	10 000 kWh	2.00 M€/year	4800 kW	0
20% self-sufficient	2.01 M€/year	4800 kW	1.81 M€/year	4800 kW	10 000 kWh	2.01 M€/year	4800 kW	0
30% self-sufficient	-	-	1.82 M€/year	4800 kW	10 000 kWh	-	-	-
40% self-sufficient	-	-	-	-	-	-	-	-

5.2 Results for the three demand profiles

In the following section, results originating from the outputs of the 72 cases have been analyzed. The three different demand profiles are addressed separately, followed by a general result and summary.

5.2.1 Demand profile 1 - Office facility

When analysing Table 5.1 and 5.2, it could be concluded that the system only invested in a hydrogen system if the fixed self-sufficiency degree was set to 50% or higher. When the same system invested in a battery with 50% self-sufficiency, the total system cost was about 120 000 €/year cheaper than the hydrogen model with electricity prices from 2018, and 340 000 €/year cheaper with electricity prices from 2022. Therefore the hydrogen model was cut off from further detailed analysis.

When the low electricity prices from 2018 were considered, the cheapest way of fulfill the electricity demand was by only utilizing the grid (reference model 1), see Figure 5.2. In Figure 5.2 it can be seen that the system cost for the optimization goal 10-30% self-sufficiency for all models follows the same pattern since the cheapest way to achieve this amount of self-sufficiency was by only using the PV's. The cheapest way of achieving 40-70% self-sufficiency, and the only feasible way of achieving 70%, was by using the battery model.

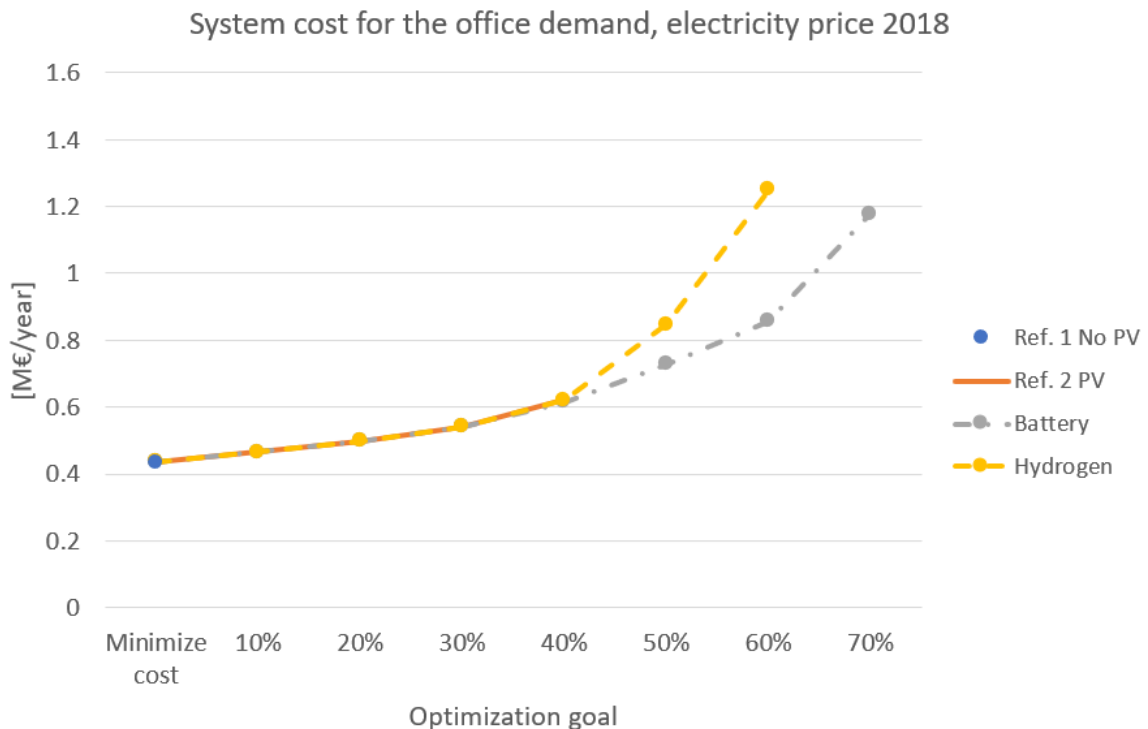


Figure 5.2: System cost for office demand and electricity prices from 2018 with different models and optimization goal. Values from Table 5.1.

When the electricity prices from 2022 were considered, the result became significantly

different. The cheapest scenario was found in the battery model, where the model invested in 4.8 MW solar PV and 10 MWh battery, meaning that it maximized both of these investments. In Figure 5.3, the total system cost for the office case is plotted for all optimization scenarios and models, with electricity prices from 2022. The battery model could fulfill the demand to a lower cost than both of the reference models and the hydrogen model. Therefore, the conclusion from this is that a scenario, in which the ratio between the installed solar PV capacity compared to the demand, enables excess electricity from the PV's that could bring profits when being combined with the investment in a battery storage system. In Figure 5.8 in Section 5.3, the demands are plotted together with the solar PV electricity production, visualizing the potential excess electricity.

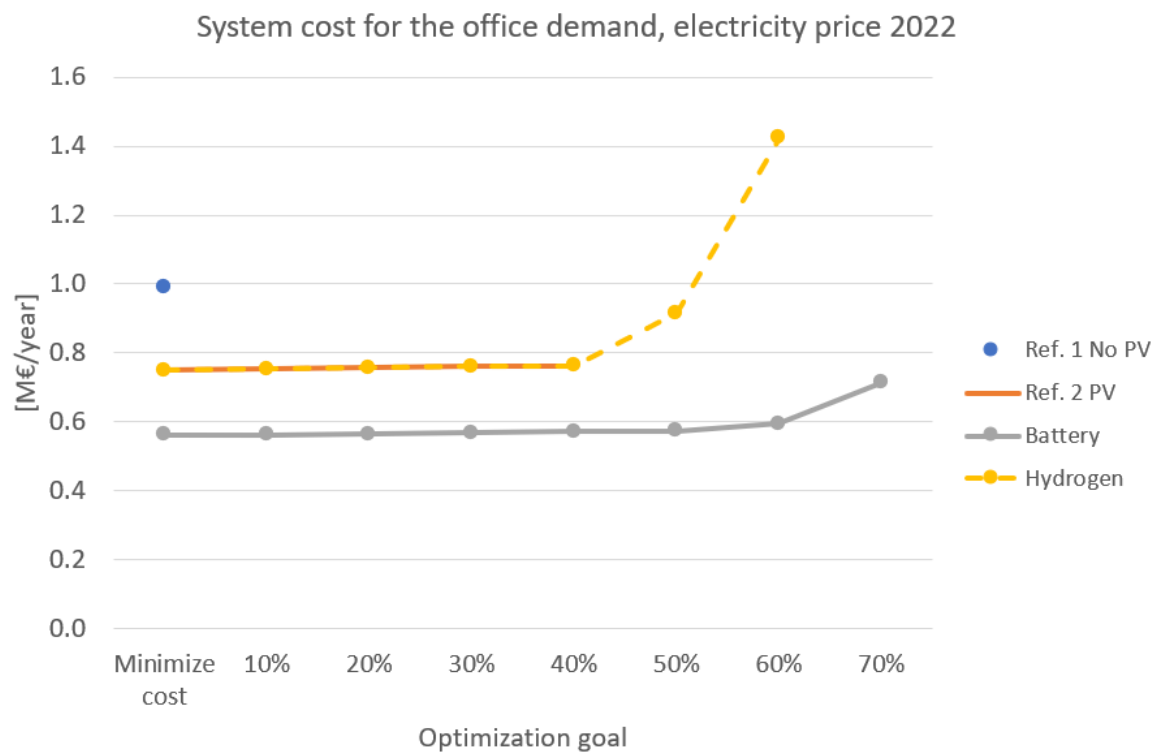


Figure 5.3: System cost for office demand and electricity prices from 2022 with different models and optimization goal. Values from Table 5.2.

After analyzing the outputs generated by the battery model, it was determined that the maximum achievable degree of self-sufficiency, given the current input parameters, was 70% for the office demand (as presented in Table 5.1 and 5.2). Increasing the degree of self-sufficiency beyond this level was not possible due to inadequate installed capacity of solar PV's. Figure 5.4 provides a detailed breakdown of the total system costs, meaning the total costs minus the total revenue.

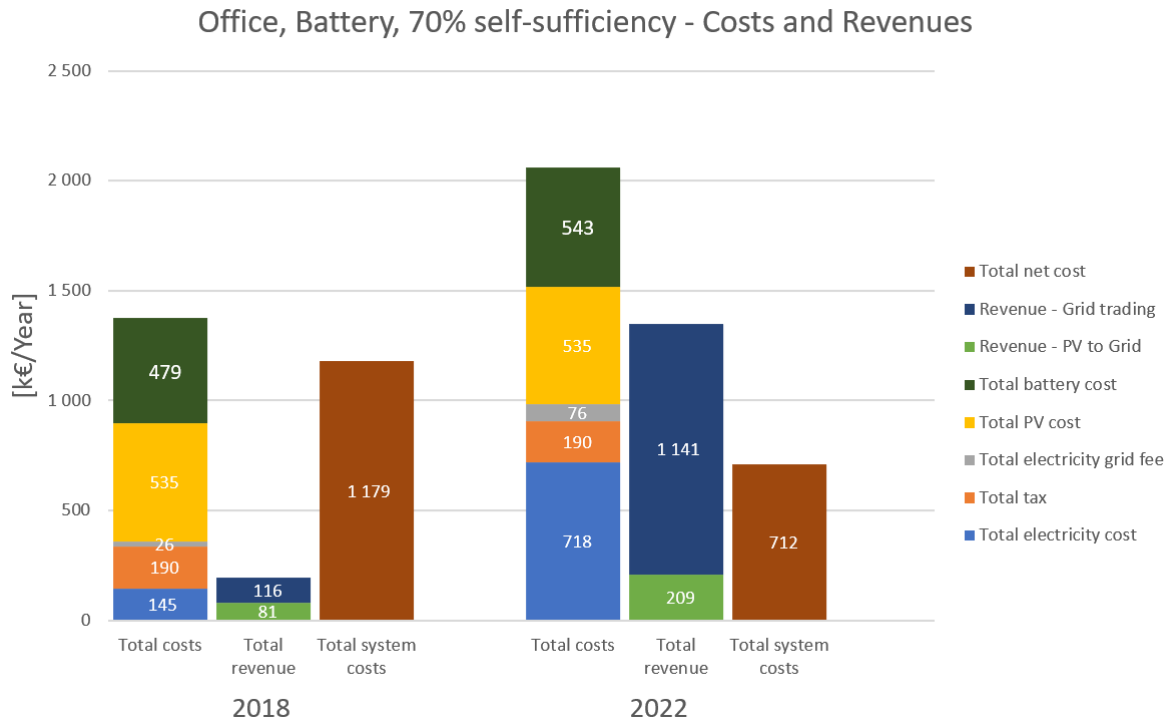


Figure 5.4: Staple diagram of shares in costs and revenues related to the battery model, office case, with 70% self-sufficiency

Figure 5.4 illustrates the total revenues and costs, split up by cost categories and by years, 2018 and 2022. The total system cost is also displayed and this value refers to the summarized costs subtracted by the revenue. First of all, it could be concluded that the costs for the installed solar PV's are the exact same for both years. It is also evident that the largest costs originate from the amount of electricity bought from the grid. In the plotted results, the degree of self-sufficiency is constrained to 70%, which implies that the rest of the demand is fulfilled by bought electricity. Hence, the amount of bought electricity is the exact same in both years. In 2018, the total cost of bought electricity equaled 144 988 €, and 718 440 € in 2022. In Section 4.1, where the electricity prices of 2018 and 2022 are compared, the big differences in the price range are illustrated. This supports the conclusion that it is the spot prices that determine the differences in the total costs of the bought electricity. With the same reasoning, one can also motivate the big change in the revenue value.

The size of installed solar PV's are the same in both cases, 4.8 MW, maximized after the possible installation area. This implied that the amount of excess electricity was also equal. The models using the optimization scenario increase the degree of self-sufficiency also minimized the total system cost. Hence, the model that had the electricity prices of 2022 as an input parameter identified more incentives in creating a business in trading electricity with the grid since the electricity prices were higher this year than in 2018. The model identified revenue potentials and profits that could be obtained by using battery storage and selling electricity to the grid during peak hours. The electricity trade with the grid was also the cause of the increased cost of electricity grid fees. Since the trade was more frequent in the 2022 case, this fee was reaching higher values.

Since the 2022 case provided more revenue opportunities, the model invested in larger battery storage compared to the 2018 case. Even though the size of the invested battery was maximized in 2022, to 10 MWh, the invested size was relatively high even in the 2018 scenario, reaching 8.8 MWh. Due to the slight differences in the invested size, the behavior in the usage of the battery was different in the two cases. This is further addressed in Section 5.3. The different behavior did not only affect the revenue, but one could also see small differences in the amount of tax that was being paid for used electricity in the two cases. However, this difference was considered very small and could thereby be classified as insignificant. Additionally, efficiency losses in the electricity trade between the battery and the grid might also have had an effect on the differences in the tax costs.

In conclusion, electricity prices influence the business potential to a great extent.

The return of investment for the battery was also calculated for the highest possible self-sufficiency degree, which was 70% for the office demand, for the battery model, and prices from 2022. Equations are presented in Section 3.2. The annualized cost for the battery was removed from the yearly system cost

$$714 \text{ k€}/\text{year} - 543 \text{ k€}/\text{year} = 171 \text{ k€}/\text{year} \quad (5.1)$$

and replaced by a single time investment cost.

$$10\,000 \text{ kWh} * 580 \text{ €/kWh} = 5\,800\,000 \text{ €} \quad (5.2)$$

The yearly system cost was compared to the system cost for the reference model 1, resulting in how much money was saved each year

$$989 \text{ k€}/\text{year} - 171 \text{ k€}/\text{year} = 818 \text{ k€}/\text{year} \quad (5.3)$$

The return of investment would therefore be

$$\frac{5\,800\,000 \text{ €}}{818\,000 \text{ €/year}} = 7 \text{ years.} \quad (5.4)$$

5.2.2 Demand profile 2 - Production facility

In the cases generated by the production demand profile, the electricity demand was significantly higher in comparison to the office demand. First of all, it was evident that the demand would always exceed the electricity produced from the solar PV system. Therefore, a facility with such high electricity demand could not achieve complete self-sufficiency and would have to purchase additional electricity from the grid in order to fulfill its demand. Based on the data presented in Table 5.4, the maximum degree of self-sufficiency achievable by the cases that contained the production facility's electricity demand was only 10%. The costs and revenues of this system were analyzed in a similar manner to the office case and are illustrated in the bar chart in Figure 5.5.

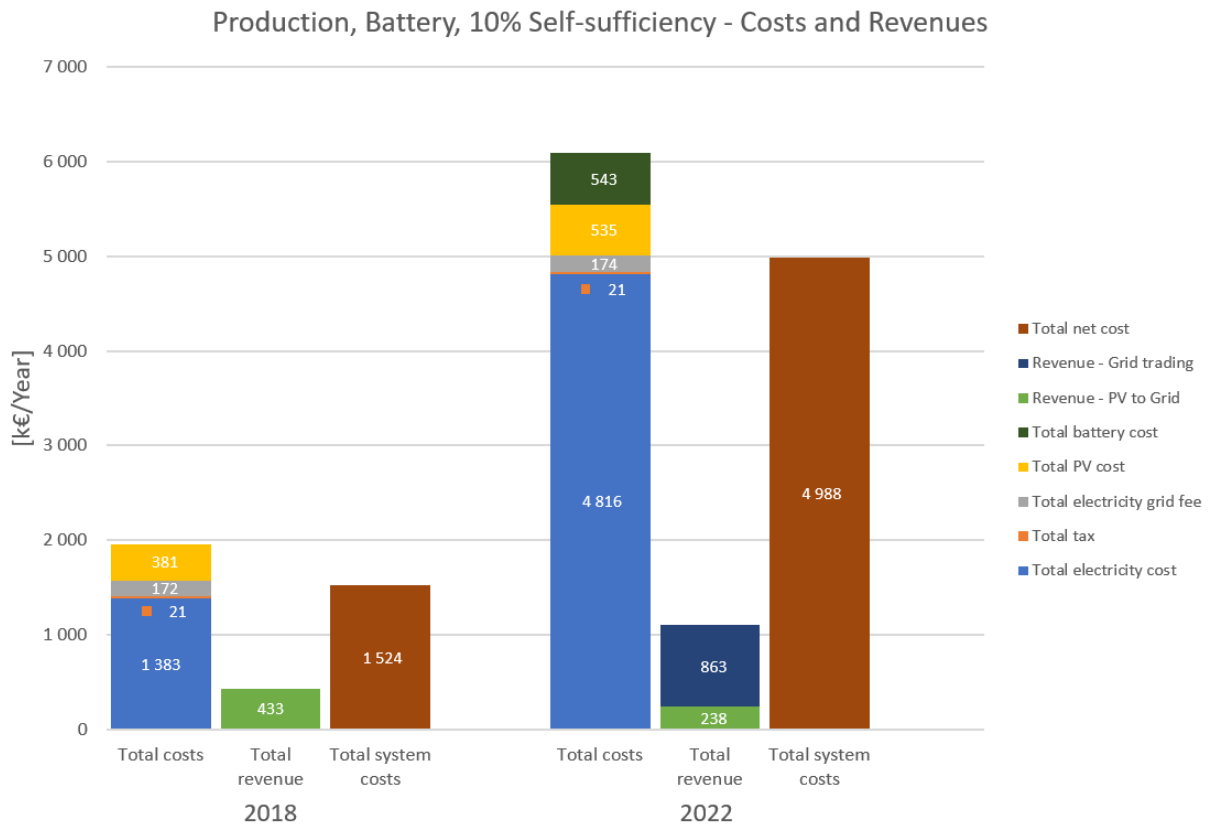


Figure 5.5: Staple diagram of shares in costs and revenues related to the battery model, production case, with 10% self-sufficiency

It could be concluded that the costs in general reached higher values in comparison to the office case. The electricity demand was much higher in this case, resulting in higher costs. From studying the bar chart in Figure 5.5, one could also conclude that the total system cost, unlike the office cases, increased by 3 464 000 € from 2018 to 2022. This was because the total electricity demand was higher for the production facility, and the maximum self-sufficiency degree was lower and fixed to 10%. This implied that more electricity had to be bought from the grid. It was also relevant to consider the distinction in excess electricity. Since the maximum electricity that can be produced by the installed solar PV's did not reach the demand profile, there was no excess electricity and therefore nothing to sell back to the grid, enabling a revenue stream. Instead, the revenue that was present in this case came from electricity bought from the grid during off-peak hours and sold back during times when the spot price was higher. Additionally, the total revenue was even lower than in the office case, as a result of the high amount of bought electricity that was needed to supply the high demand.

Furthermore, it was also relevant to investigate the investment costs related to the solar PV's and battery storage. As shown in the bar chart, no investment in an energy storage system was profitable in the 2018 scenario, and the size of installed solar PV's was optimized to 3,4 MW. In the 2022 scenario on the other hand, the incentives of selling electricity to the grid resulted in a larger investment in battery storage which was maximized to 10 MWh. The solar PV size was also maximized, to 4,8 MW, in the 2022 case.

The return of investment for the battery with 10% self-sufficiency and electricity prices

from 2022 was calculated in the same way as for the office demand (Equation 5.1-5.4). For the production demand, the return of investment for the battery was 6 years.

5.2.3 Demand profile 3 - Warehouse facility

In the warehouse facility, the average demand is, as well as for the production demand, oversized in relation to the installed solar PV capacity in order to be completely self-sufficient. Thereof, the same reasoning gave the conclusion that a facility with this type and size of demand could be up to 30% self-sufficient at most. Figure 5.6 shows the shares in the costs and revenues.

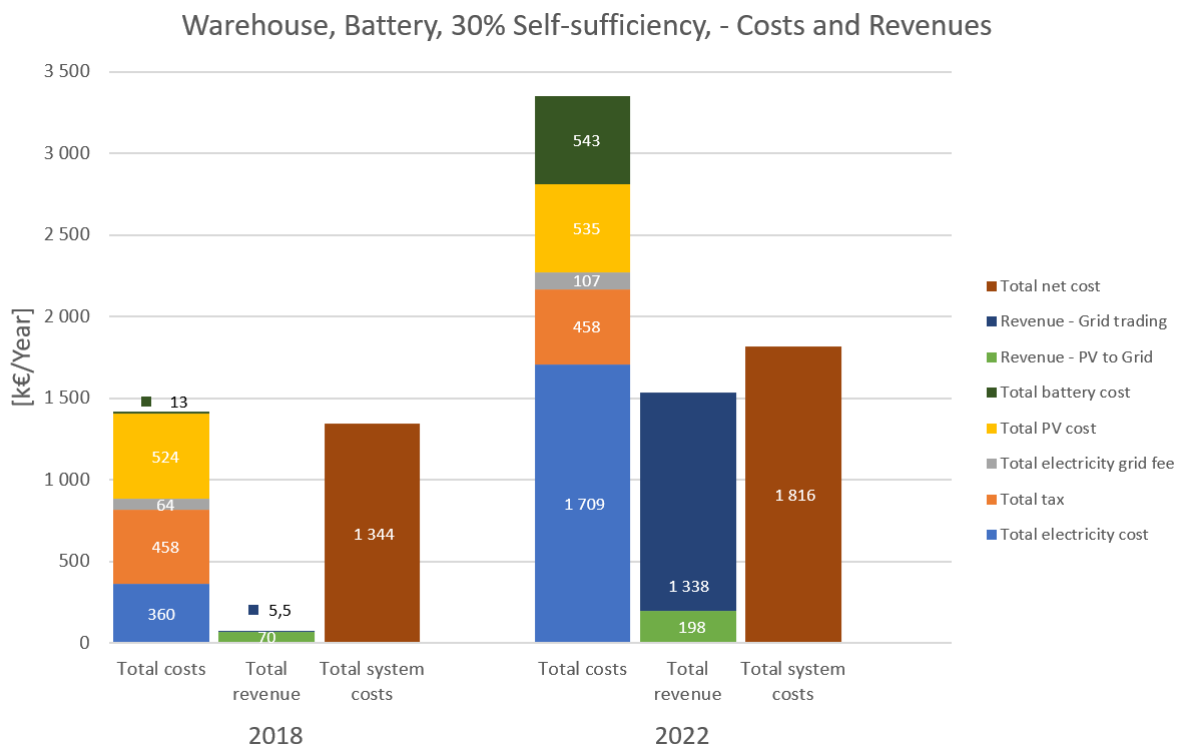


Figure 5.6: Staple diagram of shares in costs and revenues related to the battery model, warehouse case, with 30% self-sufficiency

It could be concluded that this result confirmed the reasoning carried out for the previous cases with the two other demand profiles that have been addressed. Firstly, one could see that the electricity prices still constituted the largest part of the total costs. However, the self-produced solar electricity did at some points exceed the total demand, resulting in excess electricity. This affected the total revenue streams that increased as the electricity prices rose, which created more incentives of trading with the grid. These incentives were also the reason for the model to invest in a larger battery year 2022 compared to 2018, which could be seen from studying the total battery cost in the staple diagram. In the 2018 scenario, the size of the battery reached 844 kWh which in the 2022 scenario was increased to the maximum value of 10 MWh. The battery was not only used for storing self-produced electricity, but also for storing bought electricity. The invested size of solar PV's on the other hand did not differentiate much between the scenarios, ranging from 4,4 MW 2018 to 4,8 MW 2022. Furthermore, even though the revenue streams increased a lot, the total cost was still higher with 2022 prices, once again proving its ability to influence the results.

5.2.4 Comparison of cost structures

From the results presented in this chapter, it could be concluded that the 2022 results were more interesting to discuss. The present volatile electricity prices in 2022 incentivized economically beneficial investments in solar PV's and batteries. Therefore, the cost structures of the reference models as well as for the battery model were plotted in Figure 5.7, for the office demand with electricity prices from 2022.

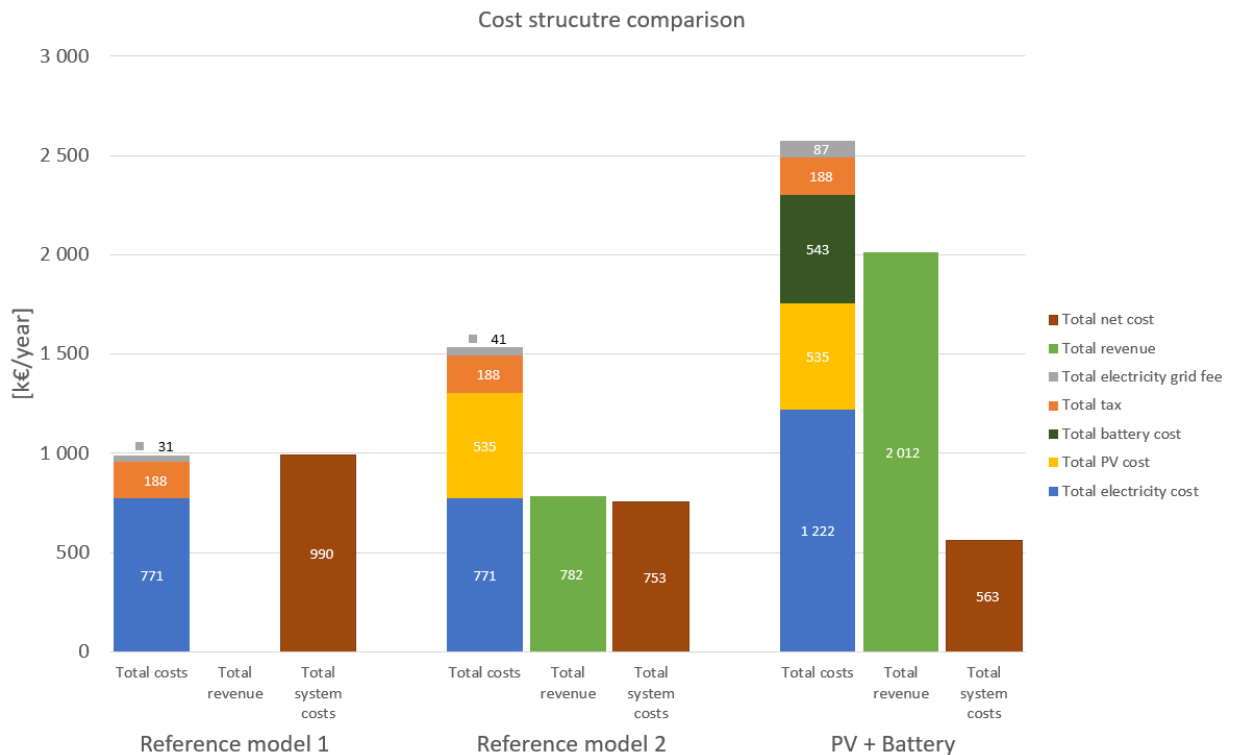


Figure 5.7: Staple diagram of shares in costs and revenues, comparing the reference models with the battery model with the office demand and electricity prices of 2022 as input

A noticeable trend emerged in the rising expenses associated with the investments of Solar PV's and storage systems, as well as the increasing revenues generated from it. Consequently, the total cost of the system decreased. In the case of reference model 1, which follows a business as usual approach and relies solely on purchased electricity from the grid to fulfill its demand, the total cost comprises only the expenses incurred for buying electricity, such as the spot price, tax, and electricity grid fee. In reference model 2, an investment in Solar PV's is made, resulting in a higher total cost, but also providing the opportunity to sell PV produced electricity to the grid, thus generating a revenue stream. Additionally, the battery model's results show another case which provides the possibility of storing electricity in a battery storage system. This followed the same pattern as upgrading from reference model 1 to reference model 2, resulting in a higher total cost due to more significant investments, but at the same time enabling an increased revenue stream, decreasing the total system cost. The conclusion from this is that even though the

investment costs, self-evidently, increases with the extended systems, the revenue stream increases even more, reducing the total system cost.

The return of investment for the battery with 30% self-sufficiency and electricity prices from 2022 was calculated in the same way as for the office demand (Equation 5.1-5.4). For the warehouse demand, the return of investment for the battery was 6 years.

5.3 Model behaviour

In this section, some interesting results and analysis of the model behaviour is presented.

5.3.1 Excess electricity

The ratio between total electricity demand and solar PV capacity was different in each demand, presented in Table 4.2. This affected how much excess electricity the solar PV's produced, which in turn affected if an energy storage was suitable or not. As seen in Figure 5.8, the highest demand; production, was always higher than the electricity supply from the PV's- This implied that there were almost never any excess electricity in this demand case. Excess electricity was present at some points when the solar irradiation was high during the weekends, leaving little room for an energy storage since the supply from the PV's was directly used for the demand. For the other two demand profiles, the situation was different. In both the office and warehouse cases, excess electricity was present almost every day which opened up the possibility to invest in an energy storage.

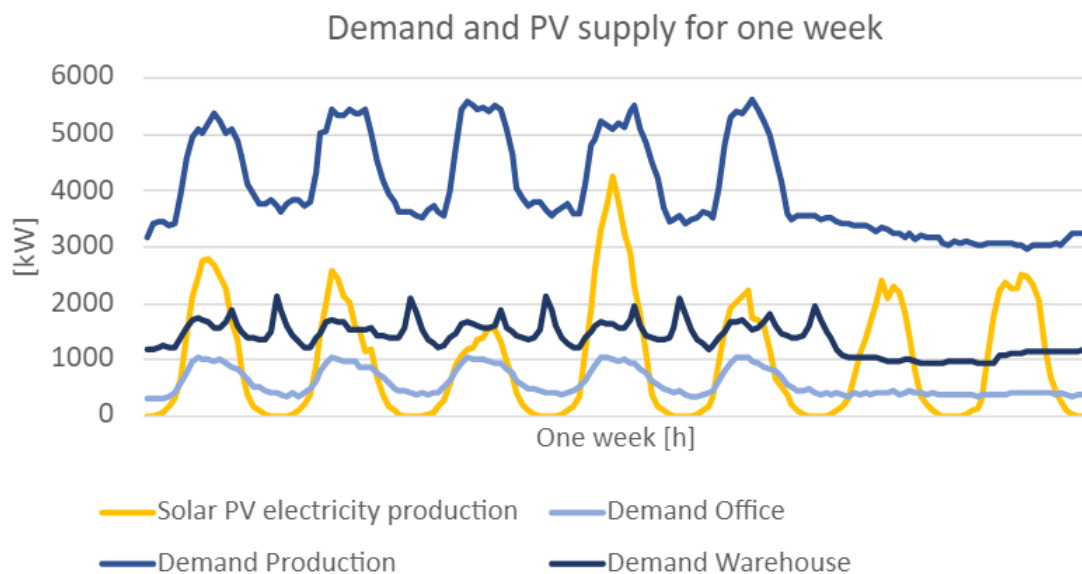


Figure 5.8: Supply of electricity from the solar PV's plotted together with the three demands during a week in May

5.3.2 Dependency on the grid

When plotting the total amount of bought electricity from the grid for the office case, originating from the battery model with 70% self-sufficiency and electricity prices for 2022, an interesting pattern of self-sufficiency degree could be identified. Even if the

model was constrained to be 70% self-sufficient, the demand could at some longer periods reach higher degrees of self-sufficiency, and at some times completely independent of the grid. During spring and summer, the demand could be fulfilled only by utilizing the PV's and the battery, for longer periods of 24, 56, and 30 days in a row. There were five months of the year when the grid was rarely used, see Figure 5.9 for a visualization of this result.

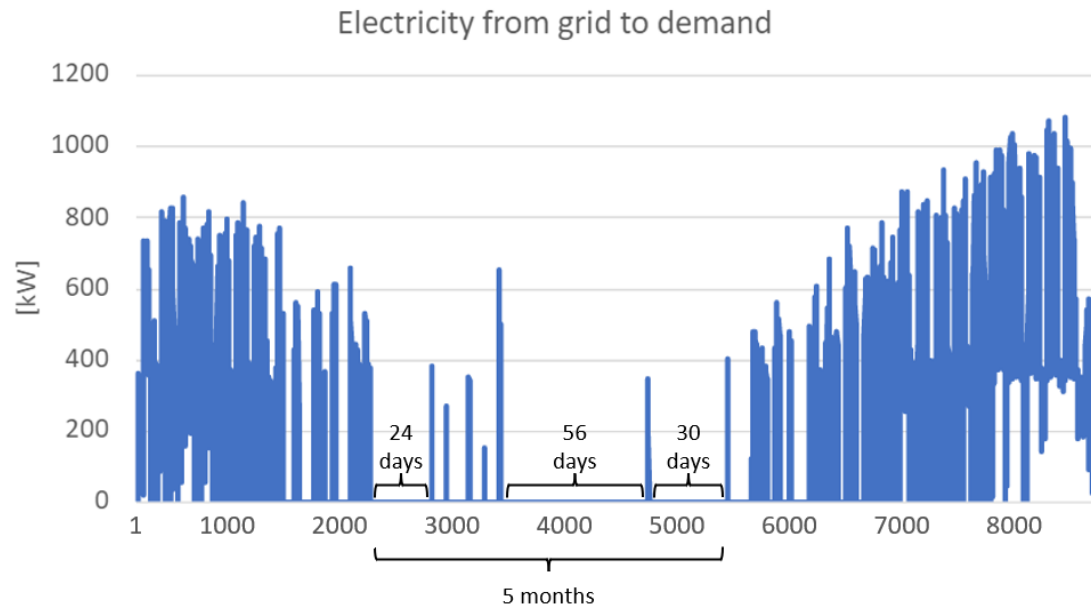
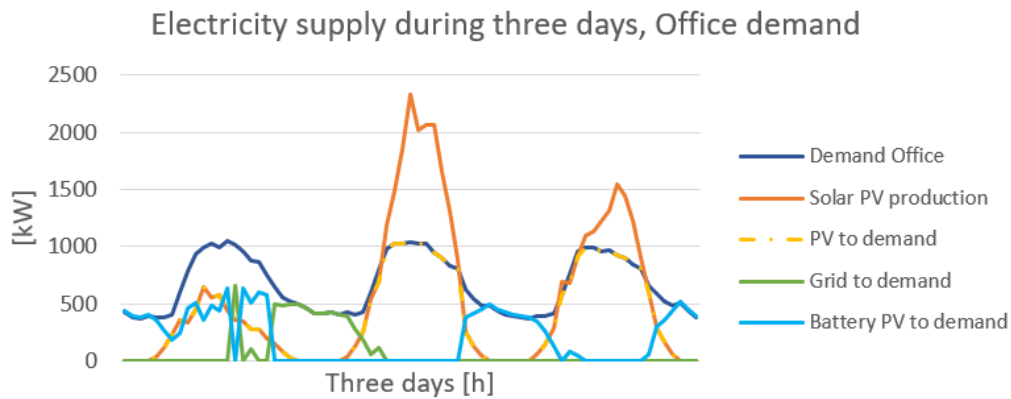


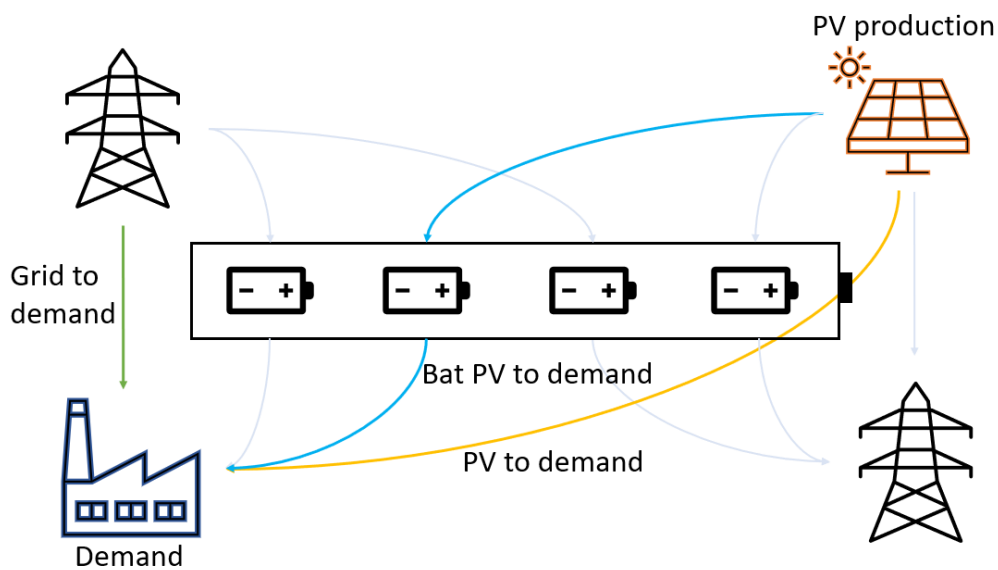
Figure 5.9: Bought electricity from the grid during one year for the case: Office, battery model, 2022, 70% self-sufficiency

5.3.3 Supply pattern

In order to analyze how the supply and demand behaved, Figure 5.10 (a) was created. It shows a plot of the office demand, solar PV production, solar PV production that directly supplied the demand, electricity supply from the grid to the demand, and electricity supply from the battery (that had been charged by solar PV's) to the demand. The electricity flows plotted are highlighted in Figure 5.10 (b). The yellow line in Figure 5.10 (a) is the supply of electricity directly from the solar PV's to the demand. From studying this, it can be seen that the model prefers to match it with the demand if possible. During the first period of the three days plotted, the solar PV's (red line) was smaller than the demand, and therefore the PV supply to demand (yellow line) was exactly the same. The rest of the demand was filled with electricity from the battery and the grid since the PV's could not provide electricity covering the entire demand. During the second and third day, there were more solar irradiation, which resulted in less dependency on the grid. From studying this graph, it can also be concluded that during the days, the PV's can provide electricity to the demand and during the nights, the battery supplies electricity to the demand.



(a) Electricity supply and office demand for three days



(b) Electricity flows plotted in (a) are highlighted with the same colors here.

Figure 5.10: Supply and demand behavior for the office

5.3.4 Cost reductions enabled by the battery

The usage of the battery has been investigated in order to visualize how it can provide benefits with its different flows. As mentioned above, the main objective for the battery is to decrease the total net cost of the system, i.e. minimizing the cost, which the model solves by moving the electricity supply, mitigating peak hours, and trading with the electricity grid. Hence, the battery can be used in four different ways in order to achieve these goals, see Figure 5.11:

- **Grid-to-grid** Buying electricity at hours when the spot price is low and selling it back to the grid during an hour when the spot price is higher. This kind of trading with electricity generates revenue.
- **Grid-to-demand** The model optimizes electricity purchases so that it can mitigate peak hours in the spot prices. Storing electricity in a battery, and utilizing it during these types of hours enables cost reductions. Though, this only works with spot

prices and not fixed electricity prices).

- **PV-to-demand** The battery can enable the utilization of excess electricity by moving parts of the PV supply in order to avoid buying electricity from the grid at night and peak hours.
- **PV-to-grid** The excess electricity can also be stored in a battery and during peak hours be sold to the grid, generating revenue.



Figure 5.11: How the battery can be used in order to reduce costs

5.3.5 Remove the possibility to trade electricity with the grid

From the cost structure breakdowns, it could be concluded that a large part of the revenue came from trading electricity with the grid. This strategy was built upon the model buying electricity when the spot prices were low, stored it in the battery, and then sold it back to the same grid when the prices were high, and thereby generating a revenue. Due to this, it was tested whether the results would change if the trading possibility was removed in the battery model. This was tested for the office demand with electricity prices from 2022 and for three optimization scenarios; minimize cost, 40% and 70% self-sufficient. The cost structure for the results from the battery model and the reference model 2 Only PV, were compared, and the results are shown in Figure 5.12. The total system cost for the battery model became higher when the trading possibility was removed, but the system cost from this model was still cheaper compared to the reference model 2 Only PV. To exemplify this, in the minimize cost scenario, the battery model with trading got the system cost 563 k€/year (from Table 5.2) and without trading 696 k€/year (see Figure 5.12), and the reference model 2 Only PV got the system cost 753 k€/year. Similar trend happened in the 40% self-sufficiency scenario. The conclusion from this was that it was still profitable to invest in a battery even when the trading possibility was removed. However, the system cost of becoming 70% self-sufficient increased from 714 to 1 143 k€/year when trading was removed. It is therefore uncertain if reaching such high degrees of self-sufficiency can be economically justifiable without the revenue from trading.

The total electricity cost in the minimization scenario differed considerably between the battery model and the Only PV model. Both models were almost zero percent self-sufficient since selling the electricity from the PV's generated revenue which minimized the costs, and still the electricity cost was smaller for the battery model. This can be explained by studying the charging behavior of the battery. The battery utilized the fluctuations in electricity prices and charged the battery with electricity from the grid when it was cheap, and discharged it to the demand when the electricity prices were high avoiding price peaks, while selling electricity from the solar PV's. In summary, the electricity flow

from the grid to the battery to the demand helped minimize the cost by avoiding electricity price peaks.

In the minimize cost scenario, the battery was larger than in the 40% self-sufficient scenario. This happened since the battery utilized the grid-battery-demand flow more in the minimize cost scenario than in the 40% self-sufficiency scenario. In the 40% scenario, the demand was fulfilled with less electricity from the grid and thus the battery size decreased. In the 70% self-sufficiency scenario the battery capacity increased since this was the only way of reaching 70% self-sufficiency.

Additionally, the size of the battery was smaller when the trading possibility was removed in all three scenarios compared to when the trading was allowed, going from 10 000 kWh to 4000, 2900 and 8800 kWh in respective scenario. The reduction in size occurred since the maximization (10 000 kWh) of the battery size depended on the revenue that was received from the trading (when electricity prices from 2022 were used). The size 10 000 kWh was set as a physical limit, and if this limit was removed from the models with trading, the size would have been larger because that would have generated an even larger revenue.

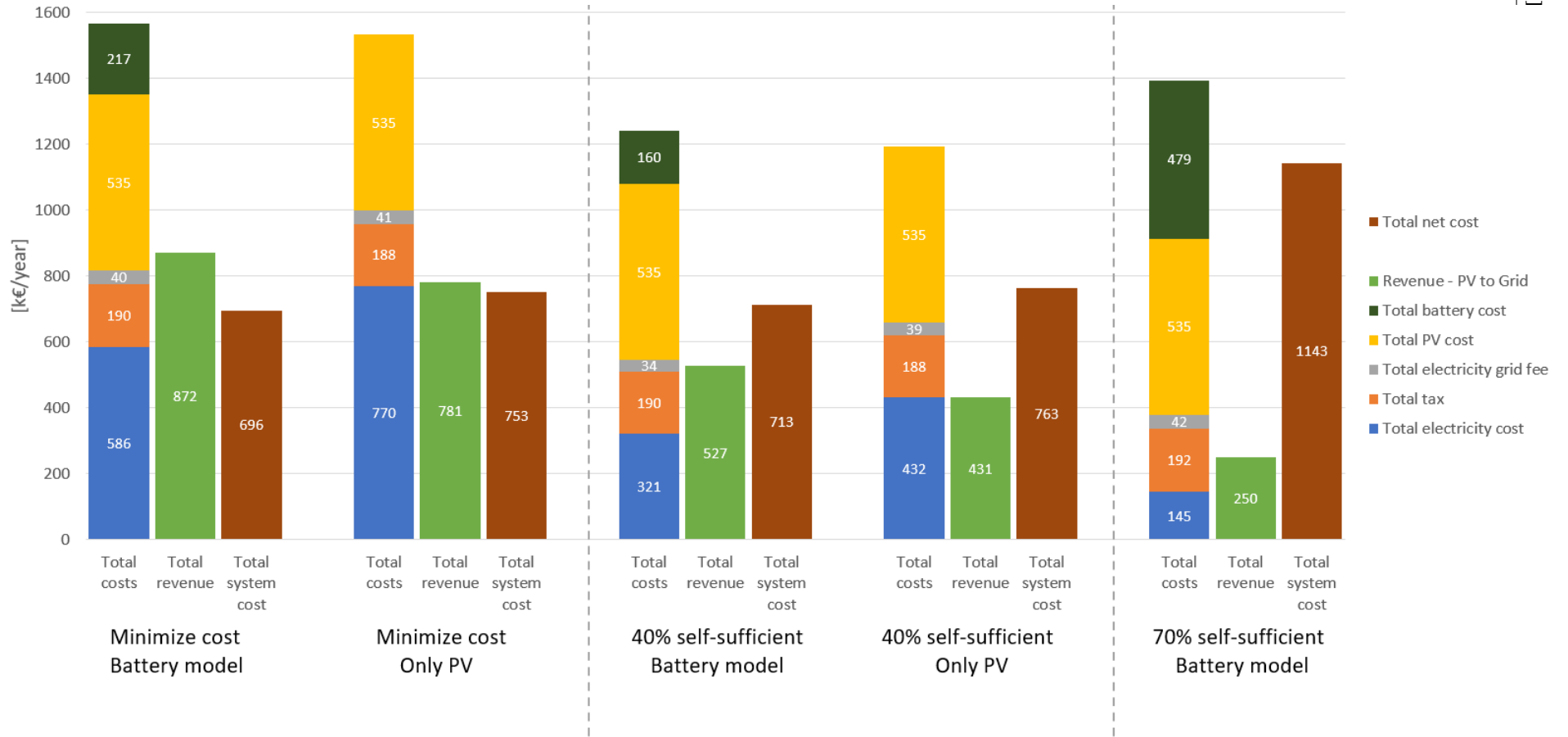


Figure 5.12: Cost comparison between the reference model 2 Only PV and the battery model for three optimization scenarios (minimize cost, 40% and 70% self-sufficiency) when the grid to grid charging of the battery was removed. The office demand and electricity prices from 2022 were used.

5.4 Future scenarios

In this section, the results regarding the future scenarios that have been investigated are presented.

5.4.1 Changes in taxes and tariffs

Two changes in taxes and tariffs were tested, primarily as a future scenario analysis, but also as a sensitivity analysis. The changes were made on the battery model, with the office demand, 70% self-sufficiency and electricity prices for 2022.

This first change was the removal of the the grid tariff compensation, which did close to nothing when comparing the results to the original case. When the grid tariff compensation was removed, the revenue decreased with roughly 35 000 €, which was the same value that the total cost of the system increased with. The second change was removing the energy tax for electricity from the PV to the demand. This changed the results such that the total cost decreased with about 134 000 €. See Figure 5.13 for comparison with the original case. The trends of the results from both the removal of the grid tariff compensation and the energy tax would be the same for all models, i.e.,

- When removing the grid tariff compensation, the total revenue decreases and the total system cost increases
- When removing the energy tax obligation on electricity from PV to demand, the total costs decreases, resulting in a decrease of the total cost

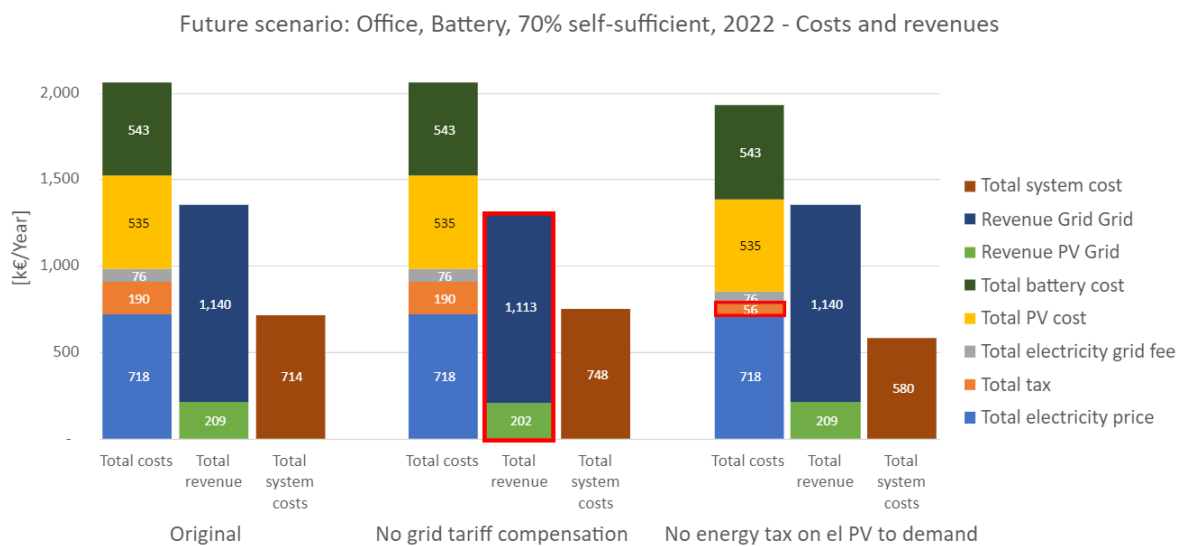


Figure 5.13: No grid tariff compensation and removing tax on electricity from the PV to demand compared to the original case for office, battery model, 70% self-sufficient and electricity prices from 2022. Changes outlined with red.

6

Discussion

6.1 Scope

Due to time limitations, the geographical scope that was chosen in this thesis was region SE3 in Sweden. Some of the parameters were chosen according to this scope, but if there would be objectives for customizing the model to other regions, it would be fully possible with some modification. Furthermore, the models that have been created can also be adapted to future changes in taxes, tariffs, and electricity prices with the same types of modifications. This makes them applicable in several use cases all over the world at different times. Since solar irradiation is very dependent on seasonal weather changes in Sweden it would be of interest to analyze other solar irradiation profiles from other parts of the world to see how that would affect the results.

The demand profiles tested represented three real facilities. However, there exists many more electricity demand patterns and it is also possible to modify the models according to new demands in order to customize the framework and output.

In this thesis, spot prices were used as electricity prices. In reality, many companies have fixed electricity prices when they buy electricity from the grid, not spot prices. This would affect the trading and potentially decrease the revenue since it would not be possible to utilize the fluctuations to the same extent, even though selling back to the grid would be to spot prices. Changing the electricity prices in the models in order to customize it would be possible.

6.2 The foundation of the models

The models were based on a linear optimization with perfect foresight of the three parameters electricity price, electricity demand, and solar irradiation for every hour of the year. The models gained a lot from this perfect foresight which enabled them to optimize the solution in a way that is not the case in reality. In reality, it is significantly more difficult to know these three parameters for certain and in detail. Therefore, it is important to keep this in mind when analyzing the results since it would be a different situation to optimize the same system in reality, compared to the way these models does it.

In reality, the revenue from the grid-to-grid battery could for example be lower since it can be difficult to perfectly optimize the trading. Since the grid-to-grid battery stand for the largest part of the revenue, this could influence the results depending on the timing of the trading. But, as shown in Section 5.3.5, investing in a battery without trading is still more economically beneficial than only having PV's (for spot prices 2022), and therefore investing in a battery without perfect trading would then still be economically

beneficial. Additionally, Nord Pool presents the electricity prices 24h ahead which helps increase the revenue from trading if applied in reality. The electricity demand pattern is often quite repetitive and the peaks are often not surprising which helps in planning the supply. Solar irradiation also follows certain patterns over the day and over a year, and weather forecasts can help in knowing how the solar PV's will perform at least some days ahead. In summary, the perfect one-year foresight that the models have helps minimize the costs, but it is not impossible to reach similar results in reality with some planning and prediction.

6.3 Flexibility services

As presented in Section 2.4.4, energy storage can provide flexibility services to the grid and, by doing so, gain revenue from it. However, this was excluded from the model due to time limitations. Since the GAMS model built for this master thesis had an hourly resolution it was difficult to include flexibility services since flexibility is often required on a minute basis. If flexibility services would be applied, additional revenue from the battery can be expected.

6.4 Area for solar PV installation

Office buildings and warehouse facilities have distinct architectural structures due to their respective functions. Office buildings are typically constructed on smaller surface areas with more levels, while production and warehouse sites are usually larger with only one level and it can therefore be argued that an office facility has a smaller roof resulting in a smaller area available for solar PV's. In this thesis, the same area was however chosen for all demands. The benefit of that choice was that the ratio between total electricity demand and solar PV capacity became different in all demand cases, presented in Table 4.2. One important aspect of the profitability of energy storage that was found in this thesis was the amount of excess electricity. The amount of excess electricity is directly linked to the *ratio between total electricity demand and solar PV capacity*. Keeping the same area for all demands has therefore given an estimation of what the ratio should be in order to utilize the energy storage system as efficiently as possible, and the results showed that the larger the ratio is, the more one can gain from energy storage. Additionally, solar PV's can be installed on a facility's parking space or other nearby area, hence, the area of the roof does not have to be the decisive factor when considering the area available for solar PV installations.

6.5 Ratio solar PV/demand

It was found that the amount of excess electricity decided how profitable an energy storage was, as well as how self-sufficient one could get. The ratio of yearly PV production divided by the total yearly demand, Equation 4.2, for the office facility was 0.98, where the solar PV's produced 4.9 GWh and the demand was 5 GWh. The highest possible self-sufficiency degree was however only 70%. It can seem like the self-sufficiency degree potentially could reach a higher level due to the ratio of 0.98. This can be explained by seasonal variations. During the summer, there was a lot of excess electricity, and during the winter, there was a deficit in PV electricity. To balance this to a higher degree than 70%, a larger battery would be needed. Thus, it would be possible to reach a higher self-sufficiency degree but it

would come at a higher cost since the battery would need to be larger.

6.6 Cable capacity

The cable capacity between the electricity grid and the facility has been taken into consideration by applying a power fee in the models, Equation 3.13 and 3.14. If the facility invests in a battery and buys more electricity from the grid than it did before, they have to pay a higher power fee. Additionally, when the facility starts selling electricity back to the grid, a power fee is added. In reality, it would also be necessary to make sure the contract with the electricity trading company allows for a higher power output or if a new contract is needed for this increase.

6.7 Sensitivity analysis

In order to discuss the validity of the results presented in this master thesis, a sensitivity analysis has been conducted. The main purpose of it is to address the uncertainties regarding future scenarios and how the development of the electricity and hydrogen market might affect the results.

6.7.1 Future of hydrogen

According to the research presented in Section 2.3.6, the market price of hydrogen is predicted to decrease. In a future scenario in Sweden, the cost estimation of hydrogen is set to approximately 5,5€ [58] which is approximately 50% of the price of today's price. Predicted to decrease is also the production cost of hydrogen. The presented research indicated a predicted decrease of 50% for the production costs of hydrogen, also addressed in Section 2.3.6. On top of this, there is also an emerging rise in the hydrogen demand which will result in greater incentives to become a hydrogen producer. In order to analyze such a scenario, i.e. extracting results from a model that directly sells the hydrogen to a demand, expressed in Figure 3.7, one would apart from a predicted market price of hydrogen, also need additional data. In that linear optimization, data such as actual hydrogen demand would be needed, along with other costs related to the transport and transfer of the hydrogen. The research made in this field is limited, and therefore there is a lack of such cost predictions.

While it is technically feasible to create a linear model that generates predictions for the future, the many uncertainties outlined above make it impractical to pursue an el-H₂-use model. Therefore, future predictions are based on the research presented in Section 2.3.6. Hydrogen technology is considered of being immature. However, one can see that the research that has been made in the field shows that the production price and the market price will both decrease equally. This implies that the potential revenue that can be obtained from producing and selling hydrogen will be the same as it is today. The total demand, on the other hand, will increase remarkably as a result of new laws and climate strategies being implemented all over the world. And what's even more important is that there will be an especially high demand for green hydrogen, such as the one produced by solar PV electricity in an electrolyzer. The result of this might be that the total revenue stream can be extended, and the market price can also be raised if the demand is larger than the supply.

6.7.2 Taxes and tariffs

The taxes and tariffs affecting the electricity trade are also an uncertain parameter. Therefore, the results presented in this master thesis should only be seen as potential outcomes that may be used as guidelines and recommendations for future business cases.

If the amount of electricity producers increases significantly, there is a risk of overloading the grid, which is limited by the physical cables that facilitate electricity trading. The grid tariff compensation might therefore not be as favorable in the future as it is today. The capacity threshold at which the electricity grid gets overloaded has been excluded for further investigation within this master thesis, but a sensitivity analysis on how a removed grid tariff compensation would affect the results was done, presented in Section 5.4. It demonstrates that the total system cost did not change significantly when removing the grid tariff compensation, indicating that the findings of this master thesis remain reliable even in future scenarios when the taxes and tariffs change.

The energy tax, on the other hand, is predicted to become more favorable for renewable energy producers in the future. Looking back at how these numbers have developed over the past years, one can identify a trend in the installed capacity allowed to invest, without the obligation to pay any energy tax. As mentioned in Section 3.5.2 the tax exemption rose from 255 kW installed PV capacity to 500 kW installed capacity in 2021, and this increasing amount of allowed maximum capacity will most likely look similar in the future. This implies that the number of small energy producers, that are below the allowed largest installed capacity, will increase since there will be more incentives for becoming more self-sufficient, both for companies and private actors. This is mainly because these types of energy producers are excluded from the energy tax obligation. In order to investigate the degree of impact that the energy tax has on the total result, a model without energy tax was run, with results presented in Section 5.4. Here, the energy tax obligation was entirely removed on the electricity that was both self-produced and used by the producer themselves. From this, it could be concluded that in such scenarios it could become even more profitable to invest in solar PV's, and potentially also storage systems, meaning that the results within this thesis would be even more favorable in that sense.

6.7.3 Electricity prices in the future

The electricity prices in 2022 in Sweden were exceptionally high and fluctuating due to different circumstances around the world. The prices are however expected to go down within a couple of years. It is therefore important to keep in mind that the results from the cases with electricity prices from 2022 might not be as relevant in the future if prices go down. The results also showed that the cheapest way of fulfilling the electricity demand with prices from 2018, no matter the demand, was by only utilizing the grid. The CAPEX of solar PV's had to decrease by 55% in order for the models to invest in PV's with 2018 prices. According to the Danish Energy Agency, the CAPEX of solar PV's for commercial buildings will have decreased to that level in the year 2040. Additionally, the economics of an investment is not the only value to consider when installing solar PV's and energy storage since these components provide self-sufficiency of electricity, which can be valuable as well.

6.8 Investment model

The investment costs were annualized to fit the properties of GAMS. When an investment is done in reality, a loan is often used to cover the expenses. Depending on the investment model used, the numbers in the results might differ if the method in this thesis would be applied in a real case.

6.9 Island mode

To get an idea of how much larger the solar PV area and the battery had to be in order for the Island mode to be feasible, two scenarios were tested.

1. No restriction of either area for solar PV's or battery storage capacity
2. Double the battery capacity and no restriction on the area for solar PV's

This was only tested for the office demand, since this was the smallest demand, and the result for the larger demands would only generate bigger numbers and even more unreasonable results. The results are presented in Table 6.1. Neither of the two scenarios gave results that would be reasonable to apply in reality.

Table 6.1: Changes that would be needed for the Island mode to be feasible, for the office demand. Area reference is the area needed in number of football fields. Battery size reference is in number of 40ft containers that would be required.

	1. No restrictions	2. Restrict battery, no solar PV restriction
Needed area	30 102 m ²	1 157 000 m ²
Area reference	4 football fields	162 football fields
Battery capacity	1 362 000 kWh	20 000 kWh
Battery size reference	540 containers (40ft)	8 containers (40ft)

7

Conclusion

These are the main conclusions in this thesis:

- Battery storage was cheaper than hydrogen storage for all three facilities investigated.
- For a battery storage system to be *economically* beneficial, the electricity prices had to be high and fluctuate (year 2022). When this was the case, it was economically justifiable to invest in a battery that could help avoid peak prices, and gain revenue from trading electricity with the grid. With the high electricity prices of 2022, becoming self-sufficient was cheaper than only fulfilling the demand with electricity from the grid.
- When the electricity prices were low (year 2018) it could still be valuable to invest in solar PV's and battery storage for a large facility if self-sufficiency and becoming a "green facility" was viewed as more important than lowering the costs.
- The amount of excess electricity (i.e., when the solar PV's are producing more than the demand) decided how high the degree of self-sufficiency could reach when combined with energy storage. The more excess electricity from solar PV's a facility had, the more self-sufficient it could get.
- Due to the seasonal variations of generation from solar PV's in Sweden it is not possible to be 100% self-sufficient in electricity production, i.e., Island mode, within reasonable limits of solar PV area and capacity of the energy storage.

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A

Appendix A - Figures

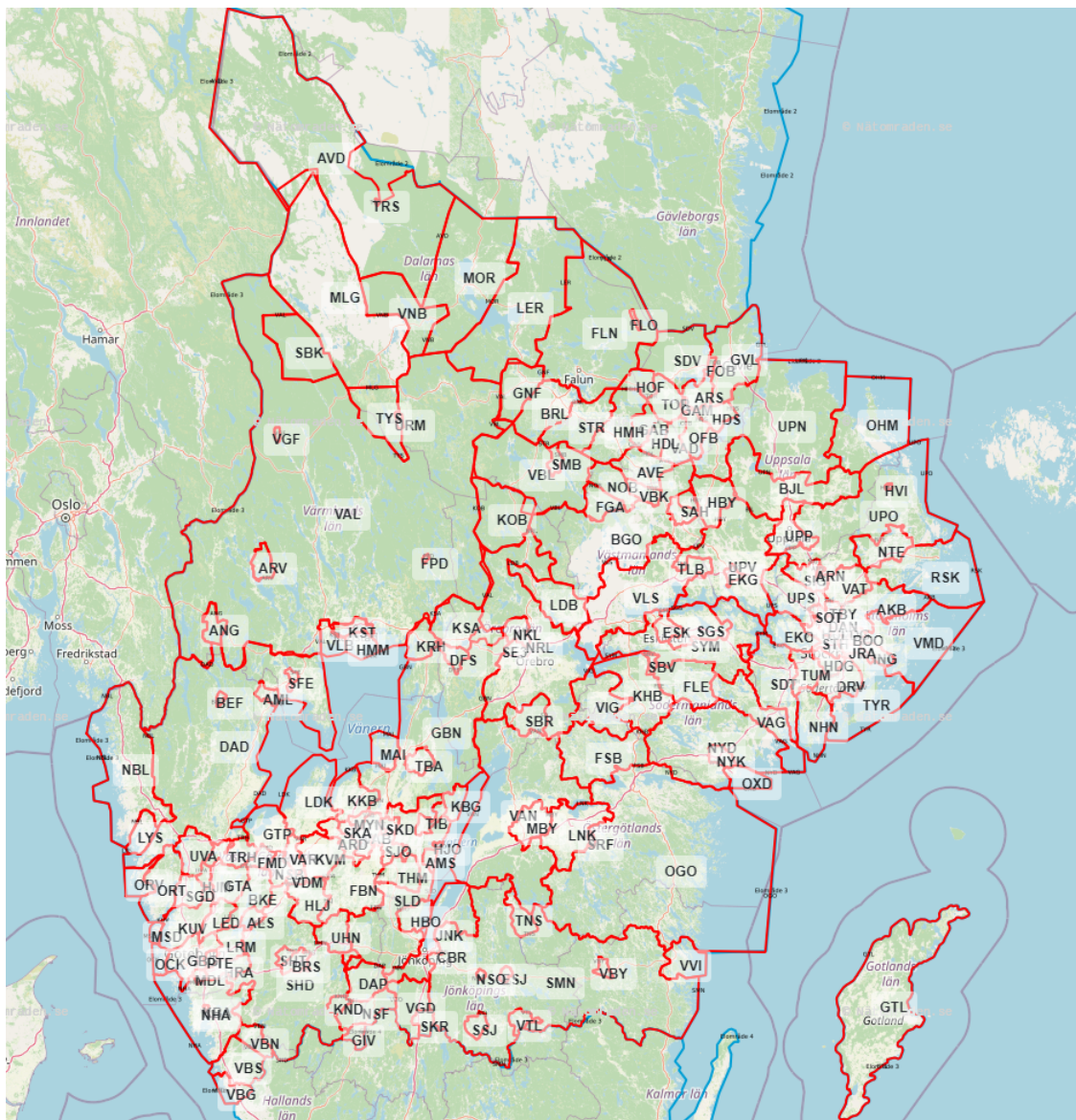


Figure A.1: Electricity grid operators in SE3 region of Sweden [66].

B

Appendix B - The Hydrogen Model

The model is a linear cost optimization model made in GAMS, based on the optimization ground to minimize the total cost of the system. In the following sections indices, sets, parameters and variables are presented. These are then used when describing the constraints and objective function which will be described for both the el-hydrogen-el model and el-hydrogen-use model.

Indices

t	Index for time step
i	Index for technologies
a	Index for flow directions entering the hydrogen system
b	Index for flow directions leaving the hydrogen system

Sets

\mathcal{T}	Set of hours of one year: {1:8760}
\mathcal{I}	Set of technologies: {PV, electrolyser, storage tank, fuel cell}
\mathcal{A}	Set of flow directions entering the hydrogen system: {GH, PVH}
\mathcal{B}	Set of flow directions leaving the hydrogen system: {HD, HG}

Parameters

PV_t	Solar irradiation profile in SE3 for every hour of the year
elp_t	Electricity price for every hour of the year
D_t	Electricity demand for every hour of the year
$areaPV$	Available area for solar PV installation
$instArea$	Installable area for solar PV installation [%]
p	Power-per-m ² for solar PV installation
tax	Electricity tax
gtc	Revenue from grid tariff compensation
u	Revenue from certificate of origin

$EgfB$	Electricity grid fee for bought electricity
PfB	Power fee for bought electricity
$EgfS$	Electricity grid fee for sold electricity
PfS	Power fee for sold electricity
$CAPEX_i$	CAPEX of technology i
$OPEX_i$	OPEX of technology i
ins_i	Installation cost of technology i
fix_i	Fixed O&M of technology i
l_i	Lifetime of technology i
r	Interest rate for annualization
a_i	Annuity factor of technology i
η_i	Efficiency of technology i
$degSelf$	Degree of self-sufficiency*

Variables

$size_i$	Installed size of technology i
SOC_t	State of charge of the hydrogen storage in time t
$charge_{t,a}$	Charging of the hydrogen storage in time t
$discharge_{t,b}$	Discharging of the hydrogen storage in time t
$supplyG_t$	Supply of electricity from the grid to the demand in time t
$supplyPVD_t$	Supply of electricity from the PV's to the demand in time t
$soldPV_t$	Sold electricity from the PV's to the grid in time t
$highestSold$	The hour that the system sells the highest amount of electricity
$highestBought$	The hour that the system buys the highest amount of electricity
$cost$	Total cost of the system

Constraints: el-hydrogen-el model

$$size_{PV} * PV_t = supplyPVD_t + soldPV_t + charge_{t,PVH} \quad (B.1)$$

$$supplyGD_t + supplyPVD_t + discharge_{t,HD} * \eta_{storage} * \eta_{fc} \geq D_t \quad (B.2)$$

$$SOC_{t+1} = SOC_t + charge_{t,a} * \eta_{electrolyser} - discharge_{t,b} \quad (B.3)$$

$$charge_{t,a} \leq size_{electrolyser} \quad (B.4)$$

$$size_{electrolyser} \leq size_{storage} \quad (B.5)$$

$$discharge_{t,b} \leq size_{fc} \quad (B.6)$$

$$SOC_t \leq size_{storage} \quad (B.7)$$

$$size_{PV} \leq area_{PV} * p * instArea \quad (B.8)$$

$$highestSold \geq sold_{PV_t} + discharge_{t,HG} \quad (B.9)$$

$$highestDemand \geq supply_{GD_t} + charge_{t,GH} \quad (B.10)$$

$$degSelf = \sum_t (supply_{PVD_t} + charge_{t,PVH} * \eta_{elec} * \eta_{storage} * \eta_{fc}) / \sum_t D_t \quad * \quad (B.11)$$

(B.1) The electricity produced by the solar PV's has to be equal to the three electricity flows leaving the PV's going to; the demand, the grid and to the hydrogen system at all hours of the year.

(B.2) The supply of electricity has to be greater or equal to the demand at all hours of the year.

(B.3) Balancing the state of charge of the hydrogen storage tank.

(B.4) Limiting the charging of the hydrogen storage to be smaller or equal to the size of the electrolyser.

(B.5) Limiting the size of the electrolyser to be smaller or equal to the size of the storage tanks.

(B.6) Limiting the discharging of the hydrogen storage to be smaller or equal to the size of the fuel cell.

(B.7) Limiting the state of charge of the hydrogen storage to be smaller or equal to the size of the storage.

(B.8) Limiting the size of the installed solar PV's to be less or equal to the area available for solar PV installation times the power-per-m² for solar PV times the percentage of the area that is installable.

(B.9) Finding the highest amount of electricity sold to the grid.

(B.10) Finding the highest amount of electricity bought from the grid.

* (B.11) Deciding what percentage of the electricity produced from the solar PV's that has to be used in the demand.

* *Added in the increase self-sufficiency degree scenario*

Objective function: el-hydrogen-el

$$\begin{aligned}
 \text{minimize } cost = & \sum_t \left(\left(supplyGD_t + \sum_a discharge_{t,HD} + supplyPVD_t \right) * tax \right. \\
 & + \left(supplyGD_t + charge_{t,GH} \right) * elp_t \\
 & - \left(soldPV_t + discharge_{t,HG} * \eta_{storage} * \eta_{fc} \right) * \left(elp_t + gtc \right) \\
 & \left. - soldPV_t * u \right) \\
 & + \sum_i size_i * \left(\left(CAPEX_i + ins_i \right) * a_i + OPEX_i + fix \right) \\
 & + EgfB + EgfS + PfB * highestDemand + PfS * highestSold
 \end{aligned} \tag{B.12}$$

(B.12) Minimize the total cost of the system (see Table 3.2). The total cost consists of:

- + energy tax on electricity bought from the grid and electricity produced by solar PV that is used by the demand (for PV installations > 500 kW)
- + electricity price for the electricity bought from the grid
- revenue (spot price and grid tariff compensation) from sold electricity to the grid
- revenue from certificates of origin generated by sold electricity originating from the solar PV's
- + CAPEX, installation cost, OPEX and fixed O&M for the components
- + electricity grid fees

C

Appendix C - Sizes of components in the hydrogen system

Table C.1: Sizes of elektrolyzer, H₂ storage and fuel cell in the four cases where a hydrogen system was invested in

Demand and year	Scenario	Elektrolyzer [kW]	H₂ storage [kWh]	Fuel cell [kW]
Office 2018	50% self-sufficiency	256	1131	87
Office 2018	60% self-sufficiency	1400	5292	382
Office 2022	50% self-sufficiency	318	1454	101
Office 2022	60% self-sufficiency	1470	5841	405

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