CASE STUDY ON THE EFFECTS OF INCREASING ELECTRIC VEHICLE AND HEATING LOADS ON A DISTRIBUTION NETWORK IN STOCKHOLM

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ABSTRACT

In future scenarios, a surge of distributed energy sources is to be expected in the grid. In Sweden, this entails a larger share of plug-in electric vehicles (PEVs) in the transport fleet and an increased use of heat pumps (HPs) for household heating In order to guarantee the successful integration of these new loads, it becomes important to evaluate their impact on the distribution network This work presents a case study analyzing the effects of PEVs and HPs in the local grid of a neighborhood in Stockholm. Studies were carried out to determine the maximum number of loads that can be handled by the grid without any need for reinforcement. Furthermore, the possibility to increase the level of penetration by means of demand side flexibility scenarios was also analyzed and their resulting losses and costs were compared. Results showed that it was possible to achieve penetration levels of up to 3 times as much than for the uncontrolled cases.

NOMENCLATURE

HP	Heat Pump
HS	Hammarby Sjöstad
PEV	Plug-in Electric Vehicle

INTRODUCTION

In connection with on-going global climate efforts, Sweden adopted a bold energy policy with the objective to reduce the emissions from transport by 70% by 2030, have 100% fossil-free power generation by 2040 and release zero net greenhouse gases into the atmosphere by 2045 [1]. Achieving these goals will have a challenging influence on the current energy and transport infrastructure at urban district level. Plug-in electric vehicles (PEVs) nowadays amount to 0.9% of the total national fleet and according to future scenarios, in 2050 this will increase to 10% [2]. Furthermore, the use of heat pumps (HPs) at both small and large scale is expected to increase in order for combined heat and power plants to be able to balance the variabilities in the grid due to renewables [3]. Both of these PEV and HP increased quantities translate into higher loads in the distribution grid.

Previous studies in the field have been carried out for distribution networks over different locations in Sweden and the world [4] [5]. In general, the impact of increased loads in the network is highly dependent on the area being studied, the capacity of the existing grid and behavioral factors. This paper aims to evaluate whether the existing distribution system infrastructure of a district in Stockholm would be able to support the mass introduction of PEVs and HPs. For this, a network model was developed and validated against measured data provided by the DSO. By use of the network model, six critical loaded hours were analyzed and the number the maximum allowance for PEVs and HPs was quantified for each of the substations in the area. These amount of additional loads were then studied for the course of a critical day in order to observe the impact that load management schemes can have on the previously calculated levels of penetration.

CASE STUDY DATA

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 [6]. Today, about 70% of the area is developed and by its estimated completion it will have 12.000 residential units, 31.000 inhabitants and employ 10.000 people [7]. 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 [8] have been working for some years to engage the tenant-owner associations and residents towards concrete energy and climate measures. Two projects to highlight from that initiative are: “Charge at Home” which makes use of policy incentives to install charging infrastructure in households and “Energy at Home” which focuses on energy-related savings at the housing associations. As a result of the second project, an increasing number of customers decide to disconnect from the traditional heating network when comparing the potential economic savings of installing residential HPs in their building. This sets a natural predisposition for HS to be an early adopter of various distributed energy resources, thus making it a very relevant test-case for this study.

Network Topology and Modeling

The modeled network within HS consisted of nine 10kV/0.4kV substations supplied via one feeder. A single line diagram of the network is shown in Figure 1 displaying “HSFS” as the feeder and the substations named in accordance to their load types. Substations have been categorized as residential (RS), commercial (CM) or mixed (MX) based on the predominance of customer types connected to the substation.

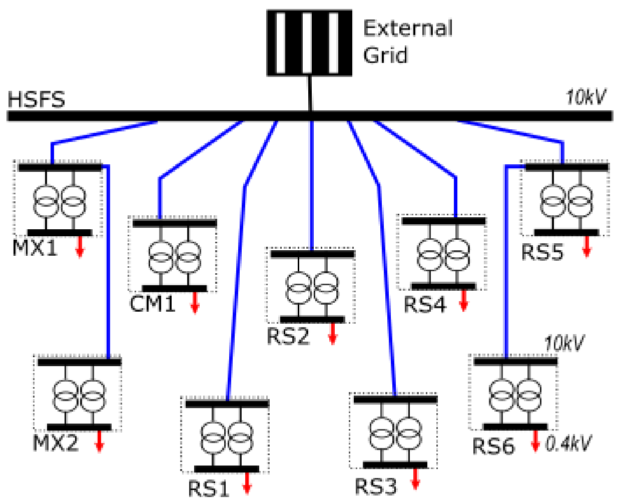

Figure 1 Single line diagram of the 10kV/0.4kV network.

This network topology was modeled using pandapower [9], a python-based tool used for load flow analysis of networks. In order to build a relevant representation of the HS network in the tool, input data concerning transformers rated values, cable properties, connected customer characteristics and system topology was provided by Ellevio AB, the electric power distribution company in the city of Stockholm. Furthermore, the DSO also provided hourly current measurements at HSFS and maximum transformer loading over the year. These were used which to validate the network model base loads. As a reference of the size of the substations categories, Table 1 shows the percent of available transformer capacity with respect to the total of the system.

Table 1 Percent of transformer rated capacity at each substation category

Substation type	[%]
Mixed (MX1-MX2)	21.1
Commercial (CM1)	10.5
Residential (RS1-RS6)	68.4

Critical Base Loads

Based on the hourly loads of the network for 2016, six critical hours were highlighted during the year and are listed in Table 2. The hours were selected based on two criteria: high overall demand at the external grid (global maximum) and also a high loads at a particular substation (local maximum). Among the selected dates, the residential predominance of the network is clearly observed as most of the critical hours coincide with the evening peak. Also, it is seen that the selected critical a hours are concentrated around the winter time, when the loads are typically higher.

Figure 2 shows the load distribution in the substations of the system for the selected critical hours. Furthermore, Table 3 shows the loading percentage achieved in the system elements (transformers and cables) related to each substation. It only displays the maximum loading achieved in the substation among the selected critical hours. It is seen that different maximum values are achieved during different days. The only date not displayed in Table 3 is 19/01 and this is due to the fact that this corresponds to a global maximum of critical loads.

Table 2: Critically loaded hours for the studied network

DATE	TIME	DAY OF WEEK
10/01	19 :00	Sunday
14/01	16 :00	Thursday
19/01	19 :00	Tuesday
24/01	19 :00	Sunday
21/09	09 :00	Wednesday
12/12	19 :00	Tuesday

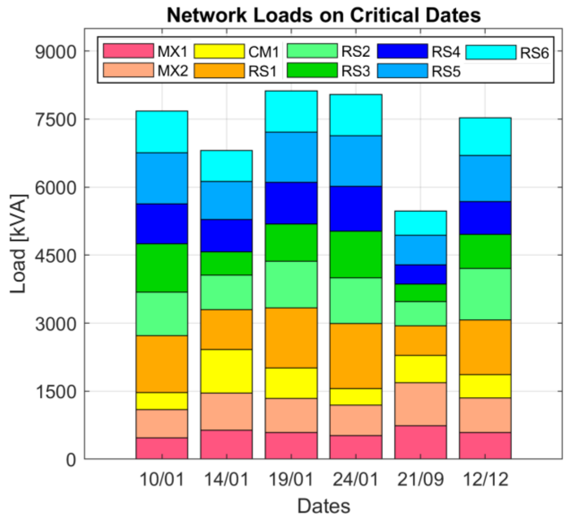

Figure 2 Distribution of system base loads.

Table 3 Maximum Element Loading Percentages

	Line Load	Trafo Load	Date
MX1	16.0	46.5	**21/09**
MX2	4.5	60.4	**21/09**
CM1	8.7	61.2	**14/01**
RS1	13.0	91.4	**24/01**
RS2	10.3	57.8	**12/12**
RS3	9.7	67.8	**10/01**
RS4	8.9	49.7	**24/01**
RS5	18.6	71.6	**10/01**
RS6	8.4	58.4	**10/01**

HOURLY MAXIMUM LOAD SCENARIOS

The studies in this section consisted of calculating the maximum level of penetration of additional loads that the network can handle without reinforcements and without resulting in any overloaded lines or transformers or

violating the voltage limits. This was done for all the substations in the network and for each of the critical hours listed in Table 2.
In order to quantify the additional loads in the form of amount of PEVs or HPs, assumptions were made for each type of load. The vehicles' charging was assumed to be performed from a standard single-phase outlet of 230V and 16A. The charger is assumed to charge with a power factor of 0.95 [10] . The pumps were assumed to have an average yearly coefficient of performance of 3.2 and referenced to a building in the area with $170kW_{th}$ of heating capacity (space heating and hot water) [11].

Uncontrolled loading

On the uncontrolled loading case the number of PEVs and HPs was increased until reaching constraints on either transformers, lines or voltages. Figure 3 shows the distribution of these load quantities over the different network substations, their maximum allowance varies within 1793-2496 vehicles and 120-170 pumps. These ranges are of course related to the existing base load at the stations among the selected dates as shown in Figure 2.

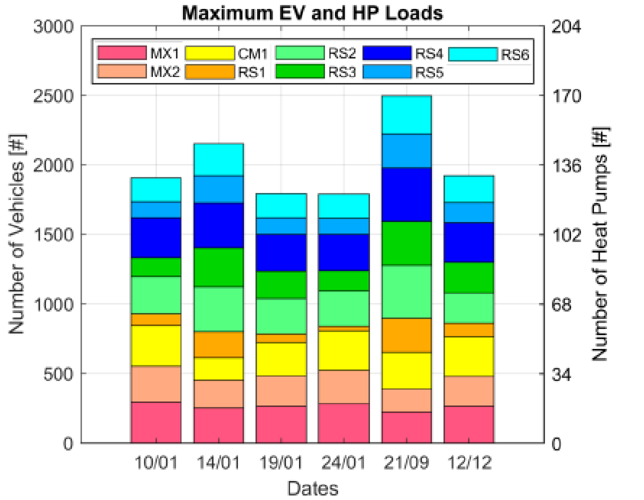

Figure 3 Maximum allowance of PEVs and HPs for the uncontrolled loading case.

It is important to highlight that across all substations and critical dates the limiting elements for further increasing the loads were the transformers at the stations. With regards to the loading of the cables, the largest load percentage amounted to 30% in the line corresponding to MX1. RS1 was the substation with the least allowance for additional loads due to its highly loaded transformer, as shown in Table 3.

Behavior controlled loading

This case followed the same principle as the uncontrolled, except that assumptions were made concerning the behavior of the loads with respect to the type of substation. The assumptions consisted on whether a given load is active during the analyzed times. During weekends, no loads are active in the commercial substation while they are considered fully active in the residential areas. During weekdays, the loads are active in the commercial substation within working hours and before/after those hours in the residential ones. The load activity in the mixed substations was assumed to follow the union of the other two categories.
Figure 4 shows the distribution of these load quantities over the different network substations, their maximum allowance varies within 510-2496 vehicles and 47-150 pumps. The variations with respect to the previous case is also displayed in the figure with dotted lines. Essentially, the changes are due to the lack of PEV/HP load activity in the commercial substation. One main difference can be observed in the figure between the residential PEVs and HPs loads for the critical hours of 14/01 and 21/09. This difference is based on the assumption that heating loads are active at the hour prior to the evening peak of people arriving home while not during morning peak of people leaving for work.

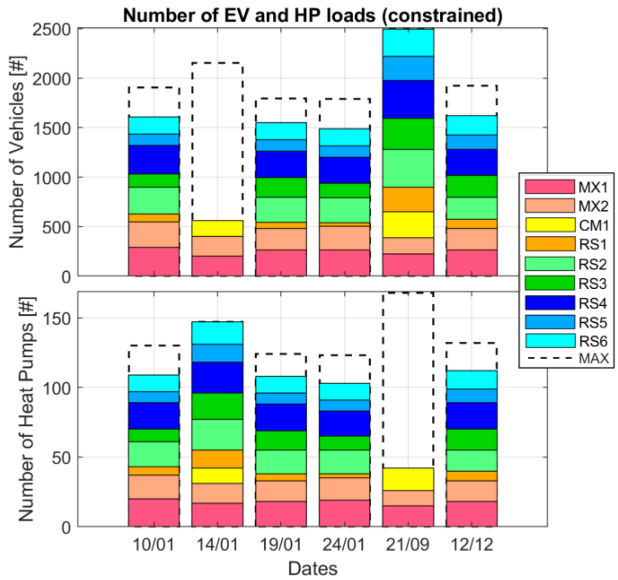

Figure 4 Maximum allowance of PEVs and HPs for the behavior controlled case

DAILY LOAD MANAGEMENT SCENARIOS

Given the majority of residential substations in the network, this part focuses only on RS1-RS6. Among the critical hours studied so far, the daily load profile of January 24th was selected for daily analysis. Figure 5 shows the base load variations in the residential substations throughout that day. The respective electricity hourly price at Nord Pool [12] was retrieved and is also displayed in the figure for three hours.
Based on the two on-going projects at HS called "Charge at Home" and "Energy at Home", daily load profiles were generated for vehicle charging and household heating. When generating these profiles, two scenarios were

considered. The first scenario assumed the amount of HPs and PEVs that were calculated in the previous section. Based on these quantities, the loads were assumed to behave in a business as usual (uncontrolled) manner. The second scenario consisted on controlling the loads based on price improvements while at the same time increasing the level of penetration of the loads. For this scenario is was assumed that the customers in the network are subject to the prices in the Nordic market directly.

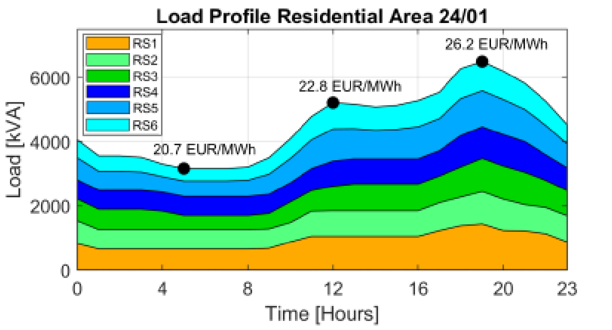

Figure 5 Load profiles during 24/01 in the residential substations

For each type of load the scenarios were compared with regards to increased level of penetration, system losses and costs. This was done by running the model of the network with the difference profile scenarios and verifying that no limits were surpassed. Since the power profile behavior of PEVs and HPs differs from one another the following subsections explain the assumptions made for each case separately.

PEV load management

Uncontrolled profile: In the uncontrolled charging profile, the charging takes place directly after the vehicle is connected to the power outlet, which in this case is in the evening after people have used their car during the day. The number of vehicles at each substation was taken from Figure 4. An average day driving distance of 36 km conducted in 44 minutes was assumed for all the vehicles in the area [13]. An energy consumption of 0.17 kWh per kilometer [14] and a charging efficiency of 88% [4] result in two hours of charging are needed for each vehicle. The resulting profile is shown in Figure 6.

Price controlled profile: In order to generate the price controlled profile the main the same charging duration as in the uncontrolled scenario was considered. However, the charging loads were shifted to take place at the times in which the electricity price was lowest. Furthermore, since this hours also happened to be less congested for the network, the amount of vehicles in the area was increased with respect to uncontrolled case. The resulting profile is shown in Figure 6.

Scenario comparison: The feasibility and impact of these two profiles on the network was evaluated in the developed power flow model. Table 4 shows the comparison between the two PEV scenarios. The system losses and the costs displayed in the table are those related only to the PEV loads. It can be seen that for three times the amount of vehicles the price controlled scenario has 144.6% more system losses and 134.4% more costs than the uncontrolled scenario.

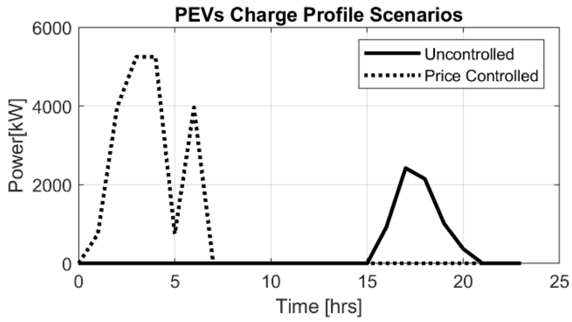

Figure 6 Uncontrolled and price controlled PEV charging profiles

With respect to the total energy consumed in the area, the losses correspond to 0.11% and 0.24% for the uncontrolled and controlled case, respectively. With respect to the total electricity costs, the charging costs correspond to 5.27% for the uncontrolled and 11.54% for the controlled. The specific charging costs per car compare as 0.18 EUR for the uncontrolled case and 0.14 EUR for the price controlled.

Table 4 Comparison of costs and losses between uncontrolled and controlled cases for PEV load scenarios

	Uncontrolled	Controlled
Number of Vehicles	983	2849
System losses [kWh]	161.1	394.1
Charging costs [EUR]	176.4	413.7

Heating loads management

Uncontrolled profile: In the uncontrolled profile for HPs, the heating follows the demand curve shown for the base load in Figure 5. The total amount of HPs installed in the substations of the system was taken from Figure 4. Since this number corresponds to the peak hour load, the number of pumps connected simultaneously for the remaining hours was scaled linearly with the base load for each hour. The resulting profile is shown in Figure 7.

Price controlled profile: The price controlled profile for the heating loads was based upon the principle of load shedding. During the peak hours the HP loads were disconnected. In order to counter-balance this and maintain the comfort temperature in the spaces being heated the loads were increased at the hours prior to the peaks, in which the price for electricity is cheaper. Since this hours also happened to be less congested for the network, the amount of connected heat pumps was increased during these hours. The resulting profile is shown in Figure 7.

Scenario comparison: As for the PEV profiles, the impact of the electric heating loads was evaluated in the network model. Table 5 shows the comparison between the two HP scenarios. It can be seen that for 1.3 times the amount of heat pumps the price controlled scenario has 8.5% less system losses and 24% less costs than the uncontrolled scenario. With respect to the total energy consumed in the area, the losses correspond to 0.61% and 0.56% for the uncontrolled and controlled case, respectively. With respect to the total electricity costs, the heating costs correspond to 30.6% for the uncontrolled and 23.9% for the controlled. The specific heating costs per pump compare as 21.8 EUR for the uncontrolled case and 12.7 EUR for the price controlled.

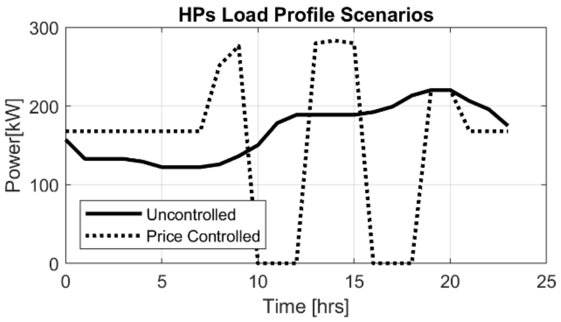

Figure 7 Uncontrolled and price controlled HP heating profiles

Table 5 Comparison of costs and losses between uncontrolled and controlled cases for HP load scenarios

	Uncontrolled	Controlled
Number of heat pumps	64	83
System losses [kWh]	1224.4	1119.57
Heating costs [EUR]	1395.3	1053.8

CONCLUSIONS

This paper evaluated the effect of future loads from plug-in electric vehicles and heat pumps for a district in the city of Stockholm. For this, the distribution network of Hammarby Sjöstad was analyzed for six critically loaded hours and during the course of a critically loaded day. The results showed the number of vehicles and heat pumps that are allowed to be simultaneously connected on the critical hours. This maximum numbers serve as a reference for planning the amount of capacity that would be needed from the external grid under these circumstances. However, it was seen that for certain substations such as RS1, this amount might be marginal and that there might be a need for early reinforcement.

Results also showed that under load management strategies, it was not only possible to increase the level of penetration of the loads, but to do so at a decrease of cost per additional load. For the case of PEVs the level of penetration were increased by up to 3 times as for the uncontrolled case. These results serve to identify possible limitations and capacity shortages in the network to allow for the smooth planning of a robust energy infrastructure for the future.

As part of future work, the model can be used within an optimization routine to find optimal load scenarios with regards to losses and costs. This study was performed considering PEV and HP loads in isolation, when in reality the increase of these loads will happen together. While the number of PEVs and HPs found within this study serve as a baseline, future studies shall consider the N-1 criterion. Finally, with regards to the heating loads, the comfort indoor temperature was not modeled directly and will be an important factor to consider in the future.

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