CHALMERS
UNIVERSITY OF TECHNOLOGY

Strategic Charging of Electric Vehicles in Public Parking Areas

Optimized charging strategies of electric vehicles from a parking area operator perspective

Master's thesis in Energy Technology

Filip Björklund
Jonathan Ekström

Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022

Strategic Charging of Electric Vehicles in Public Parking Areas

Optimized charging strategies of electric vehicles from a parking area operator perspective

Filip Björklund
Jonathan Ekström

Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
Gothenburg, Sweden 2022

Strategic Charging of Electric Vehicles in Public Parking Areas
Optimized charging strategies of electric vehicles from a parking area operator perspective

Supervisor: Reza Arababadi, AFRY
Examiner: Mikael Odenberger, Department of Space, Earth and Environment

Department of Space, Earth and Environment
Division of Energy Technology

Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in LaTeX
Gothenburg, Sweden 2022

Abstract

As part of current climate change, with focus on the reduction of green house gas emissions, the automotive industry is shifting from internal combustion engines (ICEs) to electric motors. As of 2021, in Sweden, around 45% of all newly registered vehicles are electric vehicles and it is expected that this share will increase in the future [1]. The electrification that society faces also creates challenges to the current electricity systems in place as new loads are introduced. This will not only mean there is a need to expand the current electricity generation and grid, but also that electricity has to be used smarter.

This master's thesis investigates possible advantages with implementing smart charging strategies in parking areas. A linear programming model was developed to evaluate the aggregated EV charging load in a parking garage located in central Malmö, Sweden. Real parking data on incoming and outgoing vehicles, i.e. over 8000 registered parking events in September 2021, is used as a case study allowing for one month of parking need to be analyzed. There are four cases that are compared, each with a distinct objective. The first case is a reference case in which charging is undertaken as quickly as possible, i.e. restoring the state of charge (SOC) as soon as possible directly upon arrival. Remaining cases optimizes economical aspects, where the second case minimizes the cost of grid connection capacity and the third case minimizes the cost of electricity given the spot prices on the electricity market for the investigated period. The fourth and final case is a combination of cases two and three with the purpose of minimizing the total cost. These cases were also subjected to different scenarios; a base scenario that reflect the parking garage today, a scenario with an assumed integrated solar PV system, and a scenario with Vehicle-to-Grid (V2G) implemented. Finally, a scenario investigating the impact from electricity prices in terms of grid connection capacity and value of solar PV.

Results show that smart charging may reduce the peak capacity of this parking garage by just over 70%, given a suitable governing algorithm. Given the assumptions on entrance and target SOC levels the parking area should be able to be operated in an off-grid mode without grid power supply, i.e. all charging is made from incoming EVs that have higher entrance SOC than target SOC. Avoided grid costs could in such case be used to reimburse vehicle owners for discharging some electricity to other vehicles and get free parking or even make money from parking. Case 4, minimizing the total cost, resulted in a large transferable capacity. The large capacity was used to turn a profit from arbitrage transactions and the selling of excess electricity stored in EVs entering the parking garage. A PV system can be introduced to reduce the cost of purchased electricity and peak demand, with greatest effect on the cost of purchased electricity. In current economical pricing model there are larger potential savings in using electricity in-house than selling it to the grid, which means that the savings found in this study should be larger with increasing electricity prices.

Keywords: Electric Vehicles, Charging Strategy, V2G, PV, Smart Charging, Peak Shaving, Aggregated Charging

Acknowledgements

We would like to thank our supervisors Reza Arababadi and Joachim Wallenstein at AFRY for guiding us throughout the thesis work. They have been providing us with understanding on electricity pricing and PV system installations, along with challenging our assumptions. We would also like to thank P-Malmö for providing us with the data to build our model from. Lastly, we want to thank our examiner Mikael Odenberger who has helped us immensely throughout the thesis work with both modeling expertise and thoughtful discussion.

Filip Björklund, Jonathan Ekström

List of Definitions

BESS - Battery Energy Storage System
BEV - Battery Electric Vehicle (non-hybrid)
DSM - Demand Side Management, i.e. benefits from using electric vehicles charging flexibly to reduce curtailment of renewable energy sources.
DSO - Distribution system operator, e.g. Göteborg Energi
EV - Electric Vehicle
ICE - Internal Combustion Engine
PHEV - Plug-in Hybrid Electric Vehicle
PV system - (Solar) Photovoltaic system
Smart charging - Charging strategy that determines when EVs are charging or not, with the aim of providing some type of benefit.
SOC - State of Charge
SPV-EVCS - Solar PV Electric Vehicle Charging Strategies.
V2G - Vehicle-to-Grid, in this report this is a broad definition which also entails Vehicle-to-Vehicle (V2V).
vREs - Variable Renewable Energy, typically solar or wind.

Contents

List of Figures

List of Tables

1

Introduction

1.1 Contextual Background

One of the major challenges today is undoubtedly the transition to a more sustainable society. In 2015 the Paris Agreement was signed by 197 countries with the purpose of defining future ambitions within sustainability and reducing their climate impact [3]. The Swedish government has even tightened the goals agreed upon in the Paris Agreement and created a more ambitious plan - that the transport sector should reduce its emissions by 70% compared to its' emissions in 2010 by 2030 [4]. One measure to achieve this goal is increasing the fleet of electric vehicles (EV) which in turn leads to more pressure on the electricity producers to supply more whilst having emission regulations tightened.

In addition to the ambition of lowering emissions in the transport sector, Sweden is also set for becoming zero net emissions of greenhouse gases by 2045 [4]. Electricity generation has therefore seen rapid changes towards wind- and solar power in recent years [5], [6]. There is however an issue with these types of variable renewable energy sources (VRE); they are driven by nature and non-dispatchable. For the electricity system to function well the generation must always meet the demand. Meeting the demand combined with an increasing level of variable electricity production such as wind and solar creates a need for load management. The imbalance in the system can, for instance, be solved either by having complementary generation units to VRE or by shifting the loads, also known as demand side management (DSM). Charging of EVs is one such load that can make use of DSM, which in this report will be investigated in terms of limiting the strain on the electricity grid. Furthermore, the report will also present estimates of the impact from charging directed towards low cost electricity hours.

1.2 Technical Background

Previous research have extensively dealt with questions regarding how smart charging can act as a flexibility measure for the power grid [7],[8],[9]. Flexibility meaning that the charging load can be shifted temporally to even out the generation-demand curve [10]. This has been performed on different scales, ranging from a European grid to single house holds [8],[9]. Smart charging has also been subject to research in how it varies between different European power grids - studying how smart grids have different potentials depending on where it is implemented [7], [11]. However, it is seemingly almost exclusively benefits in forms of reducing curtailment, promoting VREs and required installed generation capacities. A limited number of studies explores the perspective of grid capacity, or how to reduce the need for expanding grid infrastructure in a more electrified future.

In the existing literature there are two main different ways of modeling the EV fleet, as an aggregated fleet or as individual vehicles [12]. By modeling the EV fleet as one large storage one can save computational power and still retain some accuracy. However, this could overestimate the potential flexibility that smart charging provides [7]. In this report, EVs are modeled separately to estimate the full details in charging needs and interaction with the electricity grid.

There have been other research with some resemblance to the proposed scope of this thesis. Novoa & Brouwer (2018) from the University of California performed a study on SPV-EVCS with battery energy storage system for a parking lot at the university. This, however, didn't account for smart charging and had set parameters for amount of storage capacity, number of vehicles, rate and time of discharge [13]. Ioakimidis et al. (2018) investigates charging strategies with the aim of peak shaving buildings through Vehicle-to-Building (V2B) [14]. However, their report does not regard the installed grid capacity which this thesis aims to investigate.

1.3 Thesis Aim

This thesis aims to explore the potential of aggregated EV charging load within a parking area. Moreover to evaluate the potential benefits of governing individual EV charging in accordance with an overall objective. From the aggregators point of view, there is interest in identifying economic opportunities in infrastructure installation as well as operational costs of EV charging. One interesting aspect from a power system perspective is to identify variables that have a significant effect on the required transmission capacity and load shifting potentials. Finally, the thesis aims to explore the possibilities of integrating a PV system with the charging infrastructure and the possibilities of V2G integration.

This thesis aims to address the following research questions:

- How does smart charging affect the required installed transferable capacity in parking areas?
    – How does required transferable capacity change with the introduction of V2G?
- In what way could it be beneficial to combine a PV system with an EV charging system in parking areas?

2
Method

To answer the questions in the thesis aim linear programming was used, more specifically the software called General Algebraic Modeling System or GAMS. In GAMS various cases are formulated that receives data, created parameters, variables, and equations and optimizes with respect to an objective function. This thesis handles 4 different cases and 4 scenarios. Each case represents a charging strategy used to complete the task of charging a fix amount of KWh, based on the assumptions made, to the EVs at the garage. The first scenario is the base scenario, which tries to represent the current situation and charge as quickly as possible. Furthermore, a scenario in which the parking area has installed a solar PV system, a scenario where V2G is available, and a scenario with different electricity prices are modeled.

2.1 Model formulations

The model developed is a linear programming model, which is used to evaluate a number of different cases with different objectives, and thus, the objective function is different between the cases. Hence, the model formulation start by introducing the general equations used in all cases, whereas case specific objective functions are given under each case description. The following equations are found in each case and are the framework on which the cases are formulated from. A summary of parameters and variables used are described in appendix A.1. Equation 2.1, is used to calculate the SOC each time step.

$$SOC_{ev}(c,t) = SOC_{ev}(c,t-1) + \frac{EV_{charge}(c,t)}{EV_{size}(c)} \ \forall t \in T, \forall c \in C \tag{2.1}$$

The $SOC_{ev}(c,t)$ [-] is the state of charge of each vehicle in each time step. $EV_{charge}(c,t)$ is the amount of electricity charged to each car in each time step in $[KWh/h]$. $EV_{size}(c)$ is the size of the battery in each car $[KWh]$. Equation 2.2 is used to ensure that the charged amount over time is greater or equal to the desired charge amount.

$$\sum_{t\in T} EV_{charge}(c,t) \geq EV_{size} \cdot (SOC_{desired} - SOC_{in}) \ \forall c \in C \tag{2.2}$$

$SOC_{desired}$ is the target SOC which is set to 0.8 for BEVs and 1.0 for PHEV while SOC_{in} is the SOC when the car enters the parking garage. To control the charging capacity of each charger equation 2.3 is created. It limits EV_{charge} to be less than or equal to a set parameter that is the capacity of the EV chargers.

$$EV_{charge}(c,t) \leq P_{EV} \ \forall t \in T, \forall c \in C \tag{2.3}$$

P_{EV} is set to 11kW for BEVs and 3.7kW for PHEV. The maximum charging capacity is set to 11kW since that is the current limit in the parking garage [15].

2.2 Modeled cases

Four different cases were considered; direct charge, distributed charging, minimizing cost based on spot price, and minimizing cost based on spot price and cost of grid connection. Each case is run with a similar framework, but with a different objective function.

Case 1: Direct Charging

The first case is direct charging i.e. charging as much as possible as soon as the EV is plugged in until desired SOC is reached. The objective function used is shown in equation 2.4.

$$\text{Minimize X} \geq \sum_{t \in T} t \cdot \sum_{c \in C} c - \sum_{c \in C} \sum_{t \in T} SOC_{ev}(c,t) \tag{2.4}$$

The objective function tells the model to minimize the amount of time where all the cars are not on max charge. This is done by subtracting the accumulated SOC of all cars over the set time from the maximum charge, which equals to all cars being fully charged each time step.

Case 2: Distributed charging

The second case aimed to minimize the required installed grid capacity while still charging each car to their desired SOC, equation 2.5.

$$\text{Minimize } I_c \geq \max(\sum_{c \in C} EV_{charge}(c,t)) \tag{2.5}$$

Where I_c [kWh/h] is the installed grid capacity and is set to be larger or equal to the hour with highest total charging.

Case 3: Minimal spot price

A third case is created with the aim of minimizing the cost based on spot price of electricity, equation 2.6. This is done by minimizing the product of the consumption with the corresponding spot price of electricity for that hour.

$$\text{Minimize } C_{var} \geq \sum_{t \in T} (el_{price}(t) \cdot \sum_{c \in C} EV_{charge}(c,t)) \tag{2.6}$$

Where C_{var} [SEK] is the variable cost of electricity over the modeled month, based on spot prices, tax and a transfer fee.

Case 4: Minimal total cost

Fourth and final case is similar to the third case, however it also takes the cost of power capacity into consideration. The two costs considered are the variable and capacity cost. The objective function used is shown in equation 2.7.

$$\text{Minimize } C_{tot} \geq \sum_{t \in T} (el_{price}(t) \cdot \sum_{c \in C} EV_{charge}(c,t)) + I_c \cdot C_{power} \tag{2.7}$$

Where C_{power} is the cost of installed capacity [SEK/kW], I_c is the required transferable capacity [kW], and $el_{price}(t)$ is the electricity price at time, t, in [SEK/kWh].

2.3 Modeled scenarios

The first scenario modeled was the base scenario, which is formulated to represent the parking area infrastructure of today. The three additional scenarios created were: a PV system, a scenario where V2G has been introduced, and different spot prices with larger or smaller fluctuations than that of September 2021 in SE4. These scenarios are formulated from the base scenario but with small differences. Detailed information on the assumptions and the data used related to the scenarios can be read in section 2.4. In the scenarios with integrated PV system connected to the parking lot, the PVWatts calculator was used for a normalized electricity production of a solar park in Copenhagen, which is approximately 45km from Malmö.

When introducing V2G minor adjustments had to be made to each case because of the introduction of discharging, both to grid and other vehicles. In these cases, vehicles who were present at the parking garage had the option to discharge to grid, or other vehicles, and thus sell electricity as explained in section 2.4. The adjusted equations are presented in A.3.

The fourth and final scenario investigated was the impact of different spot prices. Spot prices used are taken from Nordpool in September SE4, December SE4, and March SE2 of 2021 and is shown in figure 2.1 [2].

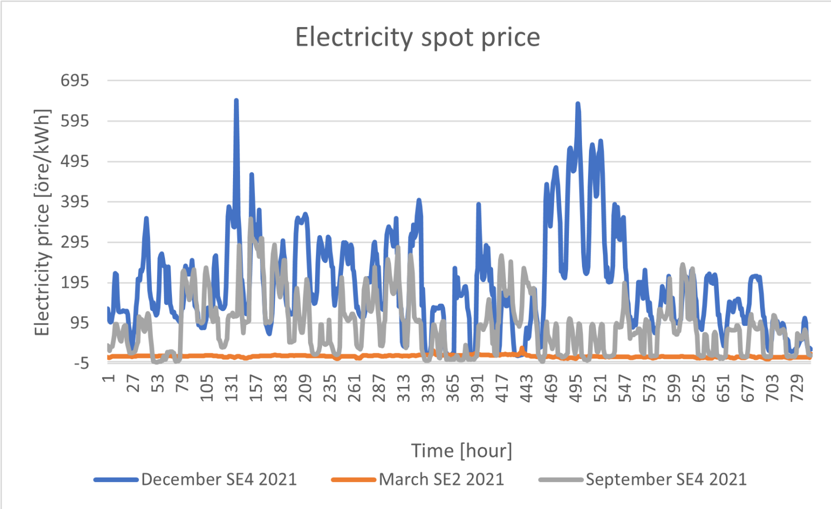

Figure 2.1: Electricity prices in SE4 for September and December and SE2 for March. March is selected to show the impact of a stable electricity price while December is selected to show a more volatile one compared to September [2].

To summarize, in table 2.1 is a matrix that shows which cases and scenarios that have been run in combination. The order presented in table 2.1 is also the order the results are presented.

Table 2.1: Combination of cases and scenarios that have been modeled are represented by an "X".

	Case 1	Case 2	Case 3	Case 4
Base Scenario	X	X	X	X
Solar PV	X	X	X	X
V2G	-	X	X	X
Electricity Price	-	-	-	X

2.4 Data input & Assumptions

The parking data stems from a real parking garage in central Malmö, Sweden, which has 670 parking spaces. A parking event is given by the difference between when a car enters and exits the parking garage. A total of 806 unique cars are tracked during the month of September 2021. Cars that entered prior to September and left after the investigated period are neglected, i.e. cars that lack either an entering or exit time. A total of 8132 parking events occur during the month. Parking events as given by the statistics is assumed to also reflect the need for parking in a future case where all vehicles are EVs. The SOC of EVs upon entrance are based on an assumed travel pattern and initial SOC at prior location. The assumed travel patterns is based on daily driving distances taken from the report on travel habits Region Skåne published in 2019 [16]. Since BEVs are not necessarily charging every day, the consumed electricity to work for BEVs is uniformly randomized, corresponding to charging between every one to three days. A consumption of 0.2kWh/km is assumed and multiplied with the travel distance to obtain a total consumption. This is then subtracted from an assumed fully charged battery to get an entry SOC for each EV. All cars entering the garage are assumed to be electric and a distribution is created based on the most popular EVs registered in Sweden during 2021, which corresponds to 45% of registered cars that year [1]. In table 2.2 the car model, its battery size, and its share is presented. The target SOC of PHEV is assumed to be 1.0, i.e. full charge, whilst the target SOC of BEVs is assumed to be 0.8 to avoid battery degradation [17]. PHEVs and BEVs have different max charging capacity, this is taken into consideration by assigning the max charge for BEVs and PHEVs to 11kW and 3.7kW respectively [18]. A total charging demand of 20840 kWh per month is yielded from the aforementioned data and assumptions.

Table 2.2: List of car models used. Each car that entered the parking area was assumed to be one of the cars below.

Car model	**Type**	**Size** [KWh]	**Share** [%]
KIA CEED SW	PHEV	8.9	9.12
VW ID.4	BEV	82	8.96
Volvo XC60	PHEV	18.7	7.90
KIA Niro EV	BEV	64	7.36
Volvo S/V60	PHEV	11.2	7.09
Tesla model 3	BEV	57.5	6.24
Toyota RAV4 5-D	PHEV	18.1	5.27
Volvo XC40	PHEV	10.7	4.61
KIA Niro	PHEV	8.9	4.50
MG ZS EV	BEV	72.6	4.41
VW ID.3	BEV	62	4.23
Nissan Leaf	BEV	40	3.86
Tesla Model Y	BEV	75	3.85
KIA XCEED	PHEV	8.9	3.66
Polestar 2	BEV	78	3.57
Skoda ENYAQ	BEV	82	3.37
Ford KUGA	PHEV	14.4	3.14
VW Passat GTE	PHEV	13	3.01
KIA Sorento	PHEV	13.8	2.93
Renault ZOE	BEV	52	2.93

When modeling the PV system, the following information was assumed; a standard module type, fixed array type, system losses of 2%, tilt angle of 20° and the panels are facing south (azimuth of 180°). The profile generated in PVWatts, which generates about 52kWh per and kW installed in September, was then multiplied by a factor of 60, 120, 185 or 240 kW to evaluate the cost effectiveness of differently sized installations. How the sizing calculation of whats possible on the parking garage is shown in A.3.

In the economic evaluation of the cases, a few assumptions are made and some data is collected. First and foremost, the total monthly cost is divided into two sub-costs;

variable cost, which is the cost of purchased electricity from the grid, and a capacity cost which is the cost of grid connection. Spot prices for the results are taken for the month of September in 2021 in SE4 and the cost of grid connection is taken from the local grid owner online calculator [1] [19]. In the calculator, the location of the real parking area is used for assuming grid connection cost applying the capacity class of ”80A or more connection” consumer category along with the electricity consumption derived from the cases. When accounting for electric variable cost, the spot price, a transfer fee of 9.6 öre/kWh and a tax of 44.5 öre/kWh are added to the variable $el_{price}(t)$ [19]. In the capacity cost there is a fixed fee at 775 SEK/month for all scenarios and a power capacity fee, which is 114 SEK/kW and month. When selling electricity, the profit is the spot price added to a loss compensation income, which is 2.92 öre/kWh for non-commercial producers at E.ON [20]. Thus, the assumed tariff structure make it more favourable to use eventual in-house power generation or surplus power brought to the parking area in EVs compared to selling it to the grid.

[1] Prices are not guaranteed for commercial users

3
Results

The results are presented in this chapter and the sections are divided into the different scenarios modeled.

3.1 The value of optimized charging

Case 1 where charging is simply done as fast as possible is presented in figure 3.1. According to the modeling results the required grid capacity is 172 kW, it requires 65 chargers, and the monthly total cost is just above 53,000 SEK. A weekly pattern can be seen where five larger pillars are followed by two shorter ones corresponding to weekdays and weekends.

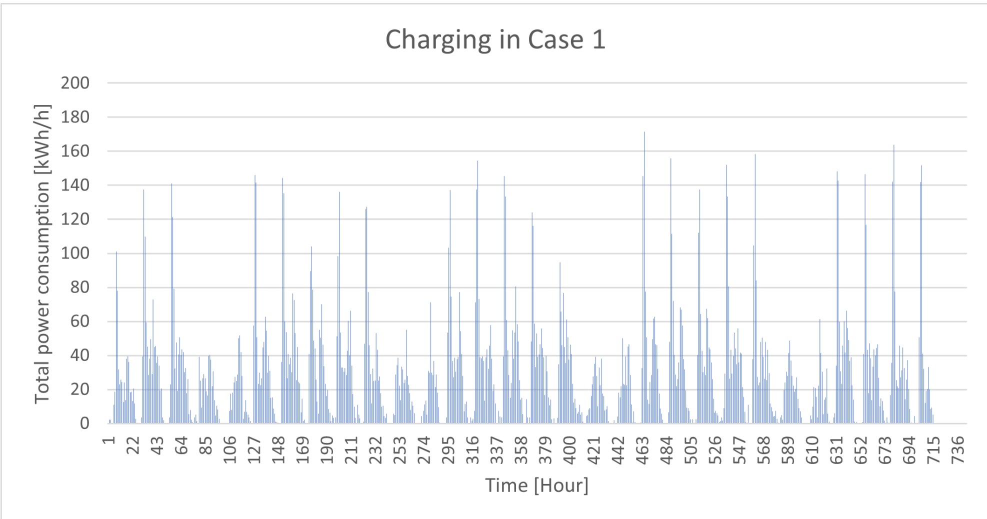

Figure 3.1: The hourly charging power as needed from the electricity grid as given in case 1, where all vehicles are charged directly upon arrival with the aim to restore SOC to its' target level as soon as possible.

The results for Case 2 is presented in figure 3.2, where the model is minimizing the power capacity required to charge all vehicles to their target SOC. In this case, charging for each individual EV can be distributed across the whole duration of its' parking to reduce the aggregated charging power of the entire parking area. It requires 47.3kW, 25 chargers, and has a monthly total cost of around 35,000 SEK.

All peaks in capacity in this case are equal since the frequency of that required capacity does not affect the cost. This entails that once the charging power required reaches a new max value, there is no longer any incentive to remain below that grid capacity any other hour during the month.

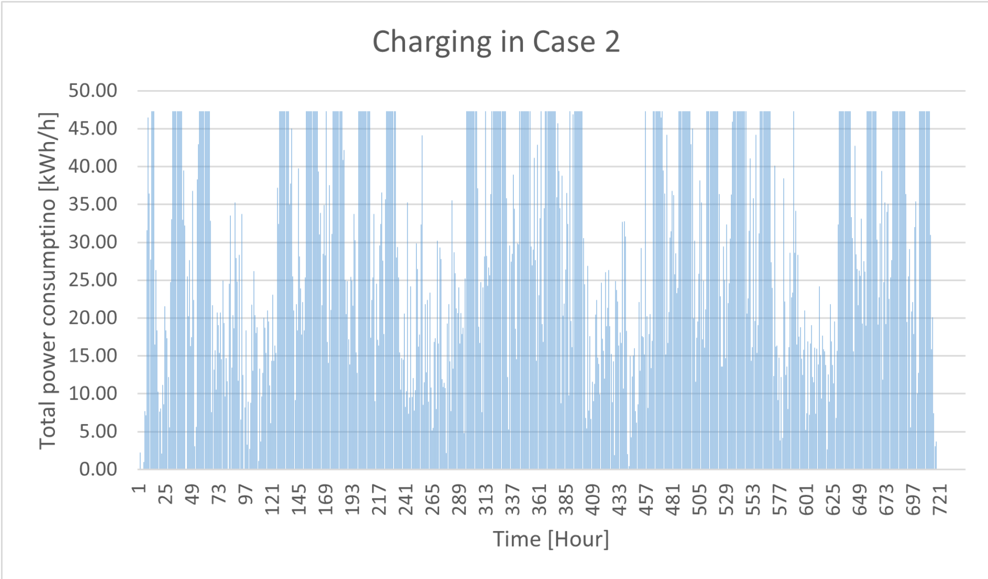

Figure 3.2: The hourly charging power as needed from the electricity grid as given in case 2, where the objective is to minimize the cost of grid connection, i.e. the capacity cost.

In Case 3, the results from which is presented in figure 3.3, the electricity price is controlling when vehicles are charging. The model is minimizing the variable cost, i.e. the cost of electricity from the spot prices. It has the highest required installed capacity of 418 kW, requires 141 chargers, and has a monthly total cost of just above 70,000 SEK. Weekly patterns becomes less clear, since the spot price is affected by both supply and demand, and the peaks are further apart than previously.

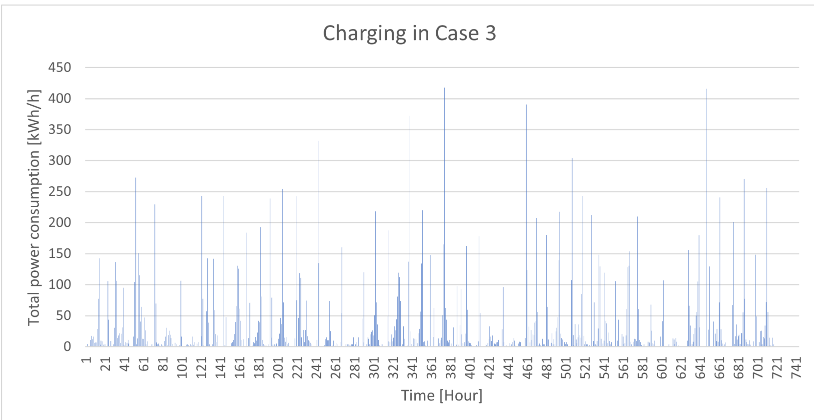

Figure 3.3: The hourly charging power as needed from the electricity grid as given in case 3, where the objective is to minimize the variable cost based on the spot price.

In figure 3.4, the results from case 4 is presented. The cost of power capacity and electricity spot prices are accounted for and the total cost is minimized in the model. The peak capacity reached is 47.3 kW, which is the same as in case 2. However, the required amount of chargers are 26, and the monthly total cost is around 30,000 SEK. There are clear similarities between case 2 and case 4, it is explained by the fact that the cost of installed capacity is weighted more heavily than the variable cost. One difference that can be seen is that case 4 reaches maximum capacity more frequently compared to case 2. The top capacity of 47.3 is reached 359 times in a month for case 4 while in case 2 it's reached 222 times.

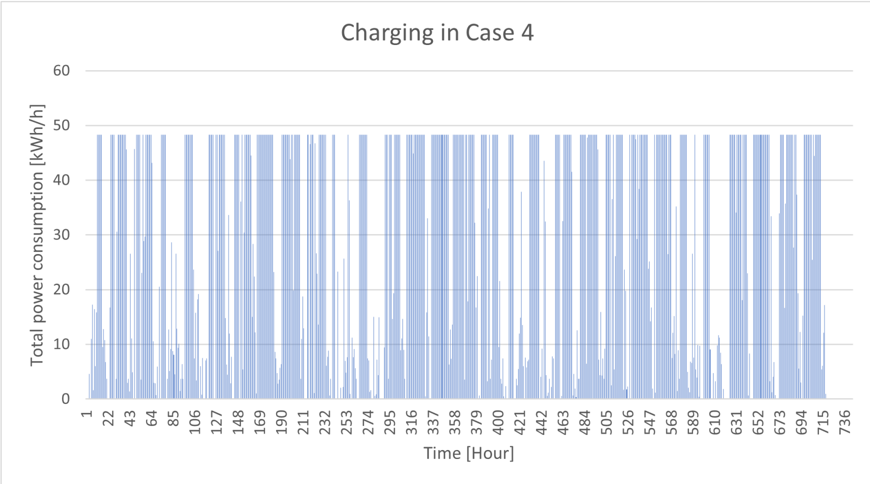

Figure 3.4: The hourly charging power as needed from the electricity grid as given in case 4, where the objective is to reduce the total cost as much as possible.

A comparison is presented in figure 3.5 together with table 3.1 that includes data regarding peak capacity, number of chargers required, and electricity cost. In figure 3.5, the hour 100 to 400 are presented for easier presentation of how the cases vary. An observation that can be made is that case 4, which has the same peak capacity as in case 2, follows the pattern of case 3 to some extent in order to reduce the variable cost as well. Case 3 has the largest peaks of all cases, which is reasonable as it tries to only utilize the lowest electricity prices for charging the vehicles. In the case of flattening the demand curve, case 2, it can be compared to the charging pattern of case 1, however with wider and lower peaks. A comparison of the two cases can be seen in figure A.1 in appendix. Similarly, the charging in case 4 resembles that of case 3 although somewhat wider and lower peaks. The comparison of this can be found in figure A.2.

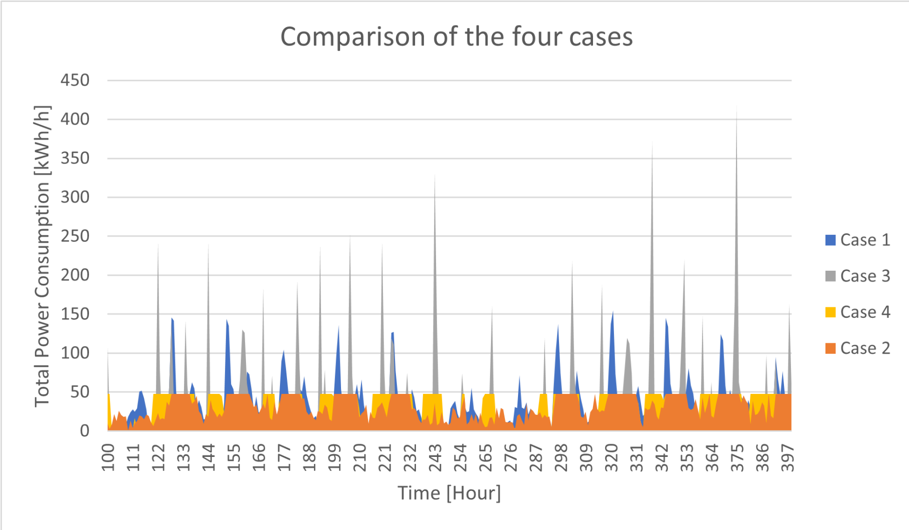

Figure 3.5: The hourly charging power as needed from the electricity grid in all 4 cases shown. Notice how the peaks of case 4 is identical in height of case 2 and also correlates the peaks of case 3.

Table 3.1: Comparison of the four cases and their required peak capacity, chargers, and the monthly cost of electricity.

	Case 1	Case 2	Case 3	Case 4
Peak capacity [kW]	172.0	47.3	418.0	47.3
Chargers required [-]	65	25	141	26
Variable cost [SEK/Month]	33 461	29 785	22 847	24 949
Capacity cost [SEK/Month]	19 562	5396	47 648	5396
Total cost [SEK/Month]	53 023	35 180	70 495	30 344

3.2 The value of integrated solar PV

In table 3.2 the results from including various sizes of PV systems are presented. The different sizes have an identical insolation profile, Copenhagen in September, which is used and the generated electricity is 52kWh per installed kW. In the results a trend of reduced savings per kW installed with increasing installed capacity is shown. This is due to the pricing model used, where reducing electricity purchased from grid is worth more than selling it to the grid.

Table 3.2: Results from simulating the four cases with an integrated PV system on the rooftop of the parking garage. In the table, the monthly savings on electricity costs are presented for four different installed capacities as well as the savings per kW installed.

Monthly savings [SEK/month]				
Installed cap.	**Case 1**	**Case 2**	**Case 3**	**Case 4**
60 kW	6006	5846	4940	5520
120 kW	11 504	10 931	9192	10 431
185 kW	16 236	16 125	13 585	15 351
240 kW	19 861	20 400	17 178	19 354
Savings per kW [SEK/month, kW]				
60 kW	100.1	97.4	82.5	92
120 kW	95.9	91.1	76.6	86.9
185 kW	87.8	87.2	73.4	83.0
240 kW	82.8	85.0	71.6	80.6

Excluding the installation of 240kW, the utilization of an integrated PV system is worth the most in Case 1. This might be due to a correlation between hours of high PV production and high charging demand, seen in figure 3.6. Meanwhile, case 3 has the lowest savings from PV. This gives an indication of a lower variable cost decreasing savings when installing a PV system, compared to the other cases' savings and variable cost.

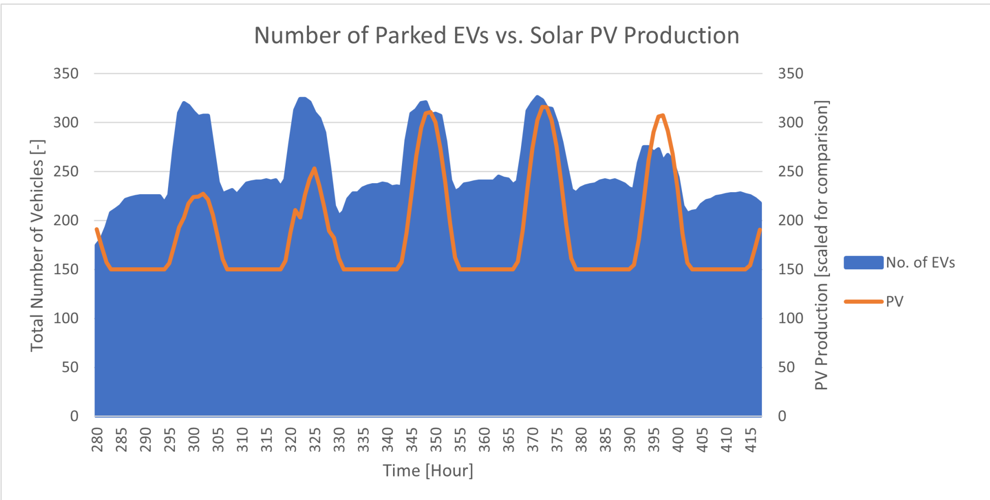

Figure 3.6: Correlation between the amount of parked EVs and the solar PV production.

Most PV retailers in Sweden have a 25 year guarantee on their PV systems and it could reach even longer lifetimes [21]. Assuming a 25 year lifetime, the total savings of installing 60kW would reach between 25000 and 30000 SEK/kW installed. However, this assumes that the average savings per month over the 25 year period is the same as those in the modeled results from September 2021.

3.3 The value of V2G

V2G is introduced in case 2, 3, and 4. In case 2, where the installed capacity is minimized the results show that the demand can be satisfied in-house, i.e. no grid connection required and demand can be satisfied behind the meter. All demand can be met by discharging vehicles entering with a SOC higher than their target SOC. The costs considered in all cases are costs related to transfer from and to grid. No vehicle-to-vehicle costs or cost of chargers is accounted for which results in this case having no monthly costs. On the contrary, in case 3 where the electricity cost is minimized, the model requires 2.1MW of installed capacity for charging and discharging. This entails a electricity cost of negative 130 000 SEK, but a total cost of 240 000 SEK. A summary of all results regarding V2G is presented in table 3.3. When minimizing the total cost, in case 4, the cost of installed capacity is considered together with the cost of electricity.

Table 3.3: Comparison of three of the cases implemented with V2G and the economical evaluation of said cases.

	Case 2	**Case 3**	**Case 4**
Peak capacity [kW]	0	2123	362
Chargers required [-]	54	287	102
Variable cost [SEK/Month]	0	-130 000	-64 000
Capacity cost [SEK/Month]	0	240 000	41 000
Total cost [SEK/Month]	0	110 000	-23 000

3.4 Impact from electricity price variations

In table 3.4 the results from altering spot prices are presented. The spot prices are varied by taking spot price vectors for different months with differences in the spot prices. They are taken from September 2021 in SE4, December 2021 in SE4 to represent higher, more volatile spot prices, and March 2021 in SE2 to represent lower, more stable spot prices. This assumes that there is an identical insolation profile for all months and that the PV system does not affect the spot prices. Average electricity prices of September, December and March were 65.5, 78.7, and 34.3 öre/kWh respectively.

Table 3.4: Results from simulating the case 4 with different sets of spot prices.

Cases	**Peak capacity** [kW]	**Total Cost** [SEK/Month]	**Monthly Savings** [SEK/kW]
Sept.	47.3	30 344	-
Sept. PV	37.6	14 993	83.0
Dec.	48.3	55 237	-
Dec. PV	42.4	28 116	146.6
March	47.3	19 213	-
March PV	32.3	12 858	34.4

4 Discussion

Discussion on the results and the validity of assumptions made is done in this chapter. There is also discussion on the effects from V2G, effects of introducing a PV system, and varying electricity prices. To conclude, limitations in the model and future work opportunities are discussed.

4.1 Number of chargers and pricing model

Considering the results of chargers required is misleading. These results are calculated by counting the number of cars charging each hour, which may work in theory but is different in practice. Due to the charging strategies applied, an EV could be charged every other hour throughout the parking duration. This would entail that someone has to plug and unplug the vehicle every hour and allocate it to another vehicle if the results were to be realistic. For the strategies to work in practice, more chargers would probably be necessary than those presented in the results.

A reflection on the results for the base scenario is that the electricity price model used may not be accurate. The prices are not guaranteed for commercial consumption. Moreover, the economical calculations in this thesis assumes an identical power subscription for all cases, 80A or above. Cases 2 and 4 both results in a connection of 47kW, which is on the limit of being obtainable in a 63A fuse where the user does not have to pay for a capacity cost. However, some DSOs have introduced new power subscription plans where the user, even with a 63A connection or lower, still has a capacity cost [22].

4.2 Effects of introducing a PV system

The results from introducing a PV system to the model seem to indicate that the cases with a higher variable cost would benefit the most from integration of PV. This makes sense in this model as it is more profitable to use the produced electricity in-house rather than selling it to the grid. There could be scenarios in which it would be more profitable to sell electricity, which would yield a different result. For example, there are campaigns for micro producers (up to 30000 kWh sold per year) which means the electricity is sold for the spot price and up to an additional 40 öre/kWh [23] [24].

4.3 Effects of V2G

There is a potential in V2G: It allows for off-grid operation in case 2, i.e. not needing to be connected to the grid to meet the charging demand and it even allows for a negative total cost in case 4. This is due to the current assumptions where some cars with large batteries enter with a high SOC and could thus discharge electricity without the need of charging. If economical incentives were introduced to promote selling electricity in parking areas a new business opportunity could be found. An example would be to allow individuals to charge their EV free of charge, if they allow the parking area operator to use their battery. The operator could use the battery for arbitrage transactions or auxiliary services and thus make gain that would be greater than the cost of charging the car. However, when discussing V2G one should also shed light on other aspects than technical and economical.

For the concept of V2G to exist there needs to be a flow of information from all parts of the system. Examples of needed information would be: duration of stay, current SOC, target SOC, and where the grid connection is made. One of the more central issues, that could be overlooked if only looking at technical aspects, is the case of privacy and personal security. By looking at where connection are made you could get driving patterns and thus information as a grid owner regarding the drivers home address, shopping preferences, workplace, community interactions, hospital visits just to name a few. This information could be used to harass an individual thus the skepticism is warranted. A potential solution to this privacy issue is to use anonymous permits when participating in the V2G service [25]. The identity of the connection could thus be unknown to the grid owner and aggregator but at a higher cost since it is adding a another actor. This additional actor would be responsible for making the connected participants anonymous to the other actors but would still need to be stored in its own database - which is in turn a security concern. It has been proven time and time again that even confidential information could get leaked and that only further induces the insecurity an individual might have to accept V2G in the future [26].

4.4 Effects of electricity price

The influence of the electricity price is present both when minimizing the variable cost and in minimizing the required peak capacity, i.e. it is more profitable to install more capacity and consume at low prices than to buy electricity at expensive hours. Another area of influence is on the profitability of PV. In the December results where the average electricity price is 2.3 times the price in March, the savings are close to 4.3 times greater. Comparing this to September where the electricity price and savings are more proportional. This is not only due to the average electricity price, but also how well the electricity price coincides with the charging demand during those months. One way of negating this effect would be to look in to storage possibilities that could temporally shift the charging demand to an hour of more desirable electricity cost.

4.5 Limitations in the model

The model that is developed aims to be as close to reality as possible, but there are several factors that are not considered in the model that could have an effect on the results. In the list below some of these factors are discussed.

- **Change of parking patterns** - The input data that is used is based on people using the current charging strategy, which is direct charging in this case. If other charging strategies were to be introduced it might have an effect on the duration of an EVs stay.
- **Uncertain future electricity price** - The model takes its electricity price from September 2021 in SE4. However, a different electricity price might sway the results and make the subscription cost less influential, as shown in the results.
- **Perfect foresight** - The model has perfect foresight, no unexpected demands interfere with the system and the system can prepare itself to its best potential before each scenario. A real world scenario would likely have less certain data regarding the duration of an EVs stay and thus largely change the way the charging strategy behaves.
- **Change in charging capabilities and desired SOC** - In future scenarios the charging capabilities could increase, i.e. an BEV could charge faster than 11kW and a PHEV faster than 3.7kW. The same goes for the desired SOC, if charging could be done much faster, a lower target SOC could be more realistic.

4.6 Future work

The area investigated in this thesis opens up other areas of potential future work. Some of these are presented in the list below:

- **The difference between paid parking time and actual parking time** - The accuracy of the duration is a vital parameter since the duration influence how a charging strategy is operated.
- **Limiting the foresight of V2G** - An interesting future work would be to only allow the model to see one day ahead and then stitch the results together for one month. A comparison could then be made between a stitched together result and one with a full month of foresight to see the impact.
- **Sensitivity analysis on various parameters** - The results gathered in this report could sway with various parameters: a larger share of BEV, limited amount of chargers, longer distances travelled to work, vehicle consumption.

5

Conclusion

A conclusion that can be drawn from the results is that smart charging, with a suitable objective, has the potential to significantly reduce the required installed grid capacity. Moreover, the results also indicate that there is economic incentives to do so. With the introduction of V2G having a grid connection could become obsolete since it allows for Off-grid operation operation of the parking area, given applied assumptions. Off-grid operation did, however, not turn out to be the most lucrative option, rather investing in transferable capacity. By utilizing the available capacity, arbitrage transactions could be exploited and thus make a profit. A general conclusion from all investigated cases and scenarios is that if there would be a need to strategically reduce the capacity drawn from grid, future parking areas can offer substantial flexibility, which is especially true if widespread charging infrastructure and V2G become available.

With the introduction of a PV system, there is potential to reduce both the capacity cost and the variable cost with a greater impact on the latter. Due to the assumed economic model, the PV system is as effective as possible if the parking duration spans across the hours of high insolation. It is then possible for the production of electricity to coincide with the demand. Regarding the impact of the electricity price, a high electricity price benefits a PV system potential savings.

Bibliography

[1] Bilsweden. Definitiva nyregistreringar under 2021. *https://www.bilsweden.se/statistik/Nyregistreringar_per_manad_1/nyregistreringar-2021/definitiva-nyregistreringar-under-2021*, 2022, consulted on 2022-03-03.

[2] Nord Pool Group. Market data: Day-ahead prices. *https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/?view=table*, 2022, consulted on 2022-04-26.

[3] UNFCCC. The Paris Agreement. `https://unfccc.int/documents/184656`, 2015. Online; accessed 27 January 2022.

[4] Regeringen. Det klimatpolitiska ramverket. `https://www.regeringen.se/artiklar/2017/06/det-klimatpolitiska-ramverket/`, 2017. Online; accessed 27 January 2022.

[5] Statista. Onshore wind energy capacity in sweden from 2008 to 2020. *https://www.statista.com/statistics/870785/onshore-wind-energy-capacity-in-sweden/*, 2021, consulted on 2021-10-04.

[6] Johan Lindahl. National survey report of pv power applications in sweden. *Uppsala University and International Energy Agency: Uppsala, Sweden*, page 9, 2014.

[7] Maria Taljegard, Lisa Göransson, Mikael Odenberger, and Filip Johnsson. Electric vehicles as flexibility management strategy for the electricity system—a comparison between different regions of europe. *Energies*, 12(13):2597, 2019.

[8] Xiaohua Wu, Xiaosong Hu, Yanqiong Teng, Shide Qian, and Rui Cheng. Optimal integration of a hybrid solar-battery power source into smart home nanogrid with plug-in electric vehicle. *Journal of power sources*, 363:277–283, 2017.

[9] Verena Heinisch, Lisa Göransson, Rasmus Erlandsson, Henrik Hodel, Filip Johnsson, and Mikael Odenberger. Smart electric vehicle charging strategies for sectoral coupling in a city energy system. *Applied Energy*, 288:116640, 2021.

[10] Somayyeh Khatiri-Doost and Meysam Amirahmadi. Peak shaving and power losses minimization by coordination of plug-in electric vehicles charging and

discharging in smart grids. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, pages 1–5. IEEE, 2017.

[11] Maria Taljegard, Lisa Göransson, Mikael Odenberger, and Filip Johnsson. Electric vehicles as power and energy provider for the european electricity system-an electricity systems modelling study.

[12] Maria Taljegard, Lisa Göransson, Mikael Odenberger, and Filip Johnsson. To represent electric vehicles in electricity systems modelling—aggregated vehicle representation vs. individual driving profiles. *Energies*, 14(3):539, 2021.

[13] Laura Novoa and Jack Brouwer. Dynamics of an integrated solar photovoltaic and battery storage nanogrid for electric vehicle charging. *Journal of Power Sources*, 399:166–178, 2018.

[14] Christos S Ioakimidis, Dimitrios Thomas, Pawel Rycerski, and Konstantinos N Genikomsakis. Peak shaving and valley filling of power consumption profile in non-residential buildings using an electric vehicle parking lot. *Energy*, 148:148–158, 2018.

[15] Uppladdning. Laddplats p-huset anna, malmö. *https://www.uppladdning.nu/SiteDetail.aspx?id=9961f747-99b5-4c23-a764-95074dcba9d2*, 2021, consulted on 2022-02-22.

[16] Region Skåne. Resvaneundersökning i skåne. *https://utveckling.skane.se/publikationer/rapporter-analyser-och-prognoser/resvaneundersokning-i-skane/*, 2019, consulted on 2022-03-03.

[17] JC Burns, Adil Kassam, NN Sinha, LE Downie, Lucie Solnickova, BM Way, and JR Dahn. Predicting and extending the lifetime of li-ion batteries. *Journal of The Electrochemical Society*, 160(9):A1451, 2013.

[18] Volvo. Ladda din volvo. *https://www.volvocars.com/se/v/cars/recharge/charging-your-volvo, year=2022, consulted on 2022-04-05* .

[19] E.ON. Våra elnätsabonnemang för privatkunder. *https://www.eon.se/el/elnat/kostnad*, 2022, consulted on 2022-03-04.

[20] E.ON. Våra elnätsabonnemang för dig som är mikroproducent. *https://www.eon.se/content/dam/eon-se/swe-documents/swe-prislista-elmikroproduktion-syd-190101.pdf, year=2022, consulted on 2022-04-07*.

[21] Elinstallatören. Grattis, sveriges äldsta solceller! *https://www.elinstallatoren.se/2021/01/grattis-sveriges-aldsta-solceller/*, 2021, consulted on 2022-04-26.

[22] Göteborg Energi. Elnätsavgift - läs mer om vår omgjorda prismodell. *https://www.goteborgenergi.se/privat/elnat/elnatsavgift*, 2021, consulted on 2022-04-26.

[23] Solcellsofferter. Sälja solel: Så gör du med överskottselen. *https://www.solcellsofferter.se/salja-solel/*, 2022, consulted on 2022-04-26.

[24] Kraftringen. Solceller för hus och villa. *https://www.kraftringen.se/privat/solceller/*, 2022, consulted on 2022-04-26.

[25] Zhiguo Wan, Wen-Tao Zhu, and Guilin Wang. Prac: Efficient privacy protection for vehicle-to-grid communications in the smart grid. *Computers & security*, 62:246–256, 2016.

[26] BBC. Pandora papers: A simple guide to the pandora papers leak. 2021.

A

Appendix

A.1 Parameters and Variables

Table A.1: Variables used in the linear programming.

Decision Variables		
$EV_{charge}(c,t)$	kWh/h	The amount of electricity that a car, c, is charged at time, t.
I_c	kW	Maximum required power transfer capability
Other Variables		
$EV_{discharge}(c,t)$	kWh/h	Amount of electricity that is discharged from a car, c, at time, t.
$EV_{soc}(c,t)$	-	The state of charge of the EV battery in car,c at time, t.
C_{tot}	kr	The total cost of electricity, i.e. both power rating contract and variable cost.
C_{var}	kr	The variable cost of electricity (spot prices)
C_{power}	kr/kW	The power rating contract cost based on the peak kW each month.

Parameters & input data

Table A.2: Parameters set from input data

Parameters read from data		
Pr_{PV}	-	Production profile from installed solar PV panels.
I_{PV}	kW	Installed capacity of solar PV.
EV_{size}	kWh	Size of EV battery in car, c.
P_{EV}	kW	Charging capacity of EV chargers.
BAT_{size}	kWh	Size of the stationary battery.
P_{BAT}	kW	Charging capacity of the stationary battery.
$SOC_{in}(c)$	-	Assumed state of charge of car, c, when entering the parking lot.
$el_{price}(t)$	SEK/kWh	Electricity price at time, t, including tax, transfer fee and spot price.
$Duration(c)$	h	Amount of hours a car, c, is staying at the parking lot.
b_{eff}	-	Efficiency of charging or discharging a vehicle.

A.2 Tables & Figures

Comparison of case 1 and 2

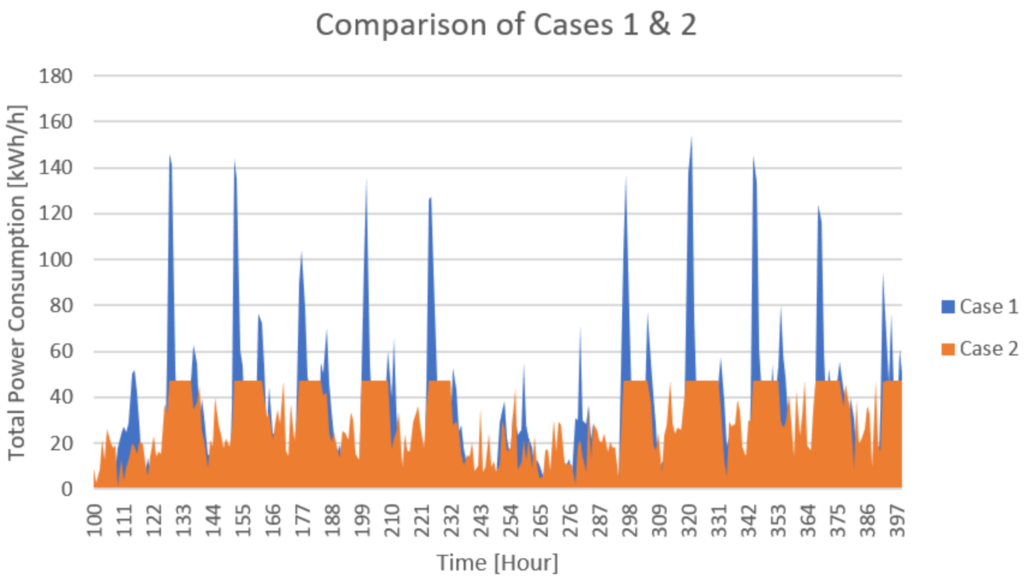

Figure A.1: Comparison of case 1 and 2, where it can be seen that charging is done at similar times for the two cases.

Comparison of case 3 and 4

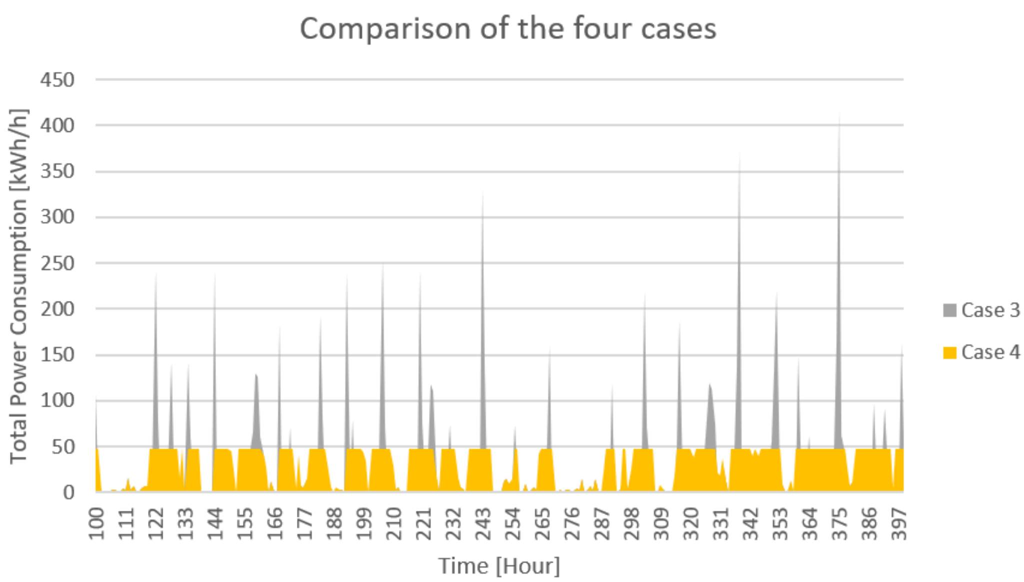

Figure A.2: Comparison of case 3 and 4, where it can be seen that charging is done at similar times for the two cases.

A.3 Equations

No changes made to code in case 1, only subtracted PV production from charging load curve in post-processing calculations.

Changes to code in case 2 with PV system

Change only made to the objective function:

$$\text{Minimize } I_c \geq \max(\sum_{c \in C} EV_{charge}(c,t) - PV_{prod}(t)) \tag{A.1}$$

Changes to code in case 3 with PV system

Changes only made to the objective function:

$$\text{Minimize } C_{var} \geq \sum_{t \in T}(el_{price}(t) \cdot ((\sum_{c \in C} EV_{charge}(c,t)) - Pr_{PV}(t) \cdot I_{PV}) \tag{A.2}$$

Changes to code in case 4 with PV system

Changes only made to the objective function:

$$\begin{aligned}\text{Minimize } C_{tot} \geq \sum_{t \in T}(el_{price}(t) \cdot ((\sum_{c \in C} EV_{charge}(c,t)) - Pr_{PV}(t) \cdot I_{PV}) + \\ \max(\sum_{c \in C} EV_{charge}(c,t) - PV_{prod}(t)) \cdot C_{power}\end{aligned} \tag{A.3}$$

Changes in code for V2G

Introducing the possibility of discharging:

$$EV_{discharge}(c,t) \leq P_{EV} \ \forall t \in T, \forall c \in C \tag{A.4}$$

The discharging and charging capacity is always equal in our model, i.e. if one invests in a charging capacity of 100kW there is also a possibility to discharge at 100kW. There is no need to invest in both discharging and charging capacity. The model also encourages in-house use of electricity since then it could avoid electricity prices certain hours and also required installed capacity. In the equation 2.1, discharging is added as well as an efficiency of 95%, η, to discredit discharging and charging the same hour.

$$SOC_{ev}(c,t) = SOC_{ev}(c,t-1) + \frac{EV_{charge}(c,t)}{EV_{size}(c)} + \frac{EV_{discharge}(c,t) \cdot \eta}{EV_{size}(c)}, \forall t \in T, \forall c \in C \tag{A.5}$$

Equation 2.2 is altered to take the discharging into consideration:

$$\sum_{t \in T} EV_{charge}(c,t) \geq EV_{size} \cdot (SOC_{desired} - SOC_{in}) + \sum_{t \in T} EV_{discharge}(c,t) \cdot \frac{1}{\eta}, \forall c \in C \quad \text{(A.6)}$$

Calculations of maximum installed capacity of PV

The area of the parking house roof is around 2400 sq. meters. An assumption was made that approximately half of the roof area could be covered with solar panels. From a heuristic approach, including spacing, a 6.5 sq. meters per kW is used for the approximation[1]. This yields an approximate maximum installed capacity on the roof top as 1200 sq. meters divided by 6.5 sq. meters/kW which results in 185 kW for the roof top.

[1]From supervisors at AFRY