Load Management Strategies to Increase Electric Vehicle Penetration—Case Study on a Local Distribution Network in Stockholm

Monika Topel [1,*] and **Josefine Grundius [2]**

[1] Energy Technology Department, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden
[2] Ellevio AB, 104 51 Stockholm, Sweden; josefine.grundius@ellevio.se
*   Correspondence: topel@kth.se

check for
updates

Abstract: As part of decarbonization efforts, countries are adapting their energy policies accordingly. Sweden has established ambitious energy goals, which include CO_2 emissions reduction in the transport sector and high integration of renewables in the electricity sector. Coupling the two can be an enabling force towards fossil freedom. An increased share of electric vehicles is therefore a promising solution in this regard. However, there are challenges concerning the impact that a surge of electric vehicles would have on the electric infrastructure. Moreover, in Stockholm there is a shortage of power capacity due to limitations in the national transmission infrastructure, which further aggravates the situation. This paper develops a scenario-based simulation study to evaluate the impact of electric vehicle loads on the distribution grid of a Stockholm neighborhood. In this process, limiting factors and bottlenecks in the network were identified as being related to the peak power and transformer capacities for the years of 2025 and 2031. Two load management strategies and their potential to mitigate the power peaks generated from uncontrolled charging were investigated for the critical years.

1. Introduction

In order to achieve the climate targets set within the Paris agreement [1], a significant transformation of the overall energy system is required. Sweden is at the forefront of this transformation with a bold energy policy adopted in 2016 [2]. In the transport sector, the country aims to reduce CO_2 emissions in 2030 by 70% compared to those in 2010. Moreover, in the electricity sector the goal is to have a 100% renewable production by 2040. The ultimate target for 2045 is to reach carbon emission neutrality. For the past 10 years, the transport sector has swiftly reduced its carbon dependency by switching from fossil fuels to other alternatives at a faster rate than any other sector. However, as of today, it is still the sector with the highest proportion of fossil fuels, with a 76% consumption [3]. The electricity sector, on the other hand, is at the other end of the spectrum with only 1% of fossil fuel consumption. Even at the latest rate of fossil fuel reduction, there is a risk that the emission target is not reached in time. Consequently, in the coming 10 years it is crucial to accelerate the diversification of the transport sector towards other energy sources.

Increasing the share of electricity use within transport is a most promising solution for achieving this needed transformation. Specifically, the rapid integration of plug-in electric vehicles (PEVs) within road transport. As shown in Figure 1, in 2018 passenger cars were responsible for 60.8% of the total domestic transport emissions [4] and the electricity use in the sub-sector accounted for a minimal 0.12% share of its total energy use by fuel [5]. Both of these facts entail that there is an enticing potential

to increase the share of PEVs and these would, in turn, cause a direct benefit in reducing the carbon footprint of the highest emitting transport sub-sector. Therefore, sector coupling between transport and electricity can be an enabling force that steers the swedish energy system into fossil freedom.
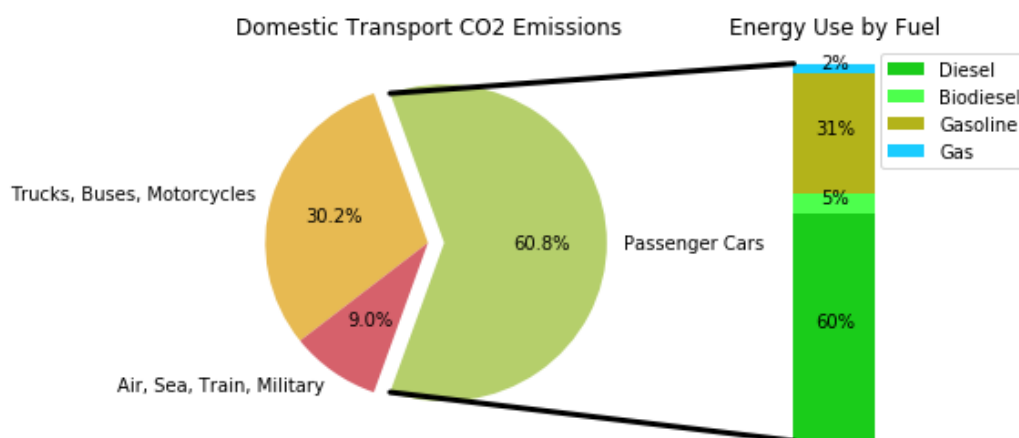

Figure 1. CO_2 Emissions in the domestic transport sector and energy use by fuel in passenger cars.

Achieving a high share of PEVs in the system does not come without challenges. The massive introduction of PEVs increases the strain on the electricity infrastructure and confronts its robustness. The behavioral nature of the PEV charging loads changes the way the network is designed, planned and operated today. Nowadays, the share of PEVs from the total cars in traffic is only 4% but the rate of increase has been doubling in the past 3 years [3]. In addition, there is an identified shortage of power capacity in the Swedish transmission grid. This translates to limitations in the distribution of electricity at regional level and it has been affecting major cities. This is the case for the city of Stockholm, where the electricity demand is increasing as part of the region's own infrastructural development [6] while the power supply is limited to 1525 MW. In accordance to the transmission system operator, this limit in power capacity will be remedied by 2030, at the earliest.

In face of this challenging situation, Ellevio AB and Stockholm Exergi (as the local DSO and heat utility, respectively) reached an agreement at the end of 2019 [7,8] consisting of securing an additional 320 MW produced locally by a local combined heat and power plant for the coming 12 years. For the time being, this solution will help avert the electricity power supply crisis in Stockholm while long-term investments and measures are set in place. However, such a situation requires monitoring and especial attention to the reciprocity between having the share of PEVs continue increasing while guaranteeing security of the power supply and the integrity of the grid components. Neither one should be an obstacle to the other.

1.1. Related Work

In order to handle a high share of PEVs at district level, it is crucial to investigate the impact that the collective PEV charging loads would have on the distribution system. Previous studies in this field have been carried out for distribution networks over different locations in the world and in Sweden. Within the extensive review carried out in Reference [9], demand side management and scenario-based analyses were been identified as categories with a major presence in the literature. In the study carried out in Reference [10], charging behavior factors were shown to have a strong influence on the results. It was found that uncontrolled PEV charging can increase load peaks by up 3.6 times and that improved charging strategies are needed to ease the effects of simultaneous charging.

A Portuguese study analyzed the impacts of home charging PEVs at night-time, and concluded that the degree of penetration increases, more strain will be put on the distribution grid, increasing the minimum system load, and increase stress on baseload units [11]. In British Columbia, Monte

Carlo simulations were performed to estimate residential and commercial demands where it was learned that PEV charging does increase the peak demand, which in turn causes voltage drop (mainly in rural areas) and transformer overloading [12]. In the UK, a Monte Carlo simulation was developed with a Spatial-Temporal model to obtain EV charging loads in busbars at different times, identifying the critical network components for up to 50% PEV penetration levels, showing low voltages at times for larger penetrations. Spatial-Temporal modelling has potential to quantify EV penetration impact and detailing vulnerable parts of the network [13]. The study carried out in Reference [14] analysed the deployment of PEVs, under numerous smart charging schemes, to facilitate a microgrid's self-consumption of solar power in the Netherlands.The main findings indicate that PEVs and smart charging schemes can make significant contributions to a well-balanced supply and demand.The system is however not deemed favourable when employed on a larger scale.

In Sweden, the work carried out in Reference [15] analyzed the impact of load management strategies in different districts of Gothemburg. The study found that steering the electric loads towards minimizing losses can reduce de need for grid investments while the strategy of minimizing costs would result in an increased peak power demand. The study conducted in Reference [16] for the Uppsala municipality investigated the need for distribution grid operators to incorporate PEV loads as a factor in their network planning and dimensioning. It was made clear in this study that PEV charging is expected to have a significant impact in the 2030 timeframe and that the parameters used for dimensioning of the network should incorporate electric vehicle loading aspects as the risk for overloading of components is high. Similarly, a study conducted for five areas in Stockholm [17] calculated the maximum number of cars that could fit in those areas while identifying network bottlenecks. It was found that the cables were the most vulnerable components in the suburban areas grid while the network in the inner city was found to be more robust.

In general, the impact of increased loads in the network is highly dependent on the area being studied, on the capacity of the existing grid and on behavioral considerations of the PEV loads. Likewise, all studies agree that load management strategies can post-pone network reinforcements but that the level of postponement is entirely case-specific. Moreover, the literature agrees that if PEVs were properly designed and controlled, they would be beneficial to the operation of the grid, by providing ancillary services. If not, supply-demand matching may be affected, as well as power quality, voltage imbalance and component overloads. This work builds upon the knowledge generated from the previous cited studies but evaluates the effects of PEV charging in a new area. Moreover, the concept of a peak power budget is introduced for the district area being studied, which is something that none of the studies before have considered. The idea with the power budget is to set an equivalent limit at district level to the one Stockholm region has imposed by the transmission system operator. In that way, it is possible to gain knowledge on how close the district is operating around the said limit and thus its influence on the power shortage situation in the region.

1.2. Scope and Objectives

This paper develops a scenario-based simulation study to evaluate the impact of PEV charging loads on the distribution grid of a neighborhood in Stockholm, Sweden. The effects of PEVs are evaluated specifically on the local infrastructure as well as in the existing power capacity limitations in the region. The paper also investigates the extent to which load management strategies can mitigate the peaks generated by uncontrolled charging.

For this, different scenarios for electricity usage are developed based on regional trends and demographic data. Then, based on the extension of a previously developed model [18], power flow analyses are conducted in the intermediate voltage grid of the area in question. Studies are run considering different time resolutions and PEV charging behaviors. More specifically, load management strategies for controlling the PEV charging loads are implemented and compared in terms of their impact in the network. In this process, bottlenecks in the distribution network of the

neighborhood of Hammarby Sjöstad are identified both at the level of the network components and in the overall peak power capacity to the area.

The remainder of the paper is organized as follows—an overview of the case study, input data and the developed scenarios are presented in Section 2. Section 3 explains the modeling scheme and the simulation framework implemented in the paper, as well as the research questions addressed. Section 4 shows and discusses the results obtained for each of the simulations. Finally, Section 5 concludes the paper and provides an outlook for the future.

2. Case Study and Scenarios

The selected area of study of this work is Hammarby Sjöstad (HS), a district located in the southeast of Stockholm. Since its development, HS has been globally recognized as a very successful urban renewal project for its approach of integrating sustainability into city planning [19]. Today, about 70% of the area is developed and by its estimated completion it will have 12,000 residential units, 21,000 inhabitants and employ 10,000 people [20]. As both a result and a cause of its success story, HS is used today as a demonstration platform with a number of test-beds in smart energy, sustainable transport and sharing economy.

Within HS, citizen driven initiatives [21] have been working for some years to engage the tenant-owner associations and residents towards concrete energy and climate measures. One project to highlight from that initiative is called "Charge at Home" which makes use of policy incentives to install charging infrastructure in households. This sets a natural predisposition for HS to be an early adopter of PEVs, thus making it a very relevant test-case for this study.

The first step in the analyses carried out in this work was to develop a set of scenarios for the years of 2016, 2020, 2025 and 2031 in HS. The scenarios were developed using year 2016 as a reference and scaled for the other years based on different input data and assumptions. For the years in study, each scenario establishes:

- an aggregated electricity demand,
- a level of PEV penetration,
- a power capacity limit,

The aggregated electricity demand listed above refers only to the base loads in the area. The PEV loads will be subsequently constructed from the PEV penetration levels. The data extracted from different sources and the respective assumptions to construct the scenarios are explained in Sections 2.1 and 2.2.

2.1. Electricity Demand

The electricity consumption in HS for the year 2016 was calculated based on measured data provided by Ellevio AB, the distribution system operator of the area. In 2016, the total electricity demand in HS amounted to 76.5 GWh with an maximum peak of 15.61 MVA and an aggregated peak of 20.29 MVA. Figure 2a shows the two peak values in terms of the distribution among the 20 substations in the area. The difference between these two values is that max-peaks is the actual maximum of the yearly load time-series while agg-peaks is the sum of the partial maximum loads at each substation. Since partial peak values can happen at different occasions, their aggregation results in a higher value. Figure 2b shows the daily distribution of the loads on the max-peaks case which corresponds to wednesday 20 January 2016. The peak to average load ratio on this day is equal to 1.39. The scenarios were built considering the agg-peaks case while the max-peaks is considered for the studies performed in later sections.
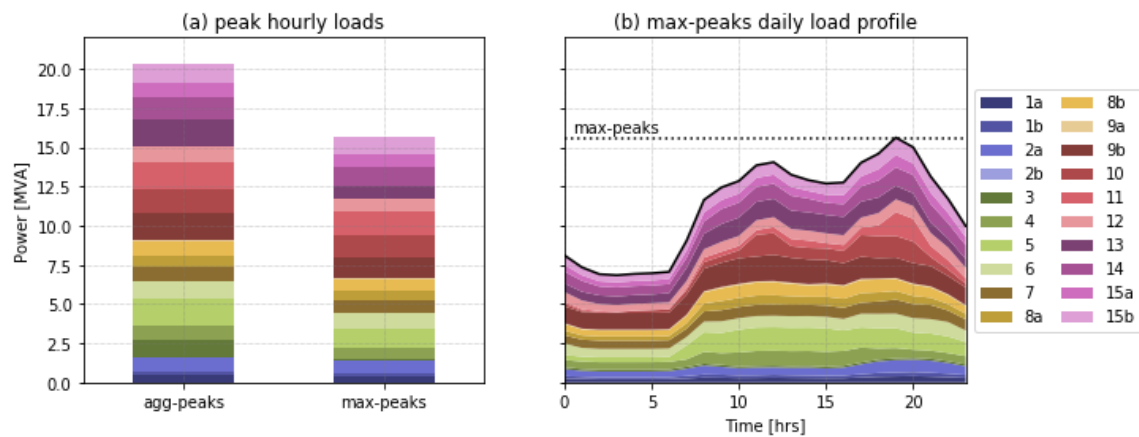
Figure 2. Electricity consumption in 2016 for the substations (1a-15b) in HS (**a**) aggregated peak load versus actual maximum peak load (**b**) daily distribution of loads for the maximum peak case.

In order to scale the 2016 base load demand onto the other years of study, the changes in the base loads electricity consumption were considered proportional to those of the population. For this, population data and its growth projections were obtained [22,23] and interpolated for the years of interest to this study. Table 1 shows the corresponding numbers for the city of Stockholm (Sthlm) and for HS. While the population in the whole city is expected to increase in the selected years, the population in the HS district is constant after 2025 which is when the on-going contructions for housing are expected to be completed.

Table 1. Population in thousand inhabitants for the city of Stockholm and the district of HS as well as electric vehicle (PEV) penetration shares considered in the scenarios

	Population		
Year	Sthlm	HS	PEV Share
	(1000 Inhabitants)		(%)
2016	936.6	18.4	2
2020	987.9	19.9	10
2025	1052.5	21.4	59
2031	1145.5	21.5	133

2.2. Electric Vehicle Penetration

Before building scenarios for electric vehicle penetration, the total amount of cars in the district was quantified. Car ownership in the city of Stockholm has been relatively steady for the past two decades [24]. Since HS is a part of Stockholm city, this value was assumed constant for the years of study as 370 cars per 1000 inhabitants. The total amount of vehicles in HS was then estimated using this ratio and the population from Table 1.

Table 1 shows the values that were defined as the share of electric vehicles that can be expected in the district of HS for the studied years. These values were gathered from electric vehicle statistics [25] and their future trends in the City of Stockholm [26]. Historic data from Reference [25] was gathered up to year 2019 for Stockholm and for Sweden. Based on this information, the projected rate of growth of PEVs was regressed towards future years. In parallel to this, the Power Circle organization has assessed the long term market development of PEVs in Sweden as one following the S-curve model of new technology adoption [26]. This forecast was adapted to the population of personal vehicles in Stockholm and is considered in this work. Figure 3 shows the historic electric vehicle data, its future regressions as well as the Power Circles forecast.
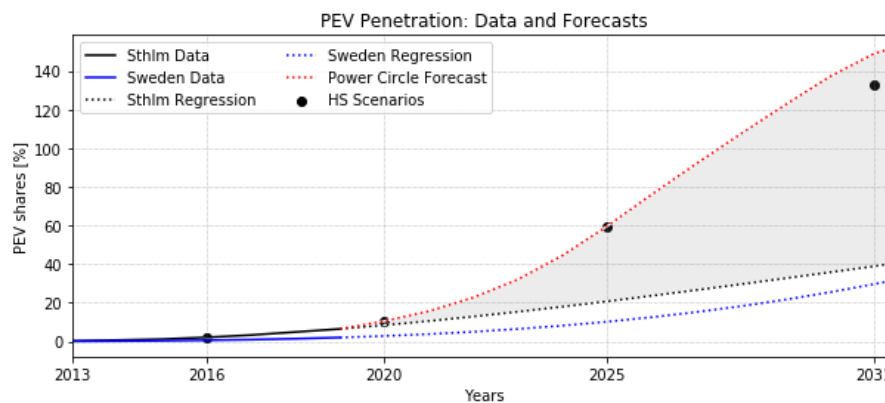
Figure 3. Electric vehicle statistics, their future trends and the selected shares for Hammarby Sjöstad.

The PEV penetration scenarios that were considered for HS within this work are also shown in Figure 3. It can be seen in the figure that the values selected for the district are in the high end of the forecasted range. The reason for this being the amount of smart energy initiatives that are currently on-going at HS (as mentioned in Section 2). The year 2031 was chosen to be more conservatively within the range due to the fact that the population in HS (Table 1) will have already reached saturation by then.

It is important to highlight that the Power Circles forecast only takes into account PEV development from a market growth perspective and it does not take into account how many vehicles or inhabitants are in total in the municipality in the future, this is the reason why the PEV penetration share for 2031 is 133%. Although this number appears to be counterintuitive, it is simply interpreted as a high-electrification scenario in which the entire car fleet is made of PEVs and there is an increased amount of vehicles in the total passenger car fleet in comparison to today's share. The value is therefore kept for the subsequent calculations performed in this paper. In that way, all the scenario years PEV shares are calculated using the same car ownership and future projection assumptions.

2.3. Power Capacity Limits

As established in Section 1, the amount of power available from the transmission level to the Stockholm distribution grid is limited to 1525 MW and the local heat utility has agreed to supply an additional 320 MW in the coming years. In this study, those limitations corresponding to the whole region were scaled down to an equivalent capacity limit for the district of HS. This was done in order to establish the concept of a peak power *budget* against which to compare and control the eventual peaks of the PEV charging loads of the district.

The Stockholm situation has been previously documented [6,27] and well described in a figure that presents a timeline of the available power capacity contrasted with the expected growing electricity demand. However, the additional power capacity agreed upon with the heat utility is not included in the aforementioned studies. Therefore, the first step was to extract those values for the years selected in this study and include the additional 320 MW agreed for the Stockholm region. Then, a scale down to HS equivalent capacities was done based on the ratio between regional and local peak demands for the reference year 2016. Figure 4a hereby shows the corresponding power capacity and demand for Stockholm and Figure 4b shows the scaled down equivalent of those values for HS' electricity demand.

The population development for the city and the district are also shown in Figure 4. It can be seen that while the rate of electricity demand increase for HS is proportional to the population growth, the one for Stockholm city is not. This relates to the assumption made in Section 2.1 and to the fact that the demand for the Stockholm case includes all electrification loads (including PEVs) while the one for HS only reflects the base loads (excluding PEVs). Even with this difference, the scenarios created for HS still reflect the reality of the region with regards to the increasing gap between demand and power capacity in the coming years until 2031 when the transmission limitations are solved.
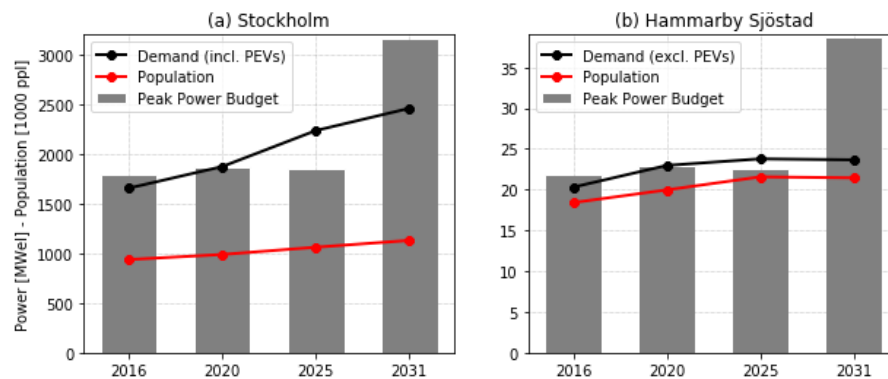
Figure 4. Electricity demand and available power capacity for the selected scenario years: (**a**) Stockholm region situation (**b**) Hammarby Sjöstad scaled from the Stockholm situation and the electricity loads.

3. Method and Models

Once having defined the scenarios, they were used as part of the modeling scheme shown in Figure 5. Essentially, a choice of scenario year also defines the percentage of electric vehicle share, base loads and capacity limits in the area as per the clarifications in Sections 2.1–2.3. These attributes then serve as an input to three models, namely: A PEV load model, a load management model and a power flow model. The models are explained in more detail in the coming Sections 3.1–3.3. The methodology proposed in this work, uses the presented scheme towards addressing the following research questions:

- Does a certain level of electric vehicle penetration become problematic for the network? and if so:

  - Is the problem related to the installed network infrastructure or to the external capacity limits?
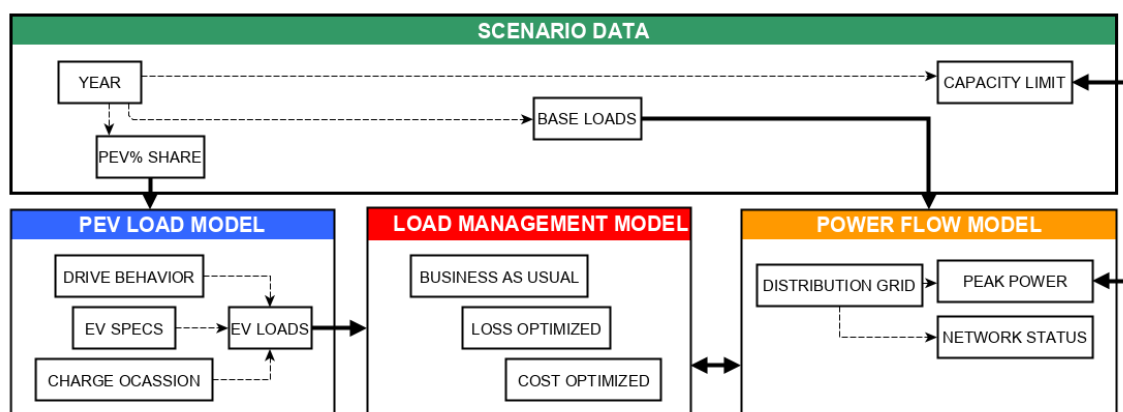 - To what extent can an optimized load management strategy alleviate the strains in the network?

Figure 5. Process flow chart of the models used in this work and their interactions.

3.1. Power Flow Model

The intermediate voltage grid of HS was modeled using pandapower [28], a python-based tool used for load flow analysis of networks. In order to make a relevant representation of the reality, the network model was developed using input data provided by the DSO concerning transformers ratings, cable properties, connected customer characteristics, system topology and hourly load measurements. In Figure 6, the one line diagram of the power system is observed. The network is composed of 20 substations of 12 kV/400 V and 2 external feeders. Based on this system, the power flow model solves the respective nodal power balance equations and calculates the voltage levels,

current flows, system losses, peak power and the overall status of the network components for different load inputs.
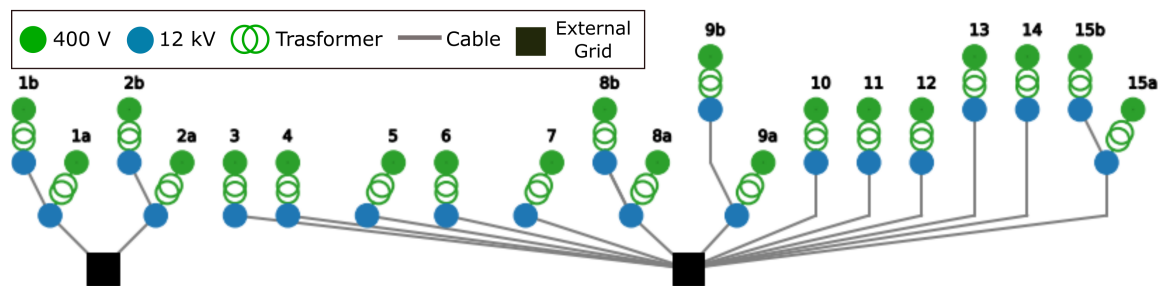

Figure 6. Topology of the modeled network in the district of Hammarby Sjöstad (HS).

3.2. Electric Vechicle Load Model

The PEV load model calculates the load profile of the electric vechicles in each substation based on their charging requirements and driving schedules. The first step is to distribute the total number of PEVs per network area, per type of activity and per type of car. In spatial terms, the PEVs are distributed among the substations based on the demand distribution of connected customers. The distribution for commercial and residential activities is also based on the shares of customer types. Figure 7 shows the relative size of the demand per sub-area and it also categorizes their activities in terms of commercial (COM) or residential (RES). For distributing the PEVs in terms of car type (e.g., pure electric or hybrid electric) a mix representative of the market popularity of PEV models in Sweden [26] was considered. Besides determining the car type, this last distribution serves to obtain valuable attributes such as battery size and driving range.
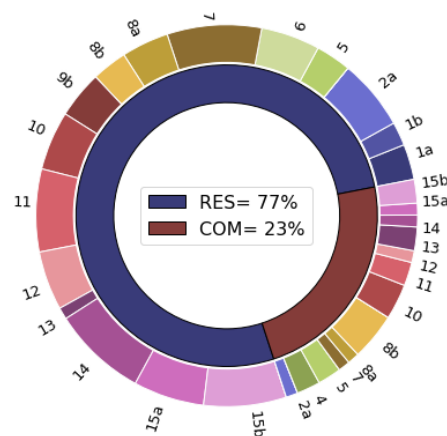

Figure 7. Electricity demand distribution in the substations of HS categorized by residential (RES) and commercial (COM) activities.

Once the PEVs are distributed, the next step is to take into account their driving behavior. The start of trips for a weekday was withdrawn from the national travel survey [29] as well as the driving distances and duration of trips [30]. In order to obtain variations in the charging profiles the driving behavior parameters were randomized for each PEV within a 10% range of the average values. It was assumed that each car performs two trips per weekday. As a consequence of the driving behavior randomization, the distance and duration of each trip is not necessarily the same. Based on this information it is thus possible to calculate the end times of each car's trip.

Having established the driving schedule of each PEV, the next step is to translate this into charging requirements. An initial state of charge for the batteries was assumed at the start of the day for each car within a random range between 80–90%. The charging occasion of each car was determined by their

activity type. Commercial PEVs charge in the window between the end of the first trip and the start of the second trip. Residential PEVs charge directly at the end of the second trip, towards the end of the day, until the beginning of trip one on the next day. Combining the driving behavior parameters with the state of charge and a charging power of 3.68 kVA (standard single phase 230 V and 16 A outlet) it is then possible to calculate the magnitude of the PEV loads and produce a charging profile for each substation.

3.3. Load Management Model

The purpose of the load management model is to control the PEV loads (P^{PEV}) towards fulfilling a certain objective. In order to do this, a linear programming formulation was adopted using the Gurobi optimization solver [31] coupled with the power flow model of the network. Two load management strategies were developed: loss-optimal and cost-optimal. The loss-optimal strategy seeks to conduct the charging of the vehicles at the lowest amount of system losses, which most favourable from the DSO's perspective. The cost-optimal strategy takes into account the electricity costs perceived by the end-users and aims to conduct the charging at the lowest possible costs for them. The objective functions and constraints considered for the strategies are presented in Table 2.

The total system losses are calculated as the difference between the power fed into the system through the external feeders, P^{EF}, and the total power consumed within the system by the base loads and by the PEV loads, P^{BL} and P^{PEV}, respectively. This is done considering all of the substations, SS, as well as the external feeders, FS. Moreover, as the loads are also time dependent these are added up for the entire optimized time period, T.

The total electricity costs are calculated as the sum of the electricity market price, $Price^{EL}$, and the network tariffs, $Tariff^{NET}$. The electricity prices were obtained from the spot price at Nordpool [32] while the tariffs were taken from the DSO's available subscriptions [33]. Since there are different network tariffs to choose from, it was assumed that the entire area was subscribed to time based tariffs, in which a higher tariff applies on weekdays between 6 h to 22 h. Only the variable part of the network tariffs was accounted for, as it is the part that is subject to variations in the consumption. Also, the share of the electricity costs that is related to taxes and government fees was not included in this calculation. The two load management strategies were subject to the same set of constraints:

- A peak power budget constraint in order to keep the base loads and the PEV loads within the established power limit, P^{MAX}, defined for each scenario year,
- A network infrastructure constraint to avoid exceeding the installed transformer capacity, P^{TRAFO}, from each substation,
- A charging energy constraint in order to guarantee that the charging requirements of the vehicles are met by the optimized PEV loads to the same level as in the business as usual (BAU) case, $P^{PEV\ BAU}$,
- A scheduling constraint to ensure that charging is conducted within arrival and departure hours of each vehicle. P^{MIN} was defined as the minimum power required by the vehicles if they were to distribute their charging equally throughout their window of connection to the grid.

Table 2. Objective functions and constraints formulated for the load management strategies.

Objective Functions:		
minimize	system losses	$\mathbf{min} \sum_{h=1}^{T} \left(\sum_{f=0}^{FS} P_{h,f}^{EF} - \sum_{s=0}^{SS} (P_{h,s}^{BL} + P_{h,s}^{PEV}) \right)$
minimize	electricity costs	$\mathbf{min} \sum_{h=1}^{T} \left((Price_h^{EL} + Tariff_h^{NET}) \cdot \sum_{s=0}^{SS} (P_{h,s}^{BL} + P_{h,s}^{PEV}) \right)$
Constraints:		
subject to	peak power budget	$\sum_{s=0}^{SS} (P_{h,s}^{PEV} + P_{h,s}^{BL}) \leq P_{sce}^{MAX}$
	network infrastructure	$P_{h,s}^{PEV} + P_{h,s}^{BL} \leq P_s^{TRAFO}$
	required charging energy	$\sum_{h=1}^{T} P_{h,s}^{PEV} \geq \sum_{h=1}^{T} P_{h,s}^{PEV\ BAU}$
	vehicles schedule	$P_{h,s}^{PEV} \geq P_{h,s}^{MIN} \in [h_{arrive}, h_{depart}]_{car}$

4. Results and Discussion

In order to adress the research questions presented in Section 3, three different studies were carried out. The first two questions were adressed by evaluating the scenarios for different time resolutions, namely: a critical hour and a critical day. In these two studies, a BAU or uncontrolled charging behavior was considered. The third question was adressed by modifying the charging behavior through the implementation of load management strategies. The coming sections present and discuss the results in more detail.

4.1. Simultaneous Charging on a Critical Hour

The critical hour study addressed the proposed research questions as an absolute worst case scenario. In which, all the PEVs connect simultaneously at the given hour. The base loads considered for this study are those corresponding to the *agg-peaks* case from Figure 2a. For each scenario year, the PEV penetration was maximized until a certain limiting criteria in the network was reached. Figure 8 shows the resulting maximum PEV penetration for (a) the transformers, (b) the cables and (c) the peak power capacity as limiting criteria for the substations in HS. All the values shown in terms of the percentage of PEVs allowed by the infrastructure. The expected PEV share from the scenarios in Table 1 (EVSCE) is also displayed in the figure with black dashed lines. The actual base loads are not displayed in the figures but are considered for the calculations.

In general, it can be seen in Figure 8a,b how the installed infrastructure allows for less PEVs in the coming years. This is in connection with the scenarios shown in Figure 4b, in which the future base loads are increasing. Thus allowing less room for PEVs. This is not directly the case for the peak power limitations Figure 8c given that this limitation will be expanded by 2031. Moreover, Figure 8b shows that the cables in the network do not present any limitation for PEV penetration, as the EVSCE condition was fulfilled and surpassed for all years. However, in cases like Figure 8a for 2031 and in Figure 8c for 2020, 2025 and 2031, the calculated PEV penetrations were below the expected EVSCE. These cases represent potential bottlenecks. In general, for each of the analyzed years the peak power limitation poses an earlier barrier to PEVs than the actual network infrastructure of cables and transformers.
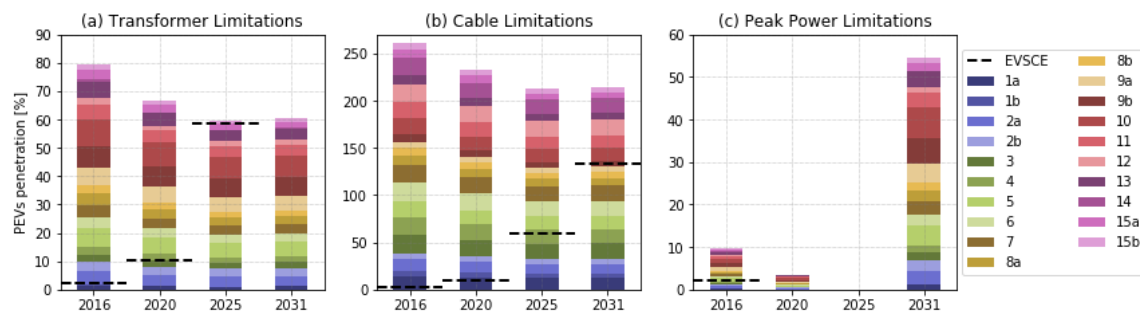
Figure 8. Maximum penetration of EVs for a critical hour considering different limiting criteria: (**a**) transformers (**b**) cables (**c**) peak power capacity for the substations in the network.

4.2. Distributed Charging on a Critical Day

Based on the findings from the previous study, an analysis of the network was carried out for a critical day. The conservative conditions of simultaneous charging and aggregated peaks were made more realistic and softened in this study. The base loads considered were those corresponding to the *max-year* case from Figure 2a which, in turn, are spread during the course of a day, as in Figure 2b. Additionaly, the PEVs connect to charge in a distributed way depending on the statistic and behavioral assumptions explained in Section 3.2.

In a similar way as before, the PEV penetration was increased until reaching a certain limiting criteria. However, instead of investigating the criteria separately, for this case, they were intercepted. In that way, the results display the PEV penetration that complies with both infrastructure and peak power limitations. As the cables in the network did not present any limitations previously it was not expected that they would become limiting when the conditions were softened. Therefore, the transformer and the power capacities were the main criteria being considered on this distributed study.

Figure 9a and Table 3 summarize the findings in terms of the allowed PEV penetration for each substation in the network and for the whole district. Table 3 lists the total PEV penetration for each year along with the corresponding breakdown for COM and RES vehicle types. Table 3 also shows the number of transformers in the area that were loaded over 95% of their capacity as a result of the PEV penetration as well as the average loading of all the transformers in the area. Additionally, the peak to average load ratio is also listed on Table 3 and can be directly compared to the 1.39 ratio that corresponds to the base case from Section 2.1.

In general, the distributed charging behavior resulted in increased PEV penetration levels for all scenario years when compared to the peak power limitation in the simultaneous hour study. This was to be expected as the cars are no longer connecting at the same time. The two problematic years found in the study were 2025 and 2031, in which the EVSCE share level was not reached. Figure 9b,c show the distributed charging profiles for the corresponding PEV shares reached on those years. The figures also display the power budget for the PEV loads, which is a result of the overall limit established within the scenarios minus the base loads at each time step.

In 2025, the EVSCE share level of 59% was not reached due to peak power limitations. This is seen in Figure 9b where the charging profile corresponding to 50% shares already reaches the peak power budget. In 2031, the EVSCE share level of 133% was not reached due to transformer limitations. In Figure 9c the PEV load profile in 2031 is well within the peak power budget. However, Table 3 shows that a total of 15 tranformers were loaded 95% (or higher) and the resulting average of all network transformers was 96.6%.
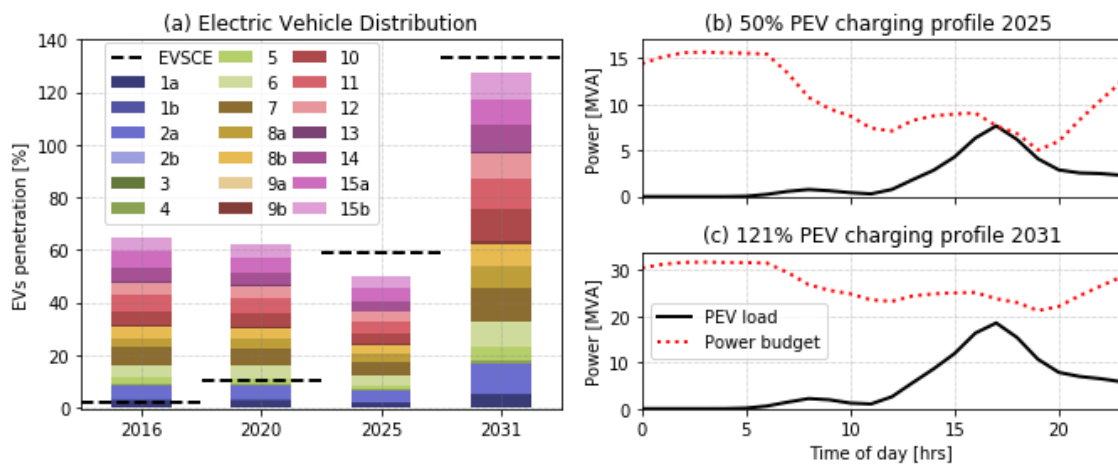
Figure 9. (**a**) Maximum PEV penetration for a critical day considering infrastructure and peak power limitations (**b**,**c**) PEV charging profile and peak power budget for the years 2025 and 2031, respectively.

Table 3. Resulting network loading and PEV penetration from the distributed charging study.

	2016	2020	2025	2031
EV Penetration %				
TOTAL(%)	65	62	50	121
RES (%)	60	57	46	110
COM (%)	5	5	4	11
Network Loading				
Critical trafos ($\geq$95%) (#)	4	7	6	15
Average trafo loading (%)	70.5	75.6	78.8	96.6
Peak to average load ratio (-)	1.65	1.65	1.62	1.90

4.3. Optimized Charging on a Critical Day

The previous studies (Sections 4.1 and 4.2) identified scenario years 2025 and 2031 as being problematic for the network due to the fact that it was not posible to reach the EVSCE target. This study focuses especifically on these two years and investigates to which extent can load management strategies alleviate the network congestions and reach the targeted scenario. For this, the expected EVSCE penetration level was assumed as the base case with uncontrolled charging behavior. Then, this same amount of PEV shares was optimized for loss and cost minimization subject to the constraints explained in Section 3.3.

Figures 10a,b show the uncontrolled and optimized PEV charging profiles for 2025 and 2031, respectively. The figures also display the available power budget for the PEV loads as a remainder of the total capacity limitation and the base loads hourly variations. It can be seen in Figure 10a how the uncontrolled case surpasses the allowed capacity budget at the afternnon peak. The optimized strategies, on the other hand, stay within the allowed power budget. The loss optimization distributes the PEV charging as evenly as possible thoughout the day, with a large concentration of power demand on the early morning hours due to the high amount of residential vehicles. The cost optimal strategy actually generates new peaks in the late evening and early morning, when the network costs are low and the power budget is more allowing. In Figure 10b, the cost optimal peak generated is more pronounced than the original peak from the uncontrolled strategy.

Table 4 compares the cases in more detail in terms of the amount of critical trafos, average transformer loading, total losses, charging costs per vehicle, maximum peak and peak-to-average load ratio. With the use of loss optimal load management strategies it is possible to reduce losses by 9.9% in 2025 and by 21.2% in 2031 with respect to the base case. Similarly, with the use of cost optimal

load management strategies daily charging costs per vehicle can be reduced by 39.1% in 2015 and by 50.9% in 2031. However, this is subject to the assumption that the costs for electricity in those years are the same as today. With regards to overall peaks and local transformer bottlenecks, the loss optimal strategy was the one that could improve the network status with regards to the uncontrolled case. Peak power reductions of 17.4% in 2025 and by 42.9% in 2031 were obtained with the loss optimal strategy. The cost optimal strategy actually resulted in less favourable conditions for the installed transformer and then maximum peaks. This is further reflected in the peak-to-average load ratio where it can be seen that the cost optimal strategy results in a higher ratio than the uncontrolled case for the case of 2031.

Table 4. Comparison between uncontrolled and optimization studies for critical years with regards to transformer status, total losses, charging costs and maximum peak and peak-to-average load ratio.

|	Critical Trafos (≥95%) (#)	Avg. Trafo Load (%)	Peak/Avg. Ratio (-)	Total Losses (MWh)	Charging Costs (SEK/car)	Maximum Peak (MVA)
year 2025			59% EV Penetration			
Uncontrolled	7	83.51	1.66	14.94	9.44	23.47
Loss Optimal	**5**	**67.55**	**1.37**	**13.46**	6.43	**19.37**
Cost Optimal	13	97.99	1.59	14.66	**5.71**	22.51
year 2031			133% EV Penetration			
Uncontrolled	15	121.42	2.00	23.20	9.35	33.83
Loss Optimal	**6**	**71.54**	**1.14**	**18.28**	6.57	**19.30**
Cost Optimal	16	112.12	2.18	22.41	**4.76**	36.87
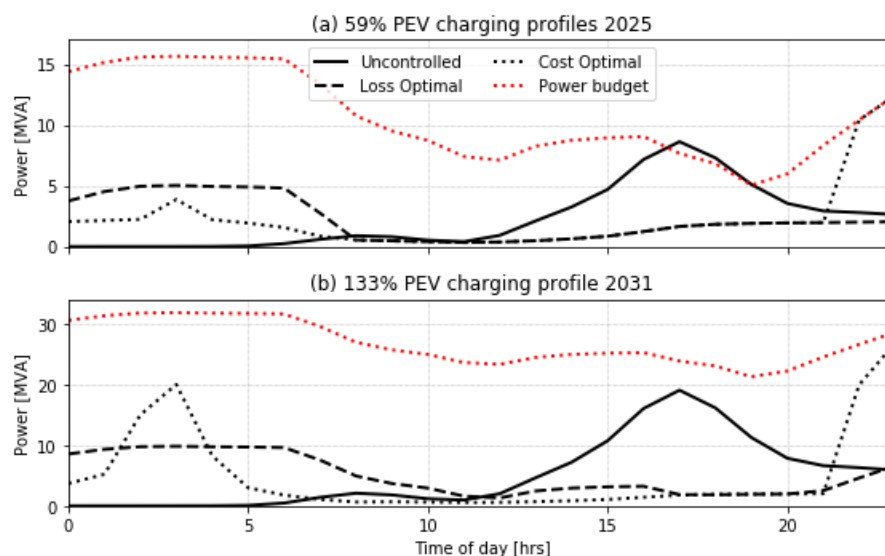
Figure 10. Uncontrolled and optimal PEV charging proviles in relation to the peak power budget for (**a**) 59% PEV penetration in 2025 and (**b**) 133% PEV penetration in 2031.

5. Conclusions

This work evaluated the impact of PEV charging loads on the distribution grid of Hammarby Sjöstad, a neighborhood located in Stockholm, Sweden. The intermediate voltage network of the neighborhood was built and power flow calculations were carried out in order to answer the question of which level of electric vehicle penetration becomes problematic for the network. This was done for different scenarios of electric vehicle penetration and base electricity demand for the coming years. The scenarios also considered the peak power limitations that currently exists in the Stockholm region by scaling down this number to an equivalent peak power budget for the district of Hammarby. Once the model and the scenarios were built, three studies were carried out seeking to answer whether

the congestions in the network were due to limitations in the local infrastructure or in the external peak power capacity.

In all scenario years, it was observed that the 12 kV network cables were well sized for all the future loads. In general, it was found that peak power capacity is an earlier limiting factor than the network infrastructure. The year 2025 was identified as critical due to the peak power budget if the PEV charging loads are left uncontrolled. In the year 2031, the peak power limitations were no longer a constraint but intead the installed transformer capacity becomes problematic if the charging loads are left uncontrolled.

Based on these findings, an analysis was also made on the potential of controlling the charging loads to mitigate the negative effects on the network. The loss optimal management strategy was found to be the most beneficial for the system, due to the fact that it was able to reduce peak power, total losses and average transformer loading with regards to the uncontrolled charging. The charging costs for the users were also reduced in this strategy, however, the cost optimal strategy achieved the most significant reductions in this regard. It was observed that cost optimization focused on the user tariffs can actually inccur in increased peaks. This highlights the importance of having the right price signals that steer the loads towards the overall benefit of the system. In this regard dynamic tariffs are a focal point of future studies as well as the network status in the lower voltage network.

Abbreviations

The following abbreviations are used in this manuscript:

BAU	Business as Usual
BL	Base load
COM	Commercial
EF	External feeder
FS	Feeding station
HS	Hammarby Sjöstad
EVSCE	Electric Vehicle Scenario
PEV	Plug-in electric vehicles
RES	Residential
Sthlm	Stockholm
SS	Substation

References

1. Paris Agreement to the United Nations Framework Convention on Climate Change. T.I.A.S. December 2015; pp. 16–1104. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 16 July 2020).
2. Agreement on Swedish Policy, Framework agreement between Swedish Parties. Government of Sweden. 2016. Available online: https://www.regeringen.se/artiklar/2016/06/overenskommelse-om-den-svenska-energipolitiken/ (accessed on 16 July 2020).

3.   Statens Energimyndighet. *Energiindikatorer*; ER 2020:18; Statens Energimyndighet: Eskildstuna, Sweden, 2020.

4.   Naturvårsverket. Utsläpp av Växthusgaser Från Inrikes Transporter. Available online: https://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-utslapp-fran-inrikes-transporter/ (acessed on 27 June 2020).

5.   Statens Energimyndighet. *Energiläget 2020*; ET 2020:1; Statens Energimyndighet: Eskildstuna, Sweden, 2020.

6.   North European Power Perspectives. Energisystemet i en ny tid, Halvstidsrapport, NEPP. March 2019. Available online: http://www.nepp.se/rapport.htm (accessed on 16 July 2020).

7.   ELLEVIO. Krisen för Stockholms Elförsörjning Avvärjd Påkort Sikt. Available online: https://www.ellevio.se/om-oss/Pressrum/newsroom/2019/oktober/krisen-for-stockholms-elforsorjning-\avvarjd-pa-kort-sikt2/ (accessed on 16 July 2020).

8.   Stockholm Exergi. Stockholm Exergi och Ellevio Is Samarbete för att Säkra Stockholms Elförsörjning. Available online: https://www.stockholmexergi.se/nyheter/stockholm-exergi-och-ellevio-i-samarbete-for-att-sakra-\stockholms-elforsorjning/ (accessed on 16 July 2020).

9.   Arias-Londoño, A.; Montoya, O.; Grisales-Noreña, L. A Chronological Literature Review of Electric Vehicle Interactions with Power Distribution Systems. *Energies* **2020**, *13*, 3016. [CrossRef]

10.   Fischer, D.; Harbrecht, A.; Surmann, A.; McKenna, R. Electric Vehicles' Impact on residential electric local profiles—A stochastic modeling approach for considering socio-economic, behavioural and spatial factors. *Appl. Energy* **2019**, *233*, 644–658. [CrossRef]

11.   Camus, C.; Silva, C.M.; Farias, T.L.; Esteves, J. Impact of plug-in hybrid electric vehicles in the portuguese electric utility system. In Proceedings of the 2009 International Conference on Power Engineering, Energy and Electrical Drives, Lisbon, Portugal, 18–20 March 2009; pp. 285–290.

12.   Kelly, L.; Rowe, A.; Wild, P. Analyzing the impacts of plug-in electric vehicles on distribution networks in British Columbia. In Proceedings of the 2009 IEEE Electrical Power and Energy Conference (EPEC), Montreal, QC, Canada, 22–23 October 2009. [CrossRef]

13.   Mu, Y.; Wu, J.; Jenkins, N.; Jia, H.; Wang, C. A Spatial–Temporal model for grid impact analysis of plug-in electric vehicles. *Appl. Energy* **2014**, *114*, 456–465. [CrossRef]

14.   Van der Kam, M.; van Sark, W. Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study. *Appl. Energy* **2015**, *152*, 20–30. [CrossRef]

15.   Steen, D. Impact on the Distribution System due to Plug-in Electric Vehicles and Changes in Electricity Usage. Ph.D. Thesis, Chalmers University, Göteborg, Sweden, 2012.

16.   Gustafsson, E.; Nordström, F. Impact of Electric Vehicle Charging on the Distribution Grid in Uppsala 2030. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2017.

17.   Gode, H.P. Network Planning for Charging Electric Vehicles in Stockholm. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2016.

18.   Topel, M.; Arnaudo, M.; Grundius, J.; Laumert, B. Case Study on the Effects of Incresing Electric Vehicle and Heating Loads on a Distribution Network in Stockholm. In Proceedings of the International Conference of Electricity Distribution (CIRED 2020), Madrid, Spain, 3–6 June 2019; p. 1556.

19.   Foletta, N.; Field, S. *Europe's Vibrant New Low Car(bon) Communities: Hammarby Sjöstad Case Study*; ITDP Europe: New York, NY, USA, 2014.

20.   Stockholms Stad. Stadsutveklingsområde Hammarby Sjöstad. Available online: https://växer.stockholm/omraden/stadsutvecklingsomrade-hammarby-sjostad (acessed on 28 June 2020).

21.   ElectriCITY. Hammarby Sjöstad 2.0. Available online: http://hammarbysjostad20.se (accessed on 27 June 2020).

22.   Stockholms Stad. Områdesfakta Södra Hammarbyhamnen Stadsdel. Available online: https://start.stockholm/globalassets/start/om-stockholms-stad/utredningar-statistik-och-fakta/statistik/omradesfakta/inre-staden/sodermalm/sodra-hammarbyhamnen.pdf (accessed on 29 June 2020).

23.   Stockholms Stad. Statisktik Årsbok för Stockholm 2020. Available online: https://start.stockholm/globalassets/start/om-stockholms-stad/utredningar-statistik-och-fakta/statistik/arsbok/statistisk-arsbok-for-stockholm-2020.pdf (accessed on 24 June 2020).

24.   Stockholms Stad. Bilinnehav. Available online: http://miljobarometern.stockholm.se/trafik/motorfordon/bilinnehav (accessed on 15 June 2020).

25. Trafikanalys. Fordon På Väg. Available online: https://www.trafa.se/vagtrafik/fordon/ (accessed on 6 June 2020).

26. Power Circle, Elbilstatistike—ELIS 2.0.3. Available online: https://www.elbilsstatistik.se/ (accessed on 20 January 2020).

27. Pasichnyi, O.; Wallin, J.; Kordas, O.; Data-driven building archetypes for urban building energy modelling *Energy* **2019**, *181*, 360–377. [CrossRef]

28. Thurner, L.; Scheidler, A.; Schäfer, F.F.; Menke, J.; Dollichon, J.; Meier, F.; Meinecke, S.; Braun, M. Pandapower—An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems. *IEEE Trans. Power Syst.* **2018**, *33*, 6510–6521. [CrossRef]

29. Trafikanalys. *National Travel Survey 2015–2016*; Statistik: 2017:13; Trafikanalys: Stockholm, Sweden, 2017.

30. Trafikanalys. Körsträckor med Svenskregistrerade Fordon. Available online: https://www.trafa.se/vagtrafik/korstrackor/ (accessed on 7 June 2020).

31. Gurobi Optimization, LLC. Gurobi Optimizer Reference Manual. 2020. Available online: http://www.gurobi.com (accessed on 20 May 2020).

32. Nord Pool. Historical Market Data. Available online: https://www.nordpoolgroup.com/historical-market-data/ (accessed on 10 June 2020).

33. Ellevio AB. Elnätspriser för Stockholm från och med 1 Februari 2020. Available online: https://www.ellevio.se/globalassets/uploads/dokument/prislistor-2020/priser-privat-2020/sakr_sth_200201.pdf (accessed on 12 June 2020).