Energy Infrastructure for Electric Vehicles: 
A Case Study in 
Hammarby-Sjöstad, Stockholm

Emilia Chojkiewicz and Tracy Lu
Adviser: Monika Topel
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Abstract

As Sweden works toward carbon neutrality, a major step involved is the switch from fossil-fuel based vehicles to electric vehicles, especially passenger vehicles. This study models a district of Stockholm, Hammarby-Sjöstad, estimates electric vehicle loading, and predicts failures of the grid, to inform ways of adjusting for future increased demand.
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1 Introduction

The Swedish Government aims to have a vehicle fleet completely rid of fossil fuels by 2030 as a step towards carbon neutrality by 2050. The country has an almost carbon-free electricity supply and has phased out oil use in residential and power sectors. But currently there are about 4,845,609 passenger cars in Sweden [1], 64.9 TWh per year are used for of petroleum and diesel used for transportation, and about 74.3% of transportation energy is fossil fuel based [2]. Based on these facts and the government's goal, there will be a major switch from fossil fuel powered vehicles to electric vehicles, especially with private, passenger cars. Now Sweden must take concrete steps to realize its vision of a fossil-fuel-independent vehicle fleet by 2030 and zero net greenhouse-gas emissions by 2050.

However, as more non-electric vehicles are replaced with electric vehicles, there will be an impact on the grid. More research and modeling is needed on such effects to inform how the country can preemptively ensure that the grid can handle the increased loads.

2 Background

Hammarby Sjöstad is a district of Stockholm, Sweden, located approximately 3 km southeast of the city center. It encompasses approximately 150 hectares of land, or 200 including water; it houses approximately 25,000 residents and employs another 10,000 [3]. The area has a long and interesting history: before the 1990s, it was commonly regarded as a ‘run-down, polluted and unsafe industrial and residential area’ [3]. However, due to an intensive urban renewal program, it is now a very pleasant residential and commercial area - a center of metropolitan life.

The urban renewal program, carried out over the past few decades, was the first of its kind. From partnerships between residents, engineers, municipal authorities, urban planners, architects, developers, the energy company Ellevio, the district cooling and heating company Fortum, and the Stockholm Water Company, the area was transformed. Combining traditional urban planning with modern architecture, the Hammarby Sjöstad project integrated the previous brownfield site with its unique waterfront location. Of particular focus was sustainability in areas of water, energy, waste, and more.

With regards to sustainable water management, the district features green roofs and an innovative rainwater harvesting system. Stormwater is drained via canals, and runoff from roads and paved surfaces is purified and treated before release. Homes have water-saving appliances and recycling technologies, with the consumption data available online as a resource for residents to learn about their habits [3]. The educational center GlasshusEtt offers further information for the general public to learn about adopting a more sustainable lifestyle.

With regards to energy, homes and businesses are powered by many experimental methods including solar, fuel cells, and biogas, with about 50% of electricity coming from renewable sources [4]. A local thermal plant run by the company Fortum provides centralized heating and cooling, which is much more energy efficient than individual apartment systems [5]. Running on treated waste water and biofuels, the plant delivers heat in the form of hot water to the end user through a distribution system composed of insulated pipes; the leftover cold water can be used for cold storage in grocery stores or air conditioning.

With regards to waste, Hammarby Sjöstad rigorously sorts household waste, and thus sends 60% less waste (0.7% of all waste) to the landfill than comparable developments [4]. All wastewater is locally treated, with the sludge used as fertilizer and the biogas byproducts used to power vehicles such as buses or trucks. Additionally, car ownership in the area is rather low - only 210 cars per 1000 residents [4]. Furthermore, since all residences are located within 300m of a light rail station, and there is an abundance of walking and cycling paths in addition to ferry, carpool, and bus systems, personal cars are not considered a necessity [4].

As both a result and cause of the success story of the district, there is a large amount of data and statistics available on Hammarby Sjöstad [6]. Additionally, due to all of these sustainability features and environmentally conscious residents, the district will most likely be one of the first adopters of electric vehicles in Stockholm. Therefore, research in this area is especially pertinent and many stakeholders - residents, the local energy company Ellevio, city officials - are interested in the modeling of the current and future grids to better plan and prepare for an electric vehicle future.

3 Objective

The aim of the project is to model the effect of charging PEVs (Plug-in Electric Vehicles) on an existing electric distribution system in Hammarby Sjöstad, Stockholm, Sweden.
4 Literature Review

The inspiration and structure for the subsequent paper was largely modeled off of a 2010 IEEE paper by Babaei et al., which modeled a district of Gothenburg [7]. The main points of the paper were about subregions, charging estimation, and an iterative method approach.

Knowing the subregion categorization predicts how demand will vary throughout the day. In primarily residential areas, the peaks occur in the mornings and evenings when people get ready for and come home from school and work. In primarily commercial areas, the peaks occur during the middle of the day, when people are using the most power at work. These peaks would probably also correspond to when people are most likely to charge their electric vehicles, meaning the grid would be at an even greater risk of failure.

The paper also proposed a way for estimating the number of vehicles charging based on time and location. The method was done for 10 to 0.4 kV distribution systems. The general idea was to multiply the power rating for a standard outlet in the region by the estimated number of vehicles, which was estimated by a factor times the proposed estimation for number of customers. This method was also adopted in this study’s estimations, but with a different power rating. In addition, the data given from the energy company provided data on customers, so instead of estimating the number customers, values from the data were used.

Finally, Babaei et al. proposed an iterative method to find max supportable loading based on the N-1 reliability criterion. Instead of performing calculations with the proposed iterative method, a Python based tool was used, as explained in the Methodology section, and this study assumes the N-1 reliability criterion is satisfied.

5 Methodology

Knowing from the literature review that subregion classification was an important factor, the first step was to similarly classify subregions of Hammarby Sjöstad. A field trip was taken and observations were recorded. Data on the network topology, substation powers, number of customers, and technical cable information was provided by the energy company Ellevio and utilized. Next, a computational model was built in PandaPower, a Python based network calculation program used to analyze power flow and optimize electrical systems. First, a base model was created, extracting the maximum loads from 2016 to model the historical worst case scenario. Then, the base model was modified to run in a loop taking branch currents in time series as inputs. Lastly, PEV loads were estimated based on the number of customers, and added into the base model. Failure points were defined and results between the base and base + PEV model were compared.

6 Results

6.1 District Categorization

Following a field trip to Hammarby Sjöstad, the district was categorized as seen in Figure 2.

The dark blue area is primarily residential, with blocks of 5-8 stories comprising so called ‘housing associations’. The red area is primarily commercial,
with office space, a car wash, a gas station, car dealerships, and other businesses. This area also includes a collection centre for the stationary automated waste disposal system as well as Fortum’s thermal plant, discussed previously. The yellow area is a construction area where an eco village is currently being built; once completed, it will add residences to Hammarby Sjöstad. Lastly, the purple area was deemed ‘transitory’, being composed of multi-story blocks which featured businesses such as banks, gyms, shops, restaurants on the ground floor, with residences on the floors above.

The map of Figure 2 also includes green dots, referring to electrical substations. The two parents substations of Hammarby Sjöstad are Skanstull (abbreviated SK) and Katarina (abbreviated KA); these step down incoming voltage from approximately 50 kV to approximately 11 kV. From these parent substations, the 11 kv cables go out further to other labeled green dots; these substations step down the voltage further, to 0.42 kV.

In order to ensure the validity of the field trip’s observations, historical current over time data was utilized. Assuming that the current is directly proportional by some voltage magnitude to the load, the load profiles were plotted in subsequent subsections for the selected residential and commercial areas.

### 6.1.1 Residential Load Profile

The selected residential subregion consisted of substations SK90, SK91, and SK91b. The area was selected based on its purely residential characteristics from field trip observations. To understand the electrical schematic of the subregion, a single line diagram is supplied in Figure 3.

![Single Line Diagram of Residential Subregion](image)

**Figure 3:** The single line diagram of the residential subregion.

In this single line diagram, the parent substation, SK, is seen at the top. Other substations not included in the subregion are disregarded for simplicity. The blue lines represent the 11 kV cables, and are labeled as N0, C0, and C1 going out to substations SK90, SK91b, and SK91, respectively. The residential subregion included a total of two branches: though whereas one branch - SK90 - included only one substation, the other branch - SK91 - included two 11 kV lines and two substations. This is seen in Figure 3, as the current carried in C0 is split at SK91b, with some proportion being stepped down and carried to a load while the rest continues on to SK91. This will have implications for analysis, discussed further on.

The orange lines represent the 0.42 kV cables, which go out to buildings and further substations where one last step down to 0.23 kV occurs; the standard electrical outlet in Sweden is rated at a voltage of 0.23 kV (or 230 V), a current of 16 A, and a frequency of 50 Hz. From there, the electricity is consumed by appliances, lighting, and so on, culminating in a load. This diagram also labels the buses, defined from zero to three in the black circles.

In order to ensure that observations match the historical data, a plot of current over time for the residential subregion may be seen in Figure 4 assuming load is directly proportional to current.

![Load Profile Graph](image)

**Figure 4:** The load profile is particularly characteristic of a residential subregion for substation SK91.

The trends are consistent with those expected of a residential subregion, especially for substation SK91. In the early morning hours, when most people are sleeping, electricity consumption is lowest. As people get up, make breakfast, etc., consumption increases, then levels off for a period in the afternoon. When people return home from work, cook dinner, watch TV, etc., consumption peaks. From the historical data, the maximum current for the SK90 and SK91 branches was found to occur in January and February, respectively, both at 19:00. Interestingly, both
peaks occurred on a Sunday, not a weekday; perhaps the most people would be at home then and consuming electricity.

### 6.1.2 Commercial Load Profile

The selected commercial subregion was the most clearly defined commercial area, with the least number of transitions or questionable classification spots. The location was analyzed and the subregion consists of the SK09, SK12b, SK12, SK15b, and SK15 areas. As a note, SK15 is not located in the region, but has also been included in the model because it is in series with SK15b, which clearly feeds into the model. A summary of these substations as a snippet of the larger grid is shown in the single line diagram, Figure 5.

![Figure 5: The single line diagram of the commercial load profile.](image)

A load profile for a typical winter (high load) weekday, weekend, and week are shown in Figure 6, 7, and 8. The trends match those described in Babaei et al. well for weekdays. Observations seen that were not mentioned in the paper are that on weekends, the commercial trend of load peaks at midday are not very apparent, because people are not coming to work. Also, some substations, such as SK09, exhibit fairly constant loading for each day, most likely because it serves a machine that does not vary based on human behavior.

![Figure 6: A load profile summary of a commercial region for a weekday.](image)

![Figure 7: A load profile summary of a commercial region for a weekend.](image)

![Figure 8: A load profile summary of a commercial region for a week.](image)

### 6.2 Base Model

The electrical grid needs to be able to withstand the largest possible load; therefore, the base model was constructed from these peaks. However, since assumptions vary slightly between the residential and commercial subregions, the base models varied as well.
6.2.1 Residential Base Model

First, a very basic model for the selected residential subregion was constructed in PandaPower, using maximum loads from 2016 at a single instant in time; 2016 was the year with the most comprehensive data, and was thus used for much of the modeling of this report. Then, variables were altered to observe their effects on the power flow. Many interesting observations were noted. Firstly, the losses were much, much smaller in the second line of a multi-line branch than in the first. However, they are much much larger in the first line of a multi-line branch than when compared to a single line branch. Other interesting findings included that the resultant current in the N0 and C1 lines was the same, and was twice as high in C0. This PandaPower result reinforces the data plotted in the profile of Figure 4, where the current in the SK91 branch is twice as high as the current in SK90 branch; this is due to the fact that the SK91 branch contains two 11/0.42 kV substations and current splits in parallel, as discussed previously.

Lastly, the active and reactive power at the external grid equals the active and reactive power at bus 0. This makes intuitive sense, since what is known as the external grid in PandaPower is the slack bus of the system, where active power may vary. In this system, bus 0 is the slack bus as labeled in Figure 3.

Tuning of the base model involved making different assumptions about whether provided maximum loads are apparent or real/active, changing the power factor, and tweaking the cable technical information, including the resistance, reactance, and capacitance. From results and given units, it was concluded that the given loads are apparent, and the given cable technical information was assumed to be correct as well. The testing of several different power factors, including 1.00, 0.95, 0.90, and 0.85 had minimal effects on the line loading and external grid: decreasing the power factor led to a tiny, insignificant percent change, less than 1% from a power factor of 1.00 to 0.85. For this reason, the power factor of 0.95 from the literature review was decided upon for the residential subregion.

With the base model tuned for one instant in time, the next step was to expand it for a time range. Although modeling with the maximum loads ensures the grid can withstand the maximum loading, this is not representative of the variation of a typical day. Therefore, the basic model was modified to run in a loop over a desired time range. It takes the 2016 hourly current data as an input, isolates the specified time range, and runs a power flow on a loop, outputting the same desired values from the initial model: line currents, line loading percentages, bus voltages, active and reactive powers on the external grid, etc.

6.2.2 Commercial Base Model

Similarly the chosen commercial region was modeled and run in PandaPower. First the raw data and information obtained from the energy company were inputted. Then, estimations were made for bus loads and power factors, and the model outputs were compared to the data to assess for accuracy and for making modifications. Although the numbers did not match up exactly, there were indicators of model plausibility. For example, output of current through each of the lines are on a decent order of magnitude, as shown in Table 2.

<table>
<thead>
<tr>
<th>Substation</th>
<th>max i</th>
<th>min i</th>
<th>mean i</th>
<th>Modeled i</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK09</td>
<td>54 A</td>
<td>1.75 A</td>
<td>10.17 A</td>
<td>7.8</td>
</tr>
<tr>
<td>SK12 + SK12b</td>
<td>92.71 A</td>
<td>11.75 A</td>
<td>35.16</td>
<td>45, 2.2</td>
</tr>
<tr>
<td>SK15 + SK15b</td>
<td>91.41 A</td>
<td>20 A</td>
<td>11.75 A</td>
<td>62.9, 119</td>
</tr>
</tbody>
</table>

Also, relative customer percentages, based on data outside of the PandaPower inputs, are similar to relative loading percentages, and output of the PandaPower model based on physical grid inputs. The percents do not match, but the ordering is similar, with SK15b and SK15 having a slight discrepancy
due to SK15 being far away in a residential area. This is summarized in Figure 9.

![Figure 9: A summary of comparing current and customer percents.]

### 6.3 PEV Model

Once the base model was set up to iterate over a time range, additional loads from PEVs could be easily added. These PEV loads were estimated using the following statistics: the amount of parking spaces was assumed to be 0.55 parking spaces per household, with approximately 210 cars per 1000 residents.

#### 6.3.1 Defining Failure

For the purposes of this study, failure is defined as a 100% line current loading percent, and a bus substation failure of \( \pm 5\% \) bus rated voltage, which in per unit is 0.95 or 1.05 \([9]\). These definitions assume that at these points, the cable lines will break and substation buses will fail, respectively.

To find a point of failure due to increased loads, a ‘car loading factor’ was added to the code. The car loading factor is the constant multiplied by the number of estimated vehicles per bus. The constant represents the percent of total available vehicles currently plugged in for that run of the model. For example, a car factor of 1 assumes that all of the estimated cars in that region are plugged in and charging at the same time.

#### 6.3.2 Residential PEV Model

Estimates of PEV loads for the residential subregion based on the number of customers are shown in Table 3.

<table>
<thead>
<tr>
<th>Substation</th>
<th>SK90</th>
<th>SK91b</th>
<th>SK91</th>
</tr>
</thead>
<tbody>
<tr>
<td>of Customers</td>
<td>203</td>
<td>293</td>
<td>306</td>
</tr>
<tr>
<td>Estimated of PEVs</td>
<td>112</td>
<td>161</td>
<td>168</td>
</tr>
<tr>
<td>Load due to PEVs</td>
<td>753 kW</td>
<td>1082 kW</td>
<td>1129 kW</td>
</tr>
<tr>
<td>2016 Max Load</td>
<td>1262 kW</td>
<td>1376 kW</td>
<td>1080 kW</td>
</tr>
<tr>
<td>Total Load</td>
<td>2015 kW</td>
<td>2458 kW</td>
<td>2209 kW</td>
</tr>
</tbody>
</table>

In Sweden, as mentioned previously, the standard electric outlets are rated at 230 V, 50 Hz, and 16 A for a power of 3.68 kW. However, since there is no data on the distribution network past the 11/0.42 kV substations, the loads cannot be modeled at the 230 V level but at the 0.42 kV level. Still assuming a current of 16 A, the charging power here would be 6.72 kW. Multiplying this by the estimated number of cars for each substation in Table 3, gives additional loads due to the charging of electric vehicles.

With the inclusion of the PEV loads, the Base plus PEV model was thus created. The model yielded many interesting results which will be discussed in subsequent paragraphs.

First, a random weekday - Monday, January 11, 2016 - was selected and input as the time range, and the relationships between different outputs were observed. The results were also compared to the same day’s Base model results. With the additional PEV loads, the outputs’ plots retained the same shapes, though often with increased magnitudes. Specifically, the line currents and line loading percents increased, as expected; this can be viewed graphically in Figure 10. With the exception of the slack bus which remained at a perfect \( v=1 \) per unit, the bus voltages decreased slightly in magnitude while retaining the general shape of the plot. Lastly, the active and reactive powers of the external grid became more negative, meaning their magnitudes increased. All these results were consistent with expectations.
An additional comparison was made between a day in January and a day in June. Since both substation’s maximum current values occurred in winter, a relationship between the cold weather and higher energy consumption was assumed. However, this proved to not necessarily be the case after several winter days were compared to several summer days; the winter line currents appeared to be on par with the summer line currents. Appendix A offers a comparison of these plots.

6.3.3 Commercial PEV Model

Building off of the Base model, estimated PEV loads were added and their effects on loading percent, bus voltages, and the external grid were evaluated. Using the week of 1/11/2016 as an example, some observations were made. Comparing the base model to the Base with EV loading, the trend and general shapes of each graph across the same parameter stayed the same. After adding loads, all of the current loading percents went up and bus voltages per unit decreased, except for the slack bus which is defined as having a reference value of one volt. The external slack grid’s active and reactive powers became more negative, increasing in magnitude.

To determine a failure point, Line L0 was analyzed because the base model indicated that it experienced the most amount of loading compared to any line, which means it would most likely be the first to fail. At a car loading factor of 1.36, the line hits a current loading percent of 100%, which means that the cable line would fail. At this point, the buses still have not reached 0.95, indicating the line would fail before the bus. A car loading factor of 1.36 translates to a scenario where 1.36 times the number of cars that exist for each station (based on previous estimations) are being plugged in at the same time.
7 Conclusion

An model of PEV charging on an existing electric grid in Hammarby Sjöstad was created. Preliminary results show that with the addition of PEV loads, the grid would not fail but would be significantly impacted.

Limitations of this study include a limited region. Furthermore, the area selected was predisposed to electric vehicle adoption, and thus would not be representative of future electric vehicle adoption in all of Sweden. Future additions to this study would include verifying and narrowing assumptions, modeling PEVs connected directly to standard outlets, including transformers in the model, accounting for human factors, and distributing PEV charging over the course of the day. However, this study provides a basic assessment of PEV charging in Hammarby Sjöstad and the potential impact on the grid.

8 Bibliography

References


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10 Appendices

Appendix A

Figure 14: The line currents on a winter day.

Figure 15: The line currents on a summer day.