Study of the potential implication from large scale BEV employment in Swedish households

Change in households rated power demand from uncontrolled charging of Battery Electric Vehicles

Master's thesis in Sustainable Energy Systems

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Abstract

The electrification of society could radically change the electricity consumption of households when loads like Battery Electric Vehicles are introduced. The annual maximum power demand (also referred to as the rated power demand) of a household, represents how much electricity a household consumes when it consumes the most in the time-span of one year. This study investigates how the rated power demand of households changes with a deployment of Battery Electric Vehicles. Data from The Swedish Energy Agency on apartments and villas electricity consumption was combined with estimated charging profiles for Battery Electric Vehicles, extracted from GPS measurements of 429 vehicles in Western Sweden.

Results from this study indicate that the increase in households annual maximum power demand (rated power demand) from the introduction of Battery Electric Vehicles can vary from a 50 % increase to a 800 % increase, depending on how many Battery Electric Vehicles are charged simultaneously and how many vehicles are connected to the same part of the grid. Limitations of current fuses indicate that load balancing and controlled charging could be a necessity.

The result shows a clear linkage between the type of household (villa or apartment), the number of inhabitants and the increase in households rated power demand. Independent of the number of households included in a combination, Apartments most frequently display a higher increase (250 %) in rated power demand compared to villas (75 %). Current household fuses are not able to cope with this increase in power demand and thus the results implicate the need for load balancing in households - distributing the increase over a longer time.

For a certain number of inhabitants, the increase can vary in magnitude, this variation seems to decrease as the number of inhabitants increases i.e. when aggregating the power demand of more and more households. The maximum possible increase, change less and less as the number of inhabitants increase, which could strengthen the argument that a neighborhood is better suited for a full introduction of Battery Electric Vehicles if only uncontrolled home charging is available. The maximum observed rated power increase with the size of the neighborhood. For a neighborhood consisting of up to 16 apartments it is 140 kW and for a neighborhood made up of 20 villas it is 150 kW, whereas the corresponding number for a neighborhood consisting of the combination of apartment and villas is 225 kW. The study indicate benefits of controlled charging as there is a possibility to reduce power demand, by strategically charge vehicles at certain periods of time.

Keywords: Rated power, Load, Battery electric vehicle, Driving behavior, Power demand, Charging, Increase.

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Joel Schelander, Gothenburg, June 2021

Contents

1
Introduction

1.1 Background

The European Union has a goal of reducing greenhouse gas emissions from transport by 2050 to a level that is 60 % below that of 1990 [1]. Transport represents almost a quarter of Europe's greenhouse gas emissions and is the main cause of air pollution in cities. Light-duty vehicles – cars and light commercial vehicles (vans) – produce around 15 % of the EU emissions of CO_2, the main greenhouse gas [2].

Electric Vehicles (EVs) have the potential for environmental benefits in terms of reducing CO2 emissions and air pollution if the amount of renewable electricity generation in the electricity system is large enough [3]. An increase in renewable energy sources such as intermittent energy sources (wind, solar and hydro power) lowers the average cost of electricity [4]. Sweden has a goal of generating 100 % of the electricity from renewable energy sources in the electricity system by 2040 [5]. One option for Sweden to reduce greenhouse gas emissions could be the deployment of Electric Vehicles. According to the Swedish Environmental Protection Agency, emission from domestic transportation represents one third of Sweden's emissions. The Swedish Climate Policy Council states that in 2030 the overall emissions from the transport sector should have been reduced by 70 % compared to the levels of 2010 [6, 7].

There are three main categories of EVs: Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV). Technically, HEV is characterized as having both an Internal Combustion Engine (ICE), powered by gasoline, gas or other biofuels, and an alternative electric motor, which is powered by electricity stored in a battery. The batteries of these cars are charged by regenerative braking systems (kinetic energy is captured during deceleration and stored in the battery) and by their ICE. In the same way, PHEVs use both an electric motor powered by batteries and an ICE powered by bio-fuels or fossil fuels. In general, PHEVs have larger batteries than HEVs and can also be charged directly from the electricity grid. These vehicles can be powered solely by electricity or by a specific fossil fuel.

BEVs only use batteries, that can be charged from the electricity grid to power an electric motor [8]. A BEV is consuming electricity when accelerating to a certain degree and regenerating electricity when decelerating. Electricity consumption can also differ with regards to velocity, the grade of the road and ambient temperature [9, 10]. The EV penetration in Sweden, i.e. the total number of electric vehicles, was 69 910 in Mars 2021 [11].

Socioeconomic characteristics are strong predictors of BEV ownership, such as wealth, income and education [12]. Purchase prices can be significantly higher for an electric vehicle compared to a conventional car. Although, prices could equalize, as production volumes increase and battery technologies continue to mature. Also, initial costs can be redeemed by fuel cost savings [13]. However, even though BEVs still hold a lower share of the automotive market, the number of BEVs is expected to increase significantly the next decades [8].

Two significant barriers for consumers to adopt BEVs are the limited range and the price [14]. A BEV purchased today involves a high initial cost [15]. Consumers with a higher income that purchase more expensive BEVs, e.g. Tesla Model S, are inclined to keep their vehicle and continue to select BEVs in their subsequent purchases of vehicles. To make cheaper BEVs (Nissan Leaf) more appealing to households with a lower incomes, the time to charge and the range of these vehicles need to improve [16].

Limited range is perceived as a challenge by BEV owners due to the limited capacity of the battery. However, as the drivers become more experienced (defined as kilometers driven) they exhibit less range-anxiety [17]. New BEV owners are early in their ownership experience. As they become increasingly accustomed to the new technology and its nuances, especially the recharging, their behavior might change [18]. BEV range limitations in everyday use is characterized by avoidance of range-stress. That is, BEV-owners reserve a considerable amount of charge as a buffer to avoid critical range situations. The comfortable range is actually only 80 % of the actual range, but it has been shown that the comfortable range increases with BEV experience [17].

Vehicles are parked for approximately 95 % of the time on average and a car battery could be available in the electricity system for large parts of the day [19]. This can assist the integration of renewable energy sources into the electricity system [20]. The charging event is used as a shifting variation management strategy, where the load from charging is shifted to periods where excessive power from renewables are generated e.g. wind power. The battery can be discharged other hours of less generation. This has the potential to reduce the cost of charging for the BEV owners [21].

Battery Electric Vehicles can be charged through single phase 230 V AC connection, three phase 400 V AC connection or external charger DC connections for fast charging. The charging rate of BEVs can vary from a few kW to tens of kW depending on the charging mode and the charging current [21]. The variation with respect to charger size is quite significant for the load characteristics. Smaller charger sizes tend to reduce the peak value of electricity consumption, spreading the load to longer time period [22]..

The charging event can occur at the workplace, at a public charging station or at home. When the charging occurs at the workplace, the vehicle can be connected to the grid during the working hours. Several BEVs can be charged with the same charger, which offers ancillary services (for example voltage or frequency regulation) to the grid [23]. Charging at public stations could alleviate range-anxiety among BEV-drivers [24]. 70 % of BEV-drivers acknowledges that they charge their vehicle at a public location (e.g. at shopping centres and restaurants). Fast charging is a relatively new technology and a public network of fast chargers is argued to be a key component of an overall BEV charging infrastructure. A 50 kW fast charging station can recharge a BEV from an empty battery to approximately 80 % of full state of charge (SoC) in 20–30 min [25]. As the number of BEVs increases, the fast-charging infrastructure will expand and future fast-chargers are expected to have a charging rate ranging from 100 kW to 500 kW [26]. Although it has been shown that these charging events supplement home charging, which stands for 82 % of the charging events [18]. Furthermore, multiple studies confirms that home charging is the most important and most frequently used location [27].

By controlling the charging (actively deciding at what time the charging should occur), existing distribution networks can be utilized more efficiently and the need for upgrade is reduced. An uncontrolled charging is when the charging commences as soon as the vehicle is plugged in to the charger. If multiple vehicles are charged simultaneously, it could cause impacts on the network operating conditions as the voltage drops beyond acceptable limits during times of high residential demand [28]. The placement of BEVs may become critical if multiple cars are charged within a neighbourhood connected by the same line to a transformer [29]. A transformer performs a step-down and step-up function of the voltage level. Connecting the distribution grid to the local grid of the neighborhood

It is possible to find differences in electricity consumption between totally identical buildings and the difference can be related to a specific parameter such as the total income of the households, where a higher income implies a higher electricity consumption [30]. How much power a household can utilize is limited by the main fuse of the household. The main fuse is a safety device that sets a limit to the power demand - making sure that the electric system of the household is not overloaded. The most common fuse for swedish households today is 16 A [31]. To cope with the lack of available current, a load balancer can be installed.

The load balancer regulates the charging power when other appliances such as stoves or washing machines are used [31]. According to Ohms law, the power P [W] is equal to the voltage U [V] times the current I [A], P=U*I. The equation could be used as a quick verification of the viability of the fuse and the current home-charging installation.

Introducing home-charging to a household, will increase the households electricity consumption mainly during the evenings [10]. Events where BEVs are charged simultaneously in a neighborhood are called coincidences - the coincidence of two or more great loads occur at the same time in the same electricity system. The coincidences caused by charging depend mostly on the charging rate, but also on the vehicles electricity consumption and the charging location [32]. Since most charging events occur at the household (home-charging) the electricity consumption of the household could increase on a daily basis and so the rated (annual maximum) power demand of the household may increase as well.

1.2 Aim

The aim of this thesis is to investigate potential implication from large scale BEV employment among different households in a scenario with a high level of BEV penetration. In this study, it will be investigated how BEVs will change the households rated power demand and how households new rated power demand can coincide with each other. Despite prior observations of households with BEVs, it remains unclear how the aggregated power demand is comparable between households. Households differ considerably in how the inhabitants consume electricity as appliances such as ovens, stoves, washing machines etc. are turned on and off at different times. This could depend on demographic factors such as number of inhabitants and if the household is located in an urban or a rural area as well as if the household is an apartment or villa. The research question for this study is:

- How will the annual maximum power demand of households change if there is a full deployment of BEVs, considering the number of household inhabitants, household location and if the household is an apartment or villa?

1.3 Limitations

The study is limited to data on 429 vehicles from The Swedish Car Movement Data (SCMD), driven in Västra Götaland and Kungsbacka in western Sweden. These vehicles have at least 30 days of sufficiently accurate GPS-measurements, covering number of trips, driving distance per trip, and parking times [33, 32]. The area is representative for Sweden in terms of urban and rural areas, city sizes and population density. The household data limiting the study consists of the electricity consumption of 16 apartments and 20 villas in Sweden, over one year. All vehicles in this study are regarded as BEVs and all vehicles are assumed to only be charged at home. Uncontrolled home charging is assumed - vehicles are charged directly when they are plugged in to the charger. This study can be viewed as a conservative estimate of the impact of a BEV introduction (worst-case introduction). When it comes to car-ownership, a household is assumed to own one BEV. Survey data describing the demography of the drivers in terms of age, family constellations, car type etc. [15] was excluded from this study as no linkage to the electricity consumption data from the survey data could be made. The main fuses limiting how much power that can in reality be obtained from the grid is not considered a limit in this study.

The computational and memory capacity is limited (Core i7 8700 processor and 64 GB of RAM memory)). The RAM memory in this study limits the size of the matrices in the calculations, i.e. limiting how many vehicles can be included in the calculations. The processor executes the calculation - the status of the processor determines the speed of the calculations. The available time for computing is limited.

2
Theory

2.1 Power limitations

To manage a certain rated power demand the cables and transformers in the grid needs to be dimensioned correctly. For a certain device, in this case a charger, it is vital that the cables can manage not only the load from the charger, it is equally important that the cable can manage the currents that can occur when there is a fault in the charger - the short-circuit current. Since the largest fault current is determined above all by the **fuse** that feeds the cable, a cable cannot be dimensioned to the rated power of a device with less than what kind of outlet it is.

Normally, the dimensioning of the cable is done so that for each size of fuse there is a minimum cross-sectional area. For example, 2.5 mm^2 conductor is required, if the fuse is at 20 A. At longer cable distances, cables are also dimensioned for the voltage drop in the grid. The voltage drops in the grid due to the internal resistance of the cable.

The fuses are normally located in an electricity central. Fuses can be divided into two categories; thread fuses and blade fuses. Thread fuses are most common in households and range from 6 A to 35 A. Each of these fuses is adapted to a part in the central that express which current the fuse should have. Blade fuses are mostly used for currents from 35 A to 1000 A [34].
In Sweden, a villa is most commonly equipped with a fuse of 16, 20 or 25 A, while an apartment is equipped with only 16 A [35]. A fuse can however manage a higher current than what is specified. A 16 A fuse can often manage currents of up to 50 A for shorter periods before it short-circuits (up to 2 seconds). The size of the fuse, that is the cross-sectional area of the cable is the limiting parameter determining which voltage drop the fuse can manage and often a larger size is selected as a security measure [34]. Voltage (U) and current (I) are directly linked to power (P) according to Ohm's law (P=U*I) and thus the size of the fuse limits how much power a household can obtain from the grid.

There are three main parameters that determine the size of the fuse that the household should select (see Table 2.1 [36]):

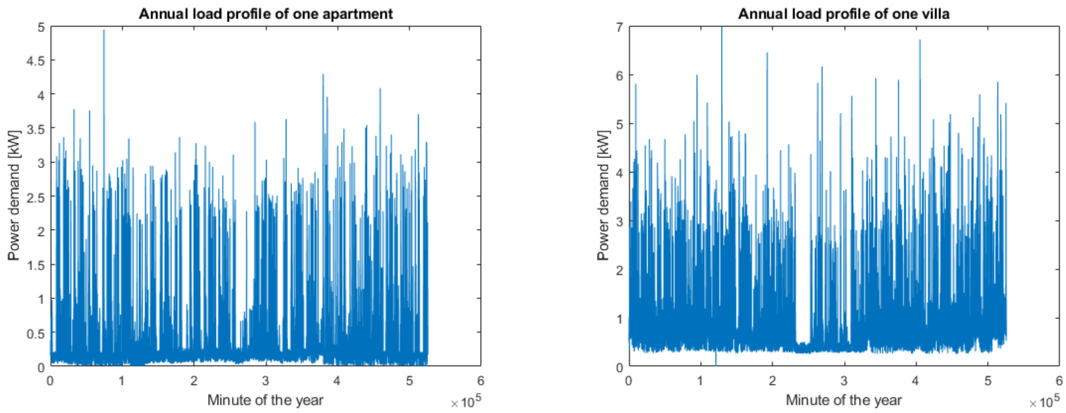
- How much electricity a household consumes annually.
- How much power a household maximally demands (the size of the household appliances)
- How the electricity is consumed over the year (if a household consumes electricity more over seasons or only occasionally).

Color	Fuse size	Annual el. consumption	Maximum power available
Gray	16 A	0-20 000 kWh	11 kW
Blue	20 A	20 000-25 000 kWh	14 kW
Yellow	25 A	25 000-30 000 kWh	17 kW
Black	35 A	30 000-40 000 kWh	24 kW
White	50 A	40 000-55 000 kWh	35 kW
Copper	63 A	55 000-70 000 kWh	44 kW

Table 2.1: Types of fuses available for Swedish households

2.2 Graphical representation of load profiles

Here the load profiles for the electricity consumption of the households are presented graphically, for mote details see section 3.3 The annual load profile of an apartment and a villa is shown in Figure 2.1. There is a power demand in kW every 10th minute of the year. It can be perceived that the rated power demand for the apartment is approximately 4.9 kW and for the villa 7 kW. The maximum power demand occurs at different times of the year.



(a) Load profile of an apartment (b) Load profile of a villa

Figure 2.1: Load profiles of the two types of household

The load profile for a BEV can be calculated from the GPS measurements (see section 3.3.2). To do this numerous assumptions need to be made (see section

3.3.3). Also a set of equations needs to be used to calculate how the battery of the BEV is charging/discharging.

2.3 Translating driving profiles into charging profiles

As an example, regard Vehicle k. The charging profile calculated is then aggregated directly on the load profile of a household (see Figure 2.1). A load profile of a BEV that is calculated through these equations is shown in Figure 2.2.

The state-of-charge (SOC) of a car battery is defined by Equation 2.1

$$SOC_{k,t} = \frac{Q_{k,t}}{Q_{max,k}} \tag{2.1}$$

where $Q_{k,t}$ is the amount of charge [kWh] in the battery (the electricity stored in the battery) for vehicle k at time-step t. Q_{max} is the maximum charge in [kWh], i.e. battery size. The SOC is 1 for vehicles when the battery is fully charged and then there will be no more load from the charging on the household. The amount of charge in the battery when the BEV is plugged in to the charger is determined by how long a distance the car has driven, calculated in Equation 2.2

$$Q_{k,t2} = Q_{k,t1} - d_{k,t} * \alpha \tag{2.2}$$

where $d_{k,t}$ is how long distance in [km] the car has traveled between home arrivals for vehicle k. $t1$ is the time of the departure from home and $t2$ is the time of home arrival. α is the electricity consumption of the BEV, which assumed to be constant at 0.164 [kWh/km]. How much the battery is charging can be calculated with Equation 2.3

$$Q_{k,t} = Q_{k,t2} + C * x \tag{2.3}$$

where C is the nominal charging rate (11 kW) and x denotes the time when the vehicle is at home and charging. Q_{max} is limiting these equations. The results from these equations will be new power demand data, showing when and how much the BEVs are charging. The power demand from uncontrolled charging has been calculated in units of [kWh/min] since this makes it possible to calculate on the GPS data and combine with the household load profiles. The power demand for every charging event will be equal to the nominal charging rate, that is assumed to be constant at 11 kW. The charging profile calculated from the GPS data is repeated 6 times and the remaining time is filled up with charging events from the profile until a full year is covered.

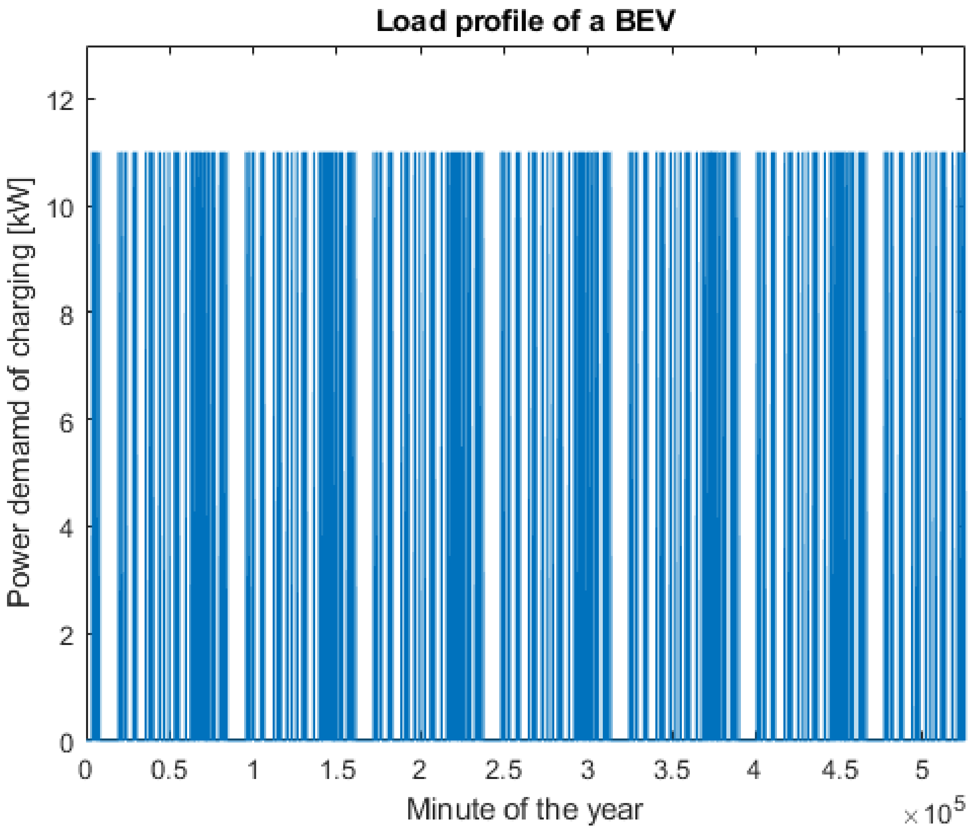


Figure 2.2: Load profile of a BEV

3
Method

To investigate how the rated power demand of households could change if there is a full deployment of BEVs, there is a need to aggregate the driving data with the electricity consumption data to obtain a new annual maximum power demand. The GPS-measurements from the driving data need to be transformed into driving profiles. These driving profiles will address when a vehicle starts a trip, how long distance the vehicle travels (how much electricity it consumes) and when the vehicle is at its home (when it charges). The electricity consumption from the charging is identified and is summarized in new load profiles (see Figure 2.2) which directly can be aggregated to the households present electricity consumption. The new load profiles will then be analyzed.

The Methodology is divided into four stages. Firstly it is described how the data is categorized (3.1 Scenarios). Secondly it is described how the households and vehicles is combined and calculated on (3.2 Sample calculations). Following a description on how the data is processed (3.3 Data), where the GPS-measurements are translated to new power demand profiles that can be aggregated to households current power demand profile. Lastly there is a description of how the data is simplified to enable calculations (3.5 Simplifications).

3.1 Scenarios

3.1.1 Categorization

By analyzing the GPS-measurements, the vehicles were categorized into urban and rural vehicles.. Among all the vehicles, 258 was identified as driving in urban areas, 103 was identified as driving in rural areas and the rest was unidentifiable, but still included in the study. The possible categories investigated are listed in table 3.1. The categories represent hypothetical neighbourhoods, which means that the households of one category is connected to the same transformer.

Type of neighborhood	Type of vehicles
All households	All vehicles
All households	Urban vehicles
All households	Rural vehicles
Villas	All vehicles
Villas	Urban vehicles
Villas	Rural vehicles
Apartments	All vehicles
Apartments	Urban vehicles
Apartments	Rural vehicles

Table 3.1: Categories being investigated

3.2 Sample calculations

The following procedure will be repeated multiple times through the Sample calculations, as there is several categories that can be considered. By analyzing the combinations of the two data-sets, it will be possible to identify what trend characterises combinations of categories - in how the total annual maximum power demand changes when the number of considered households increases. For example, it is possible to analyze the rural area and urban area separately. Below follows the procedure steps, which will be carried out in MATLAB.

1. The size of the sample is identified - the number of households (denoted J) and the number of vehicles (denoted K), so if the whole dataset is analyzed: J=36 and K=429.
2. A household *j (j=1, 2, 3... J)* and one vehicle *k (k=1, 2, 3... K)* are randomly selected and the new rated power demand is noted down. This process is repeated for K vehicles to obtain a full coverage of all the possible combinations.
3. Two households and two vehicles are selected and the new total rated power demand is aggregated and noted down. Process 2 is executed for the 2 households (this time 2 vehicles are randomly selected).
4. Process 3 is repeated for 3, 4... and J households.

The aggregated power demand of the load profiles is obtained by equation 3.1,

$$P_{rated} = max(E_{household} + E_{vehicle}) \tag{3.1}$$

where P_{rated} is the new rated power demand for households with uncontrolled BEV charging. $E_{household}$ denotes the power demand of the household $E_{vehicle}$ denotes the power demand from charging. If two households are combined, then the equation obtaining the new rated power demand is obtained by equation 3.2.

$$P_{rated} = max(E_{household,1} + E_{household,2} + E_{vehicle,1} + E_{vehicle,2}) \tag{3.2}$$

The new rated power demand between households and vehicles is obtained in the same way when combining more vehicles and households. The Real increase of the rated power demand will gain as an increasing number of households and vehicles are included in the equation. One way to circumvent this difference could be by normalizing the results by dividing the new rated power demand (P_{rated}) with the current rated power demand E_{rated} (equation 3.3).

$$G = \frac{P_{rated}}{E_{rated}} \tag{3.3}$$

G denotes how much the rated power demand has changed due to the deployment of BEVs with uncontrolled charging and irrespective of fuse limitations. Subsequently, the Real increase (D) is calculated and processed in the same way as the G-values to obtain an overview of the actual increases are (equation 3.4). There is thus one D-value for every G-value.

$$D = P_{rated} - E_{rated} \tag{3.4}$$

3.3 Data

This section describes how the two data-sets are processed, to merge them. Measurements from the electricity consumption data is measured during one year with measurements every 10th minute. The driving data is described in minutes when a trip starts and ends. To be able to merge the data-sets, the size of the time-steps need to be the same. Which is why the measurements from the electricity consumption data will be expressed in time-steps of 1 minute, so 10 time-steps will contain the same load in a row. Firstly the data of the electricity consumption data will be extracted into MATLAB from Excel. Secondly the driving data will be processed in MATLAB. Lastly, the electricity consumption data will be transferred into MATLAB so the data-sets can be merged.

3.3.1 Electricity consumption data

The goal of the study from The Swedish Energy Agency in 2009, was to monitor all main electric appliances for 400 households and 20 common areas in residential blocks [37]. The electricity consumption data was measured for 40 households for one year. All the main electrical appliances were monitored at a time step of 10 minutes - Most of the households were located in the Mälardalen region with one of these households located in the far north of Sweden and one other in the south of Sweden.

The other 360 households were monitored for one month. All the main electrical appliances were monitored at a time step of 10 minutes (electricity consumption is measured in units of Wh/10min), a direct measure was done for the rest. 9 of these households were located in the far north of Sweden, 9 in the south (Skåne region) and the rest in the Mälardalen region [37].

The households varies in demography and the demographic data regarded in this study is the number of inhabitants (1, 2, 3, 4 or 5) and whether the household is an apartment or a villa. Metadata for the households in Table 3.2 displays the annual maximum power demand and number of inhabitants for the household [37]. A household can either be heated by electricity (E) or by the district heating system (D). Metadata on heating for the apartments was not available.

Household	Maximum power demand [kW]	Inhabitants	Heating
Apartments	2.7	1	
	2.8	1	
	2.9	2	
	3.2	2	
	3.5	2	
	3.9	1	
	4.2	2	
	4.2	2	
	4.4	2	
	4.5	3	
	4.7	3	
	4.9	2	
	4.9	4	
	5.4	4	
	6.3	4	
	6.7	1	
Sum	**70.9**	**38**	
Average	**4.43**		
Villas	5.6	3	D
	6.3	3	D
	7	2	E
	7.3	4	E
	8.5	2	D
	9.2	2	E
	9.3	5	D
	9.5	4	E
	9.5	3	E
	9.6	3	E
	9.9	2	E
	10.2	4	E
	10.7	4	E
	11.8	2	E
	12	2	E
	12.1	4	E
	12.6	4	E
	16	5	E
	16.3	5	E
	18.4	2	E
Sum	**211.8**	**65**	
Average	**10.5**		

Table 3.2: Annual maximum power demand for 36 households in kW and the number of inhabitants for each household.

3.3.2 Driving data

To facilitate a well-informed and efficient transition to electrified vehicles, such as BEVs, information about individual vehicle's movements over longer time periods is needed. The Swedish Car Movement Data Project aimed to gather a larger amount (more than 700 cars) of data on the movement for privately driven cars in Sweden by measurements with GPS-equipment. The measurements were performed with commercial equipment containing a GPS unit, including a roof-mounted antenna and a unit for transmitting data. The data provides statistical data for each trip such as trip starting/ending times and locations, travelled distance, averages of speed and trip duration. There is also statistical data for each device/vehicle such as total distance travelled during measurement period, time of first/last measurement, average speed for all driving and the total number of trips [15]. The 429 cars have been selected since they have at least 30 days of good GPS measurements. This data needs to be transformed into a new driving profiles.

Every vehicle has its own id number (e.g. BEV nr. 173). After the data processing, the variables for a vehicle consist of the time of departure from home, the time when the BEV is parked at home and how long the trips will be in terms of distance. For vehicle 173, there is 224 measured trips. These measurements need to be transformed into new driving profiles. The new driving profiles have a set of trips for each measured day. Days lacking measurements implies that the vehicle is parked. The measurements stretches over a specific number of days (at least 30), they need to be repeated to cover a full year. 30 days times 12 is 360 days, the remaining 5 days will be the first 5 days of the vehicle specific driving data. A driving profile consists of three columns. The first column express the minute of the year that the vehicle arrive home, the second express the duration that the vehicle is parked at home and the third column express the distance of all the trips that the vehicle travels. The driving profiles need to be translated into charging profiles. That is - it is necessary to determine when and how much a BEV is charging. However, to make calculations possible, assumptions need to be made.

3.3.3 Assumptions

All the BEVs are assumed to always be charged at a 11 kW capacity. The vehicles time of home arrival will be approximated as the time of initiating a charging event as well, since this directly links the electricity consumption to the driving patterns. The vehicles are assumed to have a fully charged battery on the very first trip.

To set a limit on how long a charging event can be, assumptions on the battery size must be made. BEVs differs in battery size [kWh], how long range [km] they have and how much electricity they consume per km [kWh/km]. In this study, the battery size is set to 100 kWh. It is vital that the battery size is not too small, so that the electricity needed to drive the trips in the driving data is lacking. Although 100 kWh is a relatively large battery, there will still be driving profiles that contain distances that the battery cannot manage with only home charging available. These profiles need to be charged when not at home, at a public charging station for example. It is assumed that this supplementary charging uses fast chargers (42 vehicles was in need of supplementary charging). However the supplementary charging is assumed to be minimal i.e. if the battery is equal to or below zero during a trip, a fast charging event occurs - meaning that the BEV charges only with the electricity that is needed to finish the trip. Since the calculations are made on a minute basis, the charging rate of the fast chargers are not crucial (acknowledging that higher charging rates will be available in the future). Since the exact roadway grade is not known, how the electricity consumption from driving is influenced by acceleration, braking and velocity is not considered. Instead the electricity consumption from driving will be fixed to 0.164 kWh/km, which is similar to a Nissan Leaf [38]. With these assumptions, the driving profiles can be translated into charging profiles.

3.4 Aggregating the BEV load profiles with the household load profiles

With these assumptions the BEV load profile can be calculated with equations 2.1-2.3. The BEV load profile can now be directly aggregated to the current household power demand i.e. Figure 2.2 (charging rate C=11 kW) can be aggregated onto Figure 2.1a (E, household power demand). The new power demand profile is obtained through Equation 3.5 and is illustrated in figure 3.1. The new rated power demand for one apartment with one BEV is 14.96 kW and occur later in the year. This represents an increase of 205 %.

$$P_{j,k,t} = E_{j,t} + C_{k,t} \tag{3.5}$$

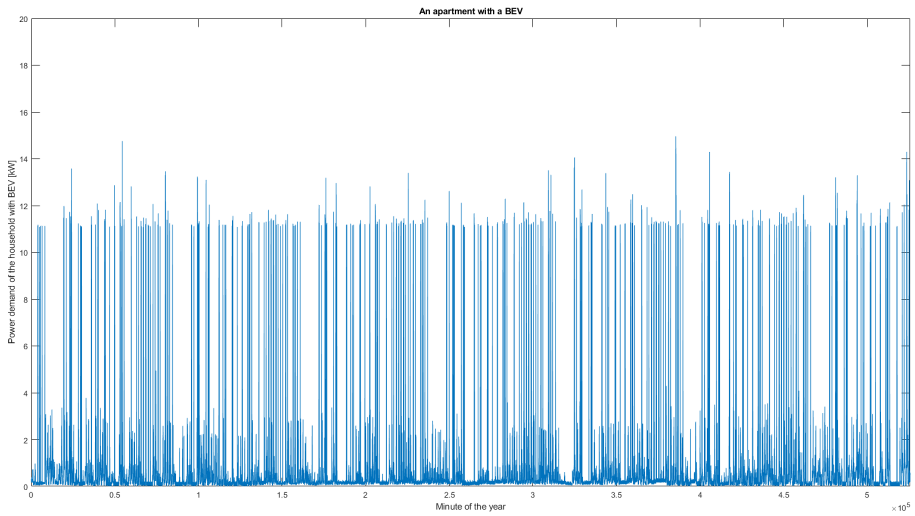


Figure 3.1: Aggregated load profiles of one apartment and one BEV

3.4.1 Combinations of households and vehicles

Households are analyzed in combinations of 2, 3, 4...J households to be able to analyze how they are affected as a whole by a full BEV deployment. Combinations of households are analyzed since this could be a representation of how a BEV introduction is influencing neighborhoods of different sizes as a whole. To faster develop a model that performs calculations on combinations, a test sample is selected. It consists of 3 vehicles (vehicle number 173, 178 and 180) and 3 apartments (Apartment 1, 2 and 3). If the combination of 2 households are analysed, two matrices are created that express which households and vehicles are combined.

$$\begin{bmatrix} 1 & 2 \\ 2 & 3 \\ 1 & 3 \end{bmatrix} \qquad \begin{bmatrix} 173 & 178 \\ 178 & 180 \\ 173 & 180 \end{bmatrix} \tag{3.6}$$

Figure 3.2: A combination matrix for households and a combination matrix for vehicles

Every row is combined and the power demand profile for the households and the vehicles are aggregated. This results in a new matrix, containing a G-value for every possible combination of households and vehicles. The number of vehicles and households included can be increased. The process is repeated for the combination of 2, 3, 4... and 16 apartments and the number of vehicles included are increased accordingly. This procedure is repeated for all types of neighborhoods and vehicles listed in table 3.1.

3.5 Executions

Executing the final script where combinations are investigated is time-consuming, which is why the data as well as the number of combinations were in need of simplifications.

3.5.1 Sampling

The charging profiles were expressed in time-steps of 10 minutes (as the initial electricity consumption data). In addition the number of vehicles were limited. When calculating on all vehicles, every fourth vehicle was considered (sample of 108 vehicles), every second vehicle was considered when calculating on urban vehicles (sample of 129 vehicles) and all vehicles were considered when calculating on rural vehicles (sample of 103 vehicles).

3.5.2 Bootstrapping

What is common for all categories in table 3.1 is that there will be a great number of combinations. Due to computational and memory limits a bootstrap estimate was conducted. A bootstrap estimate in this context is the random selection of combinations of households and vehicles. The combinations of households and vehicles that are included in the bootstrap estimate is called resamples. Due to computational and memory limits, 1000 resamples were conducted for each number of households. A certain combination of households have multiple possible combinations of vehicles. For these combinations 1000 resamples were conducted. This represent a fraction of all possible combinations of households and vehicles, yet should result in representative G-values for a given number of households and vehicles [39]. The size of the bootstrap is set to 1000, this means that of all possible combinations of households, 1000 will be randomly selected. In the same way, 1000 combinations of vehicles are randomly selected for each combination of households. This bootstrapping is common for all numbers of households combined.

4
Results

This section is divided into results for the factor of rated power demand increase (G in Equation 3.3) and results for the rated power demand increase in kW (D in Equation 3.4) found in section 3.2. Graphs presented in this chapter are those that contain comparable differences between categories. There are two types of graphs, histograms and scatter plots.

The histogram expresses how common certain increases are, regardless of how many households are combined. Thus, it gives an overview of what the most probable rated power demand increase will be. The histograms approximate the distribution of the rated power demand increase. The maximum observed frequency in a histogram represents which increase is most common for a certain category. There could be cases when only one BEV exist in the neighborhood and cases where all households have a BEV, for these graphs 36, 20 and 16 BEVs. Another viewpoint is that a certain number of households are connected to the same transformer.

The scatter plots express the relation between the increase in rated power demand and the corresponding number of inhabitants for the combinations of households. The graphs illustrate factors of increase/Real increases that can occur for a certain number of inhabitants i.e. combining a certain number of households will result in multiple possible number of inhabitants since there are multiple combinations of different households. Each dot represents a certain interval of values, there are 10^6 values for each number of households that are combined in each scatter plot, so each single value might not be directly visible to the eye. A larger number of inhabitants represent a larger neighborhood.

4.1 Factor of rated power demand increase

4.1.1 Histograms

In this section histograms for all types of neighborhoods (Villas, Apartments and All Household) are listed, each plot considering All Vehicles. Dividing the analysis into rural and urban vehicles indicate the same type of result. However, Rural vehicles indicate having similar Most Common Factor of Increase (MCFI) as All Vehicles. In general, the histograms considering Rural vehicles indicate having higher values in the distribution than those considering Urban vehicles (see Appendix A.1.1).

Villas

In Figure 4.1 it can be seen that the Most Common Factor of Increase (MCFI) can be found at a value of approximately 1.75 (75 % increase in rated power demand). The graph seems to be concentrated around the MCFI and expressing an even gradient on both sides of the MCFI.

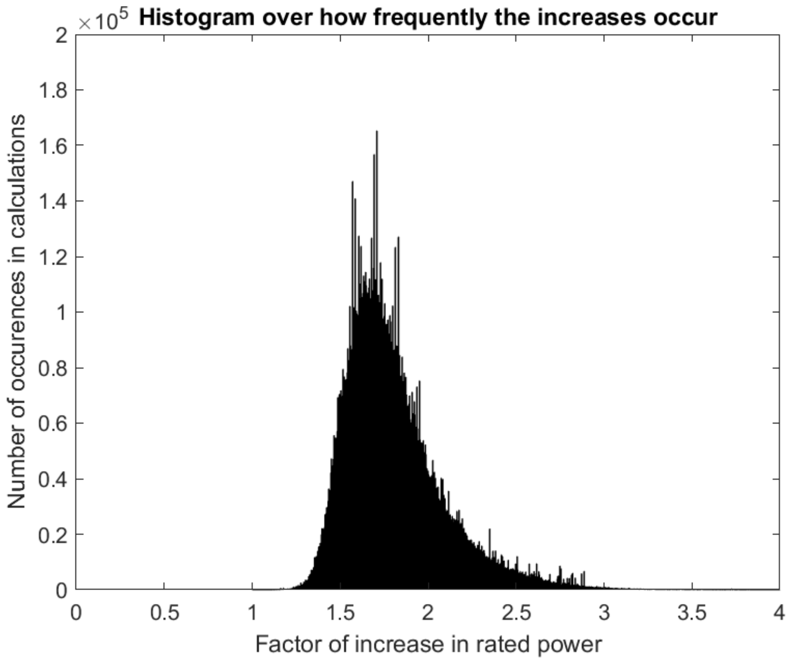


Figure 4.1: Histogram for Villas and All vehicles. The graph shows how common certain Factor of rated power demand increases are, independent of how many villas are combined.

Apartments

In Figure 4.2 it can be seen that the MCFI can be found at a value of approximately 3.5 (250 % increase in rated power demand). The distribution can be described as almost having a volcano shape (though a slightly steeper gradient at the left side) with an interval of spikes at the top. This interval seems to lie between approximately 3 and 5.

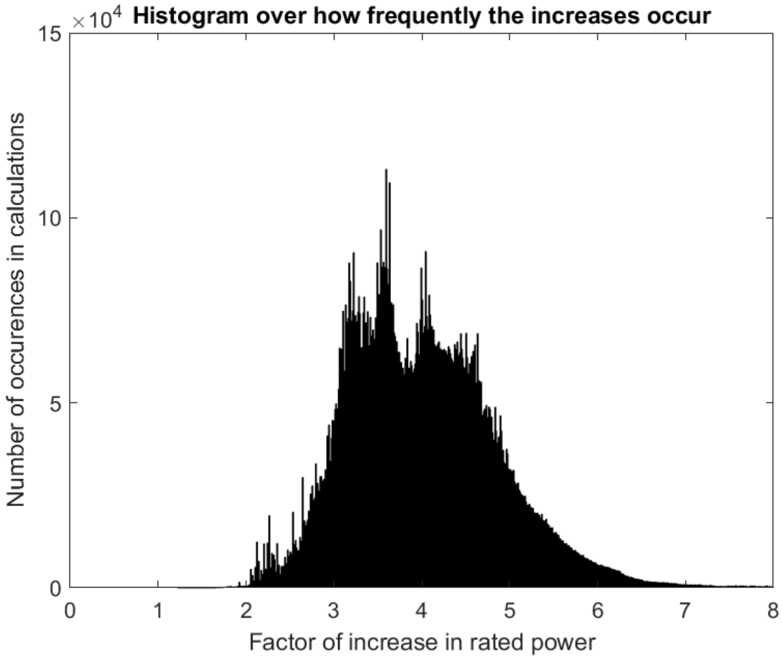


Figure 4.2: Histogram for Apartments and All vehicles. The graph shows how common certain Factor of rated power demand increases increases are, independent of how many apartments are combined

All Household

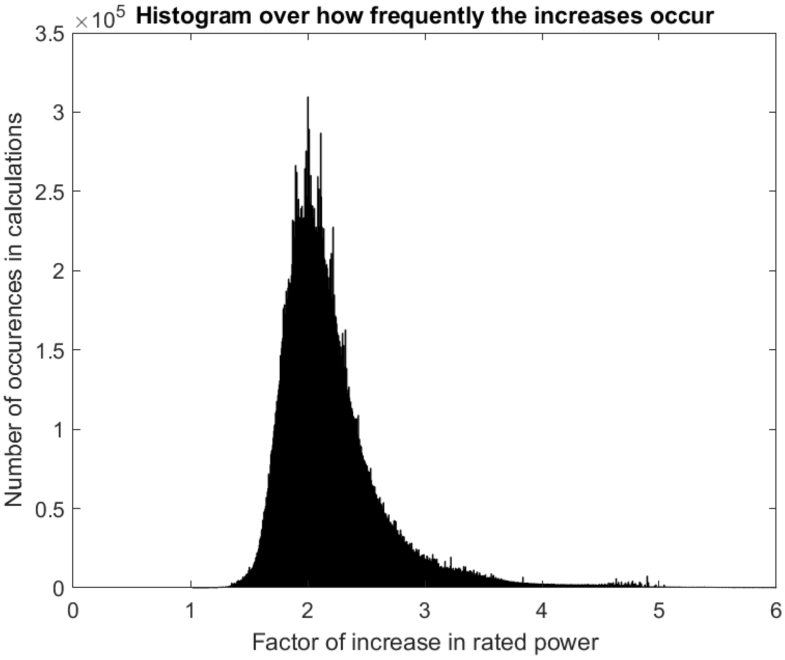


Figure 4.3: Histogram for All Households and All vehicles. The graph shows how common certain Factor of rated power demand increases increases are, independent of how many apartments are combined

Figure 4.3 has a similar appearance as Figure 4.1. However since the apartments are included in this neighborhood, the distribution is slightly shifted to the right. The MCFI has a value of approximately 2 (100 % increase in rated power demand).

4.1.2 Scatter plots

In this section scatter plots for all types of neighborhoods (Villas, Apartments and All Household) are listed, each plot considering All Vehicles. Dividing the analysis into rural and urban vehicles indicate the same type of result (see Appendix A.1.2). The Maximum Possible Factor of Increase (MPFI) appears highest at a lower number of inhabitants (fewer households are combined) and decreasing as the number of inhabitants increases (an increasing number of households are combined). One explanation for this could be that Apartments in general have a lower annual maximum power demand (between 2.7 and 6.7 kW) than Villas (between 5.6 and 18.4), see Table 3.2. The explanation for this trend for the Villas could be that the annual maximum power demand are generally lower for villas that are heated with district heating compared to those heated with electric heating (see Table 3.2).

Villas

In Figure 4.4 it can be seen that the largest Maximum Possible Factor of Increase (MPFI) is found at a number of inhabitants of approximately 16, the value of the MPFI in this point lies around 4.25 (325 % increase in rated power demand). As the number of inhabitants increase up to 65 inhabitants when all 20 villas are included in the combination, the MPFI seems to decrease to a value around 2.75 (175% increase in rated power demand).

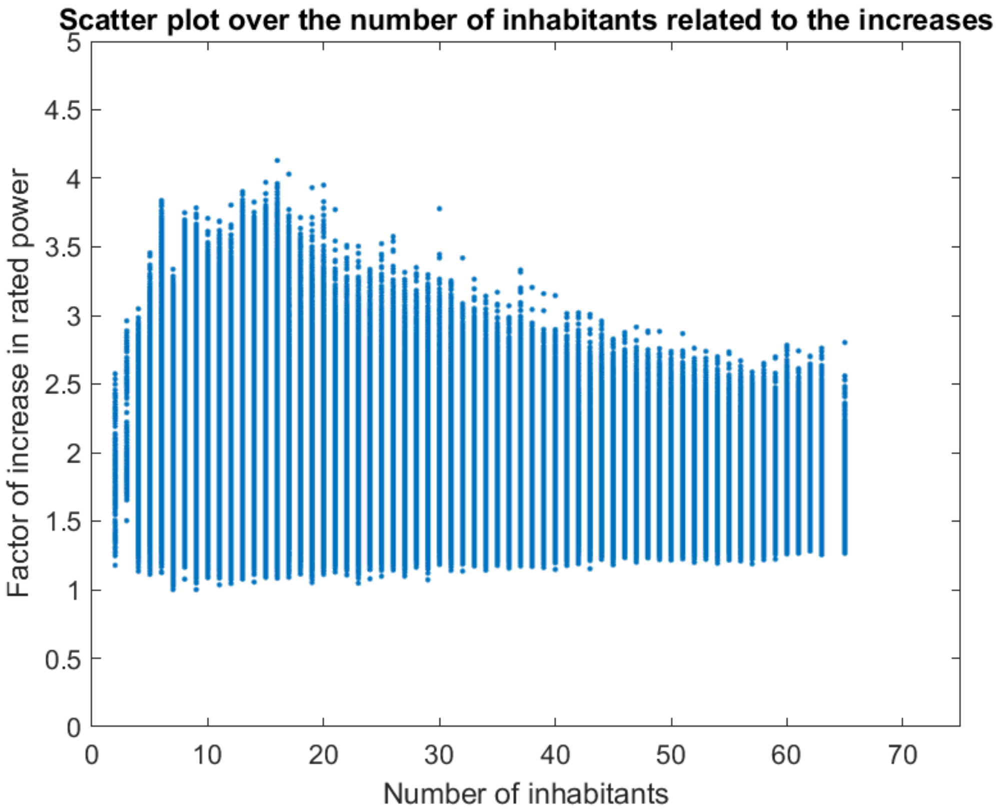


Figure 4.4: Scatter plot showing factor of increase in rated power demand for Villas and All vehicles.

Apartments

In Figure 4.5 it can be seen that the largest MPFI is found at a number of inhabitants of approximately 6, the value of the MPFI in this point lies around 9.5 (850 % increase in rated power demand). As the number of inhabitants increase up to 38 inhabitants when all 16 apartments are included in the combination, the MPFI seems to decrease to a value around 6.6 (560 % increase in rated power demand).

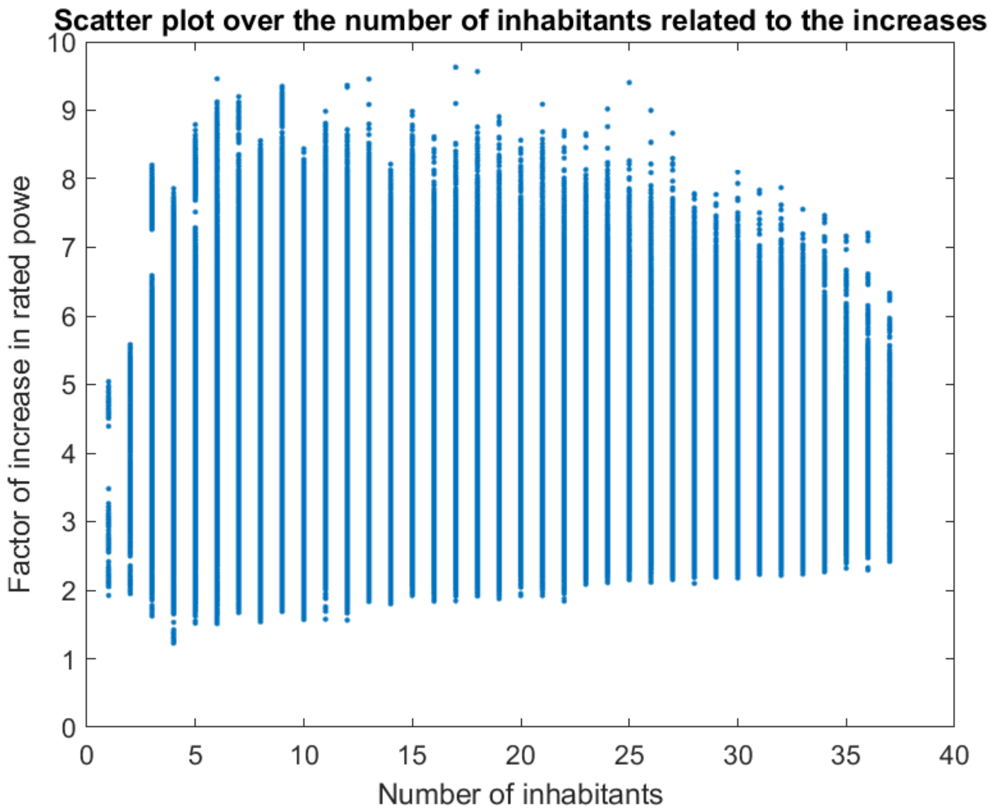


Figure 4.5: Scatter plot showing factor of increase in rated power demand for Apartments and All vehicles.

All Households

In Figure 4.6 it can be seen that the largest maximum possible factor of increase (MPFI) is found at a number of inhabitants of approximately 7, the value of the MPFI in this point lies around 9 (800 % increase in rated power demand). As the number of inhabitants increase up to 108 inhabitants when all 36 households are included in the combination, the MPFI seems to decrease to a value around 3 (200 % increase in rated power demand).

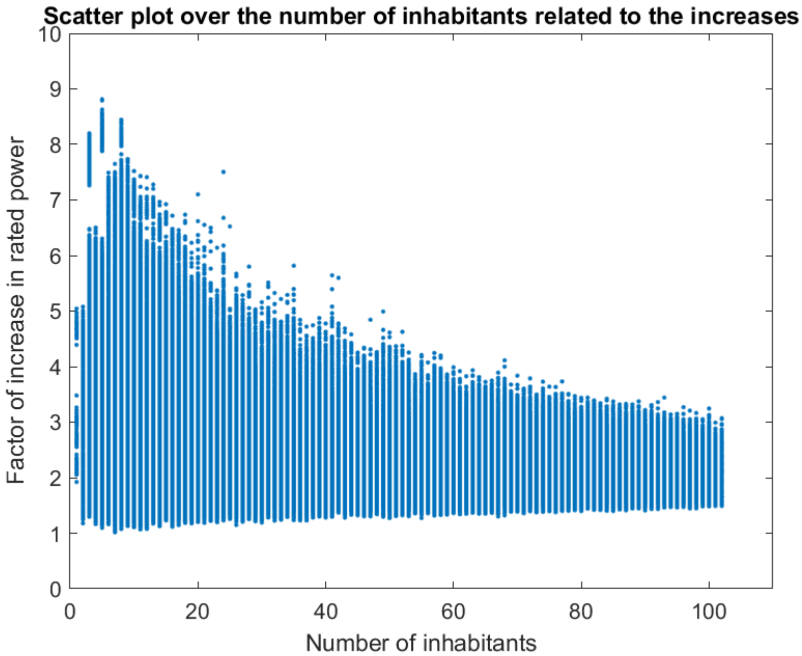


Figure 4.6: Scatter plot showing factor of increase in rated power demand for All Households and All vehicles.

4.2 Real increase

4.2.1 Histograms

In this section histograms for all types of neighborhoods (Villas, Apartments and All Household) are listed, each plot considering All Vehicles. Dividing the analysis into rural and urban vehicles indicate the same type of result. However Rural vehicles in general higher increases than the urban vehicles, both in distribution and what is the Most Common Power Increase (MCPI) (see Appendix A.2.1).

Villas

In Figure 4.7 it can be seen that the MCPI can be found at a value of approximately 35 kW. The distribution seems to spike far to the left before forming a "hill". On the left side of the hill is a increase in waves, while on the right side the gradient is full of spikes. The MCPI is found at the "top of the hill".

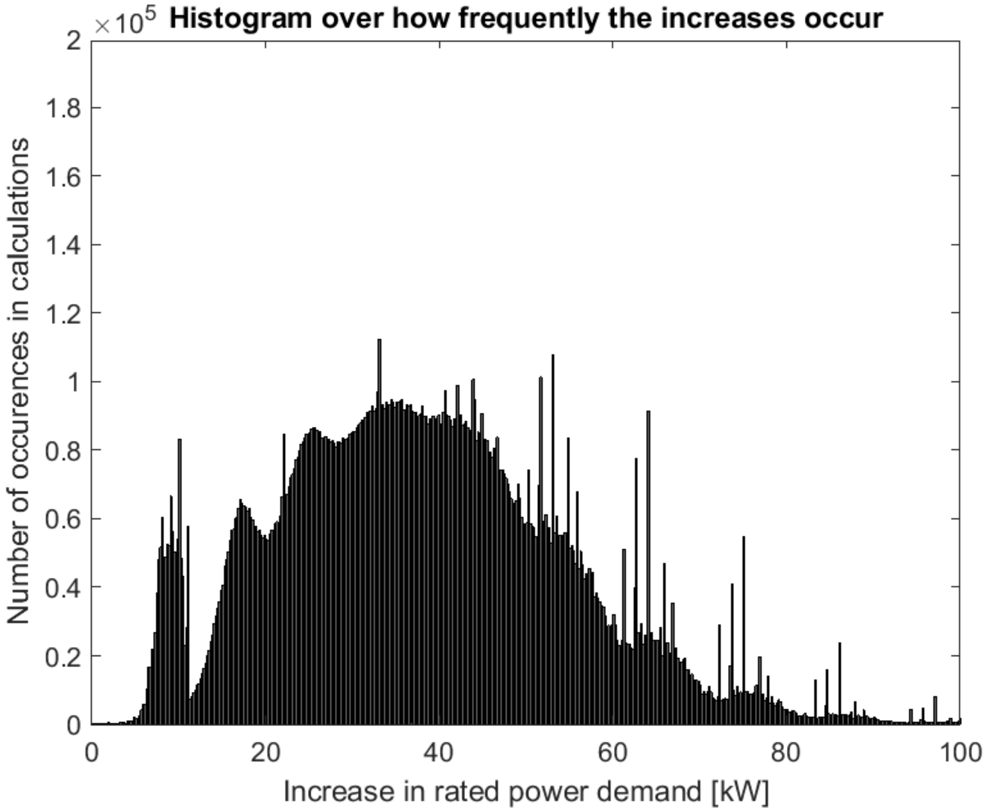


Figure 4.7: Histogram for Villas and All vehicles. The graph shows how common certain Real increases are, independent of how many villas are combined.

Apartments

Figure 4.8 displays a more fluctuating distribution, where there is a spike to the far left of the graph. There seems to be a wave-form distribution to the left and a distribution with spikes to the right, but the hill form could be viewed as less distinguishable. The MCPI is at the top, with a value of approximately 38 kW.

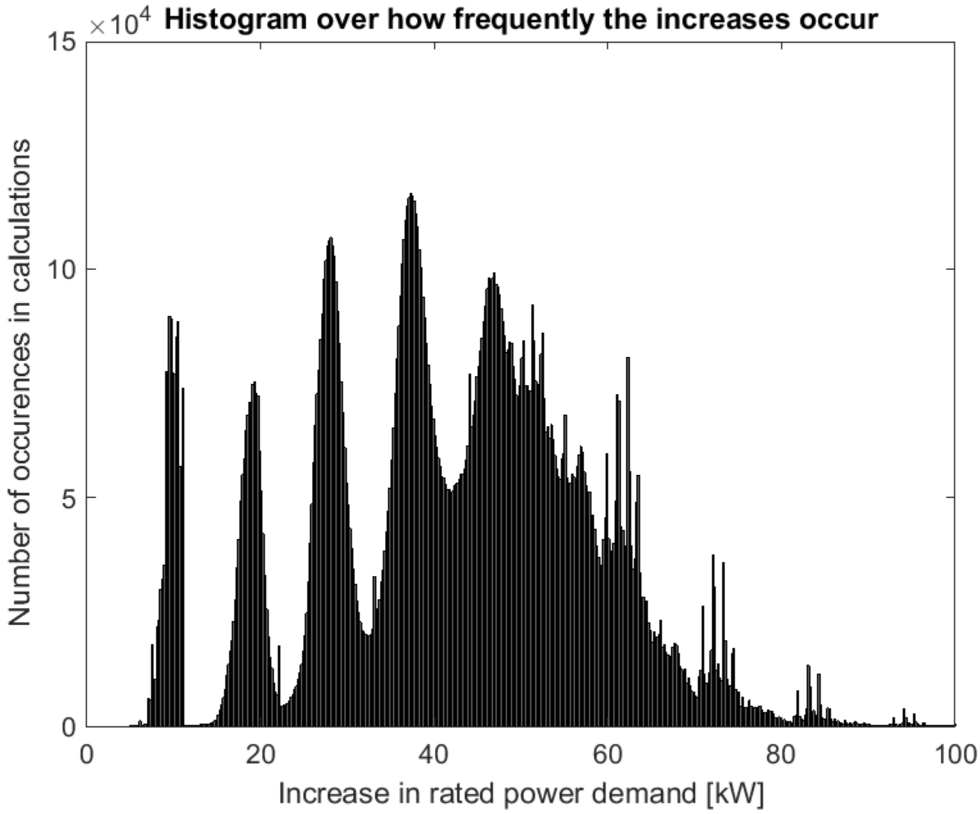


Figure 4.8: Histogram for Apartments and All vehicles. The graph shows how common certain Real increases are, independent of how many apartments are combined.

All Households

In figure 4.9 it can be seen that the most common power increase (MCPI) can be found at a value of approximately 100 kW. The distribution seems to spike far to the left before forming a "hill". On the left side of the hill is a increase in waves, while on the right side the gradient is full of spikes. It is at one of these spikes that the MCPI is found.

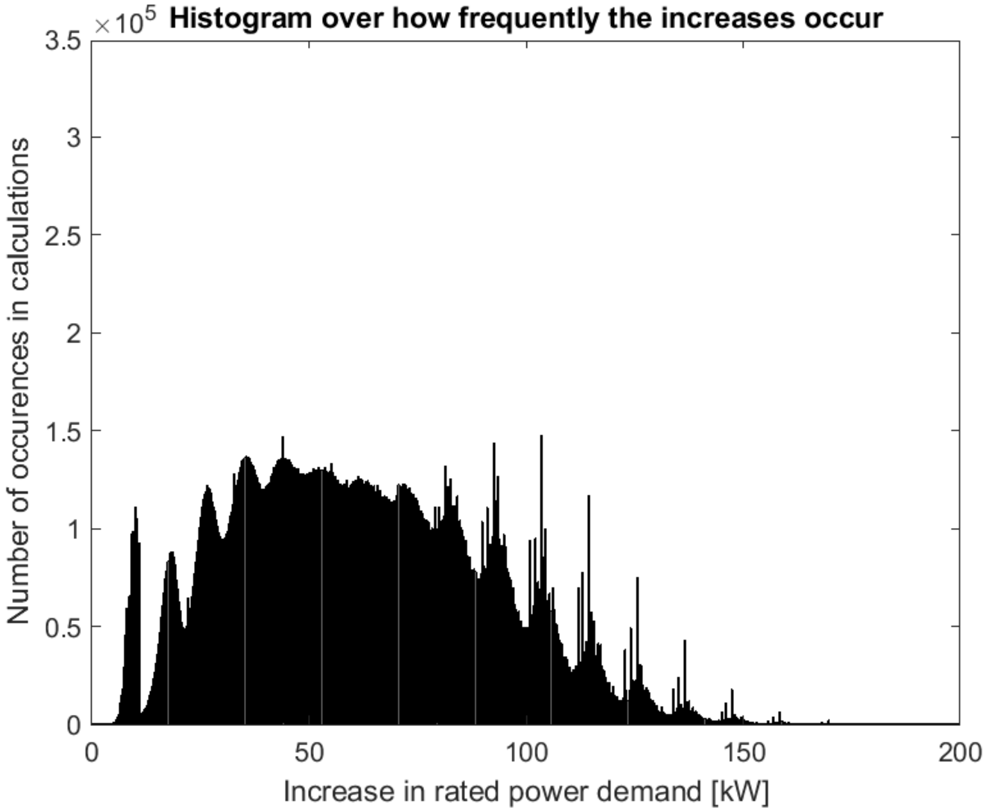


Figure 4.9: Histogram for All households and All vehicles. The graph shows how common certain Real increases are, independent of how many households are combined

4.2.2 Scatter plots

In this section scatter plots for all types of neighborhoods (Villas, Apartments and All Household) are listed, each plot considering All Vehicles. The upper side of the graphs (Figure 4.10, 4.11 and 4.12) denoted the MAXPPI (Maximum Possible Power Increase) seems to follow a logarithmic trend as the gradient of the MAXPPI is higher initially when fewer households are combined, but diminishes as more households are combined. An explanation for this could be that the likelihood that the uncontrolled charging of BEVs are less likely to coincide with each other as the number of vehicles in the neighborhood increases.

The bottom side of the graphs, The Minimum Possible Power Increase (MINPPI) seems to increase linearly as an increasing number of households are combined. This could be due to that the number of households in a combination is increasing linearly as well (1,2,3...36).

What should be noted is that MAXPPI and MINPPI are extremes that could occvur in the neighborhood, but the likelihood for this is low, as is inclined in the histograms in section 4.2.1. Dividing the analysis into rural and urban vehicles indicate the same type of result i.e. displaying the same patterns, but with the rural vehicles having higher MAXPPI values than the urban vehicles (see Appendix A.2.2).

Villas

In Figure 4.10, it can be seen that the MINPPI gains linearly up to a value of approximately 20 kW when all 20 villas are combined (65 inhabitants). The MAXPPI seems to increasingly gain linearly as the number of inhabitants increases to a value of approximately 150 kW. Per household, the MINPPI and MAXPPI become (when all 20 villas are combined) 1 kW and 7.5 kW.

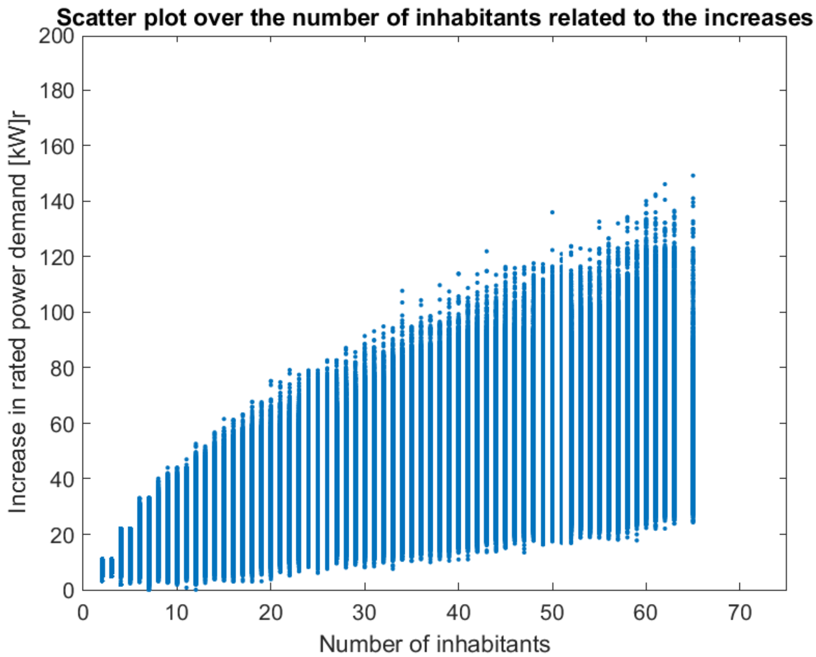


Figure 4.10: Scatter plot showing rated power demand increases in kW for Villas and All vehicles.

Apartments

In Figure 4.11, it can be seen that the MINPPI gains linearly up to a value of approximately 30 kW when all 20 villas are combined (65 inhabitants). The MAXPPI seems to loose it's gain with an increased number of inhabitants. When all apartments are combined (38 inhabitants) the MAXPPI reaches a value of approximately 140 kW. Per apartment the MINPPI and MAXPPI become (when all 16 apartments are combined) 1.875 kW and 8.75 kW.

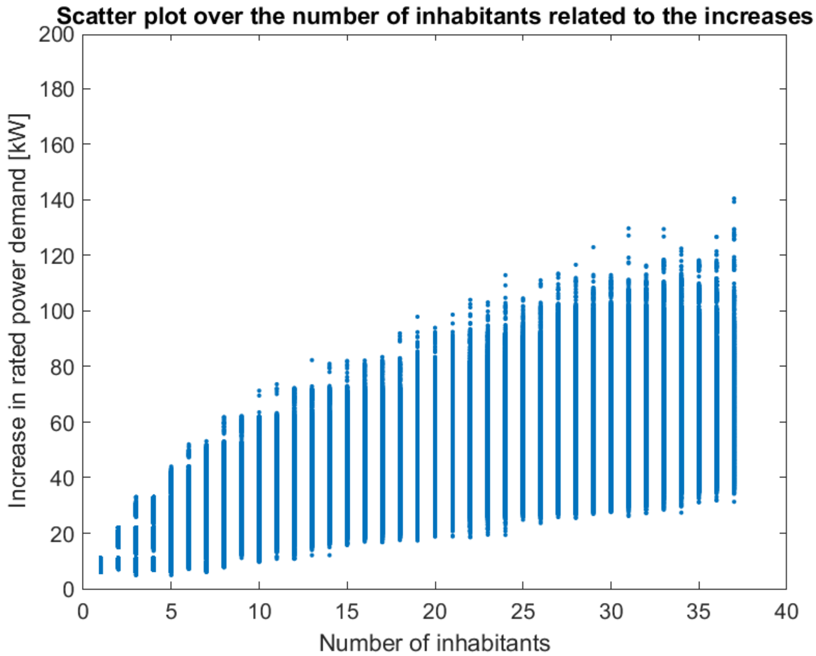


Figure 4.11: Scatter plot showing rated power demand increases in kW for Apartments and All vehicles.

All Households

The Real increase in kW, gains in magnitude with the number of inhabitants. In Figure 4.12, it can be seen that the MINPPI, gains linearly with the number of inhabitants up to a value of 50 kW when all 36 households are combined (108 inhabitants), while the maximum possible rated power demand increase (MAXPPI) seems to loose it's gain as the number of inhabitants increase. The maximum of approximately 225 kW is instead at a number of inhabitants of 90. For all 36 households the MAXPPI seems to lie at 220 kW. Per household, the MINPPI and MAXPPI become (when all 36 households are combined) 1.39 kW and 6,11 kW. .

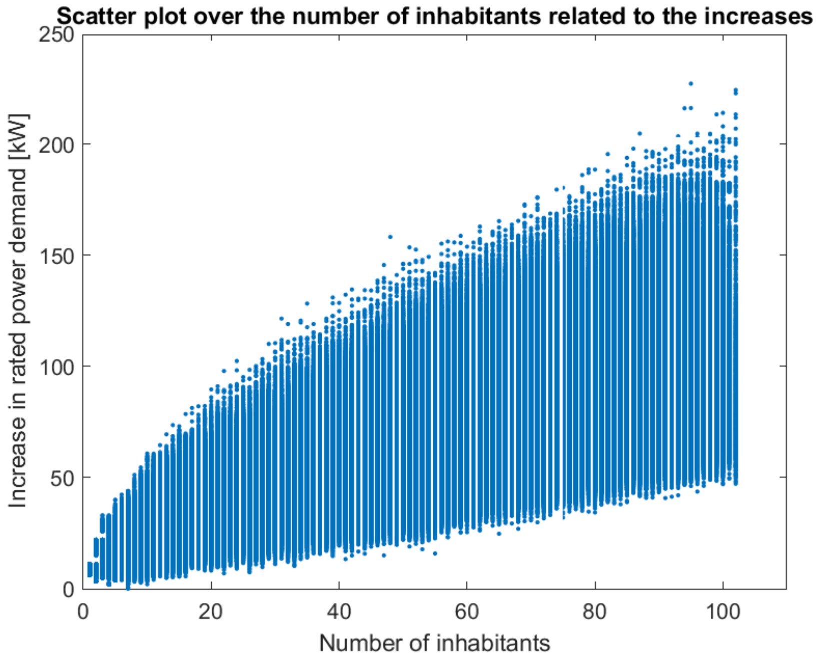


Figure 4.12: Scatter plot showing rated power demand increases in kW for All Households and All vehicles.

Difference between MAXPPI and MINPPI

Controlling when the charging events occur could imply that the rated power demand can be controlled as well. The difference between the MAXPI and MINPI values could be an estimate for how much a certain neighborhood rated power demand can differ depending on how many BEVs are charged simultaneously. The difference could also be an indicator on how much a neighborhood would benefit from controlled charging, a larger difference implies that more power demand can be regulated. In table 4.1, an approximated difference per household in kW of the MAXPI and MINPI value are displayed. These differences have been calculated for the cases when all households/villas/apartments are included (36, 20 or 16).

	All vehicles	Urban vehicles	Rural vehicles
All households	4.72	4.22	4.75
Villas	6.5	5.5	6.25
Apartments	6.875	5.625	6.875

Table 4.1: Differences between MAXPI and MINPI [kW] for 36 households, 20 Villas and 16 Apartments

It can be seen that urban areas could gain less from controlling the charging than rural areas. Notably, the values for the Rural vehicles appear similar to the values for All vehicles. One reason for this could be that since rural vehicles have longer distances to travel and thereby longer charging periods they will determine the value when all vehicles are considered as well.

5
Analysis

5.1 Analysis of Factor of rated power demand increase

The results show an increase in rated power demand (annual maximum power demand). A high increase indicates that multiple vehicle's charging profiles are coinciding with current peaks of the households and/or with each other, while a lower increase indicates that fewer charging profiles are coinciding with current household peaks and/or with each other, or that the coincidence occurs on an off-peak household load.

The magnitude of this increase does not seem to vary between rural and urban areas when it comes to the factor of rated power demand increase, this can be interpreted both from the histograms and the scatter plots. The largest difference is instead found between the types of households, where apartments (e.g. Figure 4.2) appear in the histograms to have a distribution between 2 and 6 (this means that the rated power demand increases between 100 % and 500 %), while the villas (e.g Figure 4.1) have a distribution between 1.3 and 2,6 (30 % and 160 % increase). An explanation for this could be that since the apartments in general has a lower rated power demand than the villas they are influenced more by a 11 kW load from the charger. Between apartments the rated power demand differs, but as it is low compared to the villas, the distribution will be over more and larger values, while the distribution for the villas appear more concentrated.

The scatter plots for the apartments (e.g Figure 4.5) indicates as well that the increase could be twice the magnitude compared to villas (e.g Figure 4.4). What can be identified for all the scatter plots is that the Maximum Possible Factor of Increase (MPFI) are reduced in value as the number of inhabitants increase while the minimum factor of increase seems to gain as the number of inhabitants increase. The MAXPI for uncontrolled charging of BEVs appears to have a logarithmic increase. The gain for the MAXPI is diminishing with increased number of households combined, this can be related to the reduced MPFI which seems to follow a logarithmic decrease. As the number of BEVs increase, the decreased likelihood that the uncontrolled charging of BEVs are coinciding in a larger multitude in combination with that the influence of uncontrolled charging of BEVs represents a decreasing share of the total annual maximum power demand of the neighborhood.

This trend seems to appear in all scatter plots, but it is most apparent in the scatter plots for the categories containing All households. The MPFI decreases in these plots from a value between 8 and 9 (700 % and 800 % increase), to a value between 3 and 4 (200 % and 300 %). This trend is distinguishable for all these scatter plots.

5.2 Analysis of the Real increase

In the histograms for the Real increase, there are distinguishable trends for All households, the Villas and the Apartments. The trends look similar for all the types of vehicles in the graphs of the apartments. However, in the graphs for the villas there are spikes that are different between the categories urban and rural vehicles. Villas with rural vehicles have more larger values than villas with urban vehicles. This trend is distinguishable for the graphs of All Households as well. The Apartments histograms give signs of a more fluctuating trend, with less spikes but larger variations.

The power demand profiles for the Apartments indicate that the power demand is close to zero multiple times during the year, this could explain the spike to the far left, which exists for all types of household but is most distinguishable for the Apartments. As more apartments are combined, the spike is shifted to the right. For example, in Figure 4.8 there are 5 distinguishable spikes, which could represent that for combinations with a lower number of apartments, there are more similar values between combinations. The trend after these larger spikes could implicate that the lower likelihood of coincidences between uncontrolled charging of BEVs takes the upper hand over the influence of the apartments having a lower power demand. Which could explain the appearance of Figure 4.8 to the right of these 5 spikes.

This reasoning could be valid for the histograms for All households and Villas as well, but the trend seems most apparent for the apartments. The scatter plots indicate that a rated power demand increase e.g. 50 kW, can exist both for smaller and larger neighborhoods as the increase is dependent on how many vehicles are charging simultaneously. There was 20 villas and 16 apartments - 36 households in total. This difference in number of households could be a reason why the graphs for the Apartments are more similar to each other than the graphs for the Villas or All Households are.

5.3 General analysis

In general, it seems that when combining Villas and Apartments, the graphs generated have similar appearance as those of the Villas, with the difference that they are shifted to the right as the Apartments contribute with a distribution of higher values. The scatter plots on the Factor of increase seem to converge to a smaller and smaller interval. The scatter plots on the Real increase has a maximum possible increase that has a change that seems to dissipate and thus the maximum possible increase can also be said to converge towards a certain value. These curves have a similar appearance as a coincidence curve. Even though the maximum possible increase does not seem to occur frequently, it could be relevant to consider since these are critical points that could occur. The bottom side of the scatter plots representing the minimum possible values that increases linearly with the number of households being combined.

6 Discussion

With uncontrolled charging, a rated power demand increase could overload the main fuse of households. If uncontrolled charging is used as is assumed in this study, households in rural areas could have a higher rated power demand increase in kW compared to households in urban areas, where the largest difference is between rural and urban apartments. Larger neighborhoods (which is in this case represented by All 36 households) have the lowest average per household difference between the MAXPPI and MINPPI values, which could suggest that these larger neighborhoods are more suitable early adopters of BEVs. In Table 2.1, it can be viewed that neither a 16, 20 or 25 A fuse is sufficient on its own to manage the increases presented in section 4. Considering the example in section 3.4, for a single household, a load balancer might be sufficient to cope with the increased power demand from charging. The load balancer can decrease the charging rate when other appliances are active and increase it when less appliances are active. If only uncontrolled charging of BEVs is available, there could be a need for replacing fuses when households are combined. In addition interactive load balancing could be another way to cope with the large increase in rated power demand (increases could reach 800 % for a smaller number of households in combination, see section 4.1.2). Interactive load balancing means that the power demand of one household can be decreased to compensate the increase in power demand of another. Another way to cope with the increased power demand could be to change the heating of households from electric heating to district heating.

From the perspective of individual households, increased power demand could promote the installation of PV solar panels. Since the power demand will be relatively high in some cases, the cost savings from not buying electricity from the grid could be greater if electricity from privately owned solar PVs are used to charge the BEVs. The load balancer could be combined with a battery that stores excess electricity from PV generation and/or electricity with a lower marginal price than in the evening when most charging events are expected to occur. The scatter plots implies that smaller neighborhoods can benefit from this more, as the factor of increase in rated power demand can be higher in smaller neighborhoods.

This study was limited to the assumption that each household owns one BEV, no matter how large the household is. Vehicles that were in reality driven by inhabitants from a household of five could have been assigned to a household of one inhabitant. This could have resulted a vehicle charging more than is realistic. For example if a single youth from a 1 person household drives a vehicle that is in reality owned by a family of 5. Note that this is not necessarily leading to an increased rated power demand, but rather a too high number of charging events (minutes that the vehicle is charged). Other limitations considered the computational capacity, as the size of the samples is very small compared to the possible number of combinations. Since the model was executed two times - one for calculating the factor of increase and one for the numerical increase, correlating exact values between the plots for each execution might be invalid, but it is argued that it is the trend of the graphs that should be weighed firstly rather than the absolute values. Although it is worth pointing out that the scatter plots each contain one million dots and thus all values may not be distinguishable. Increasing the sample size could have given a more detailed resolution in the graphs. The benefits of a higher resolution could be that more Real power demand increases in kW that could in reality occur would be represented. This study was a conservative estimate of the impact from the uncontrolled charging of a large-scale BEV introduction, a higher resolution would increase the possible increases in the data and could make this estimate more relatable to power demand increases that could occur in reality.This could have implications for grid operators that are responsible for the dimensioning of the grid. For example, if the resolution of this study (1000 combinations of vehicles times 1000 combinations of households (1000x1000)) gave a MAXPPI value of 200 kW, increasing the resolution to 100000x100000 could give higher MAXPPI values above 200 kW and could thus implicate a need for a more robust dimensioning of the grid..

Future research could further validate the results by changing the constellations of households being included in the dataset (to better represent a real neighborhood). The impact of a large-scale BEV deployment on the grid could become more foreseeable and more detailed if the number of combinations are increased, and if more executions are performed. Other perspectives that can be investigated is how changing certain parameters would affect the result through sensitivity analysis. Load balancing means that the charging rate can be decreased and thus prolong the time spent charging, if household invest in two BEVs the influence of load balancing could be more profound on the charging rate. Other parameters topical for sensitivity analysis could be the average electricity consumption of the BEVs or the battery sizes of the BEVs. Another perspective is to model the influence of a charging infrastructure of fast chargers and relate to GPS-data such as the data considered in this study.

7
Conclusion

The study has shown that the rated power demand could be increasing with the deployment of BEVs. The Real increase per households on average seems to be largest for Apartments (16) in rural areas (6.875 kW) and smallest for All households (36) in urban areas (4.22 kW). When regarding the factor of increase, the interval of possible factor of increases seems to become more and more concentrated towards the most common increase, 3.5 (250 % increase) for apartments, 1.75 (75 % increase) for villas and 2 (100 %) when all households are considered. Larger neighborhoods have a smoothening effect in terms of the coincidence of simultaneous charging, i.e., there is a lower probability of that all households charge at the same time as the neighborhood become larger, and thus, the average household demand increase is lower with increased size of the neighborhood.

Larger neighborhoods in urban areas obtain the lowest average rated power demand per household in kW at a large-scale BEV adoption (if only uncontrolled home charging is available). While households in smaller municipalities (rural areas) could expect a higher average rated power demand increase in kW. There are implications for benefits for controlled charging and the integration of renewable electricity to the charging events as they considerably increase the household rated power demand. Another conclusion can be made regarding the fuse of households, for single households a load balancer might be sufficient to cope with an increased power demand due to the uncontrolled charging of BEVs. However for a grid operator, the fuse that is common for neighborhoods may have to be replaced. Results indicate that fuse replacement could be necessary if a larger number of households are considered. Although the size of these fuses could be predictable as the results indicate a convergence of the maximum possible increase towards a certain value as neighborhoods increases in size. Future research could look into increasing the number of combinations investigated to make the results more realistic. Other aspects involve modelling load balancing and the change in charging rate due to this, as well as modelling the infrastructure of fast chargers.

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A

Appendix

A.1 Factor of increase

A.1.1 Histograms

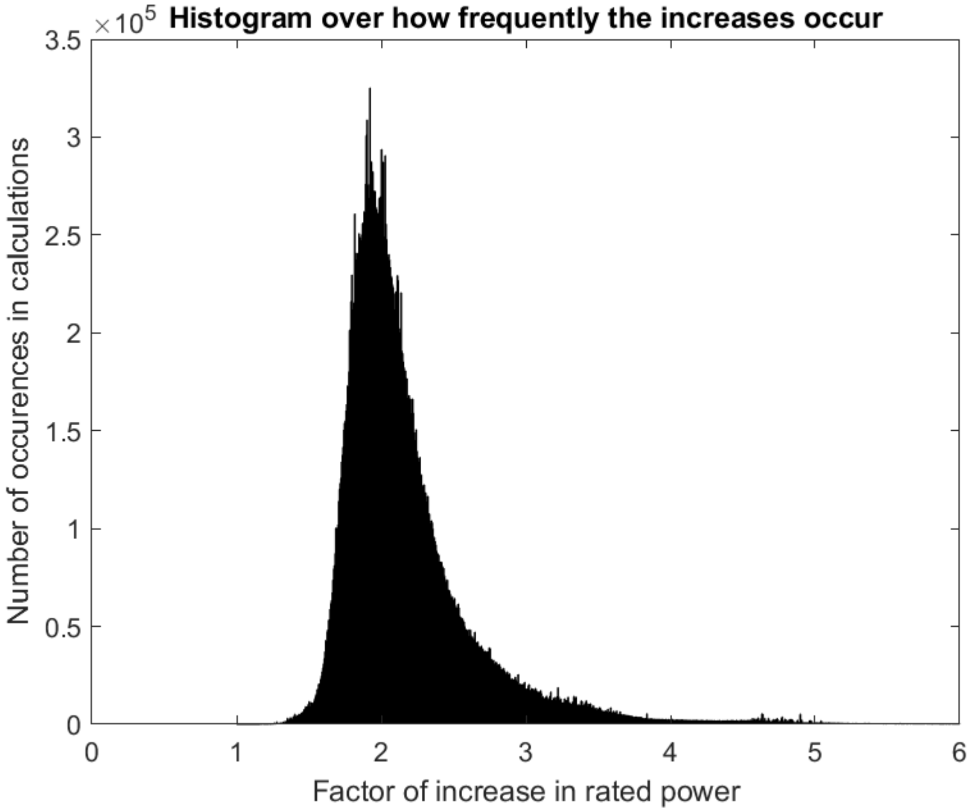

Figure A.1: Histogram for All households and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

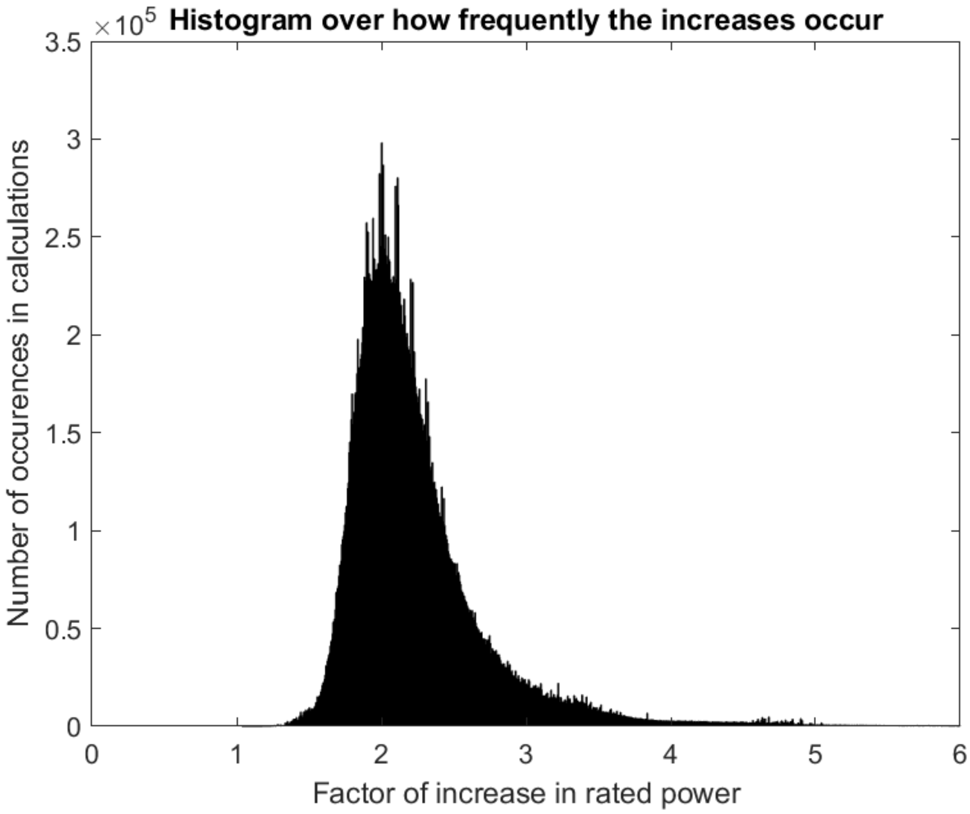

Figure A.2: Histogram for All households and Rural vehicles. The graph shows how common certain increases are, independent of how many households are combined.

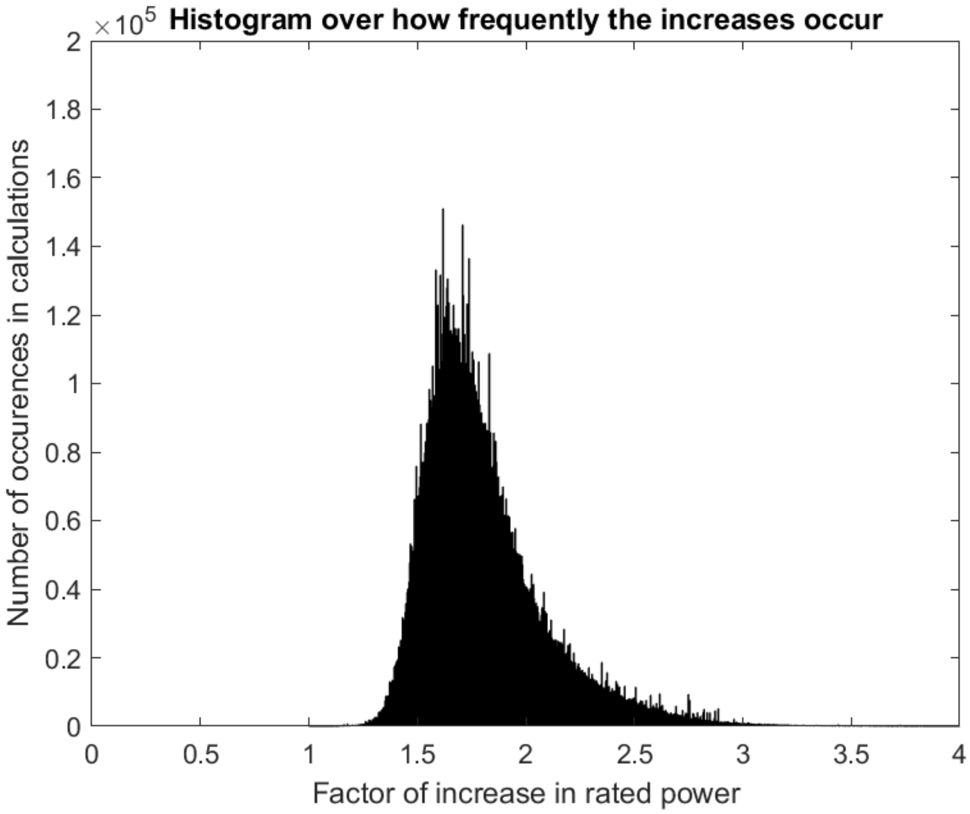

Figure A.3: Histogram for Villas and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

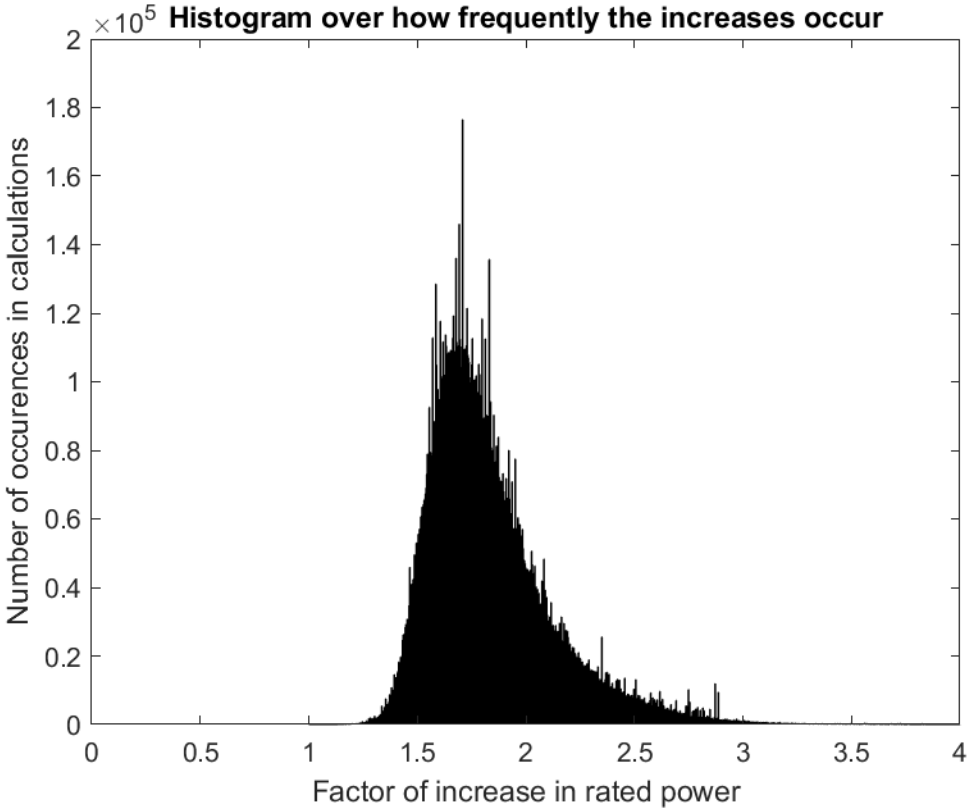

Figure A.4: Histogram for Apartments and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

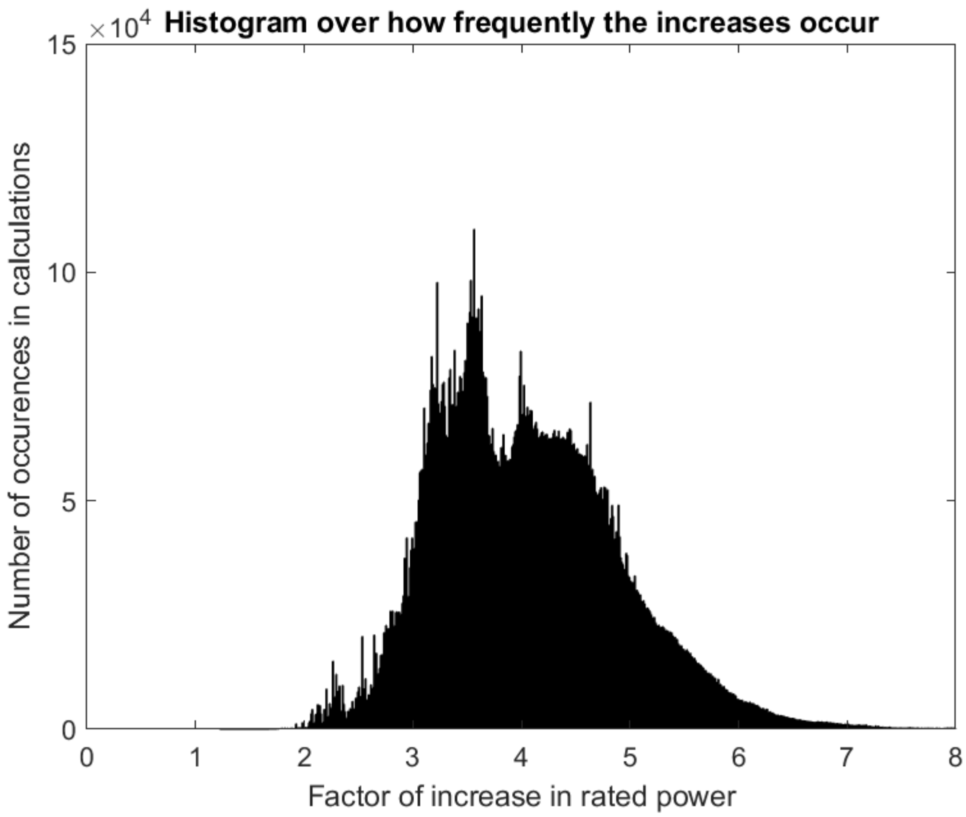

Figure A.5: Histogram for Apartments and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

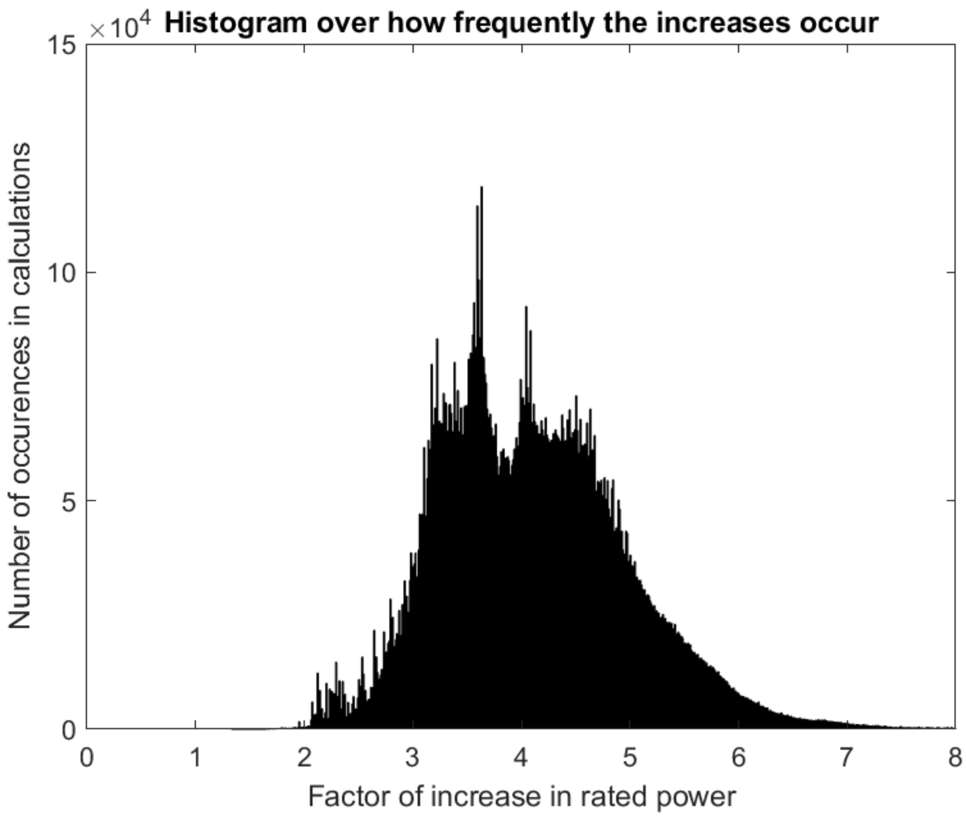

Figure A.6: Histogram for Apartments and Rural vehicles. The graph shows how common certain increases are, independent of how many households are combined.

A.1.2 Scatter plots

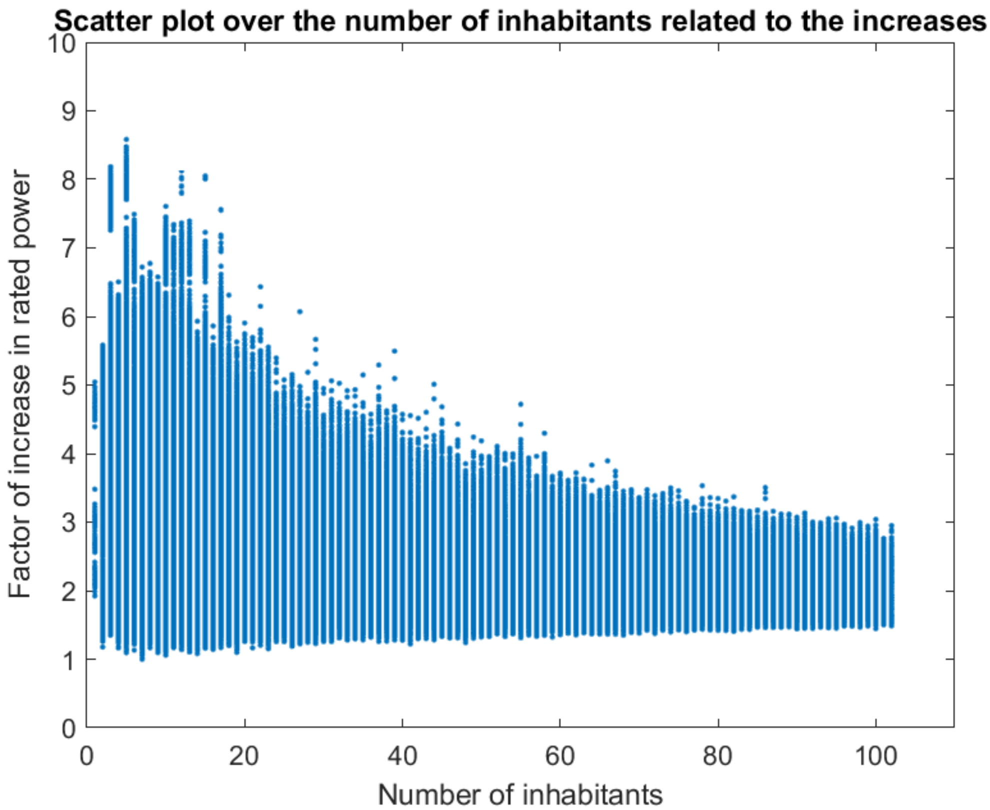

Figure A.7: Scatter plot showing factor of increase in rated power demand for All Households and Urban vehicles.

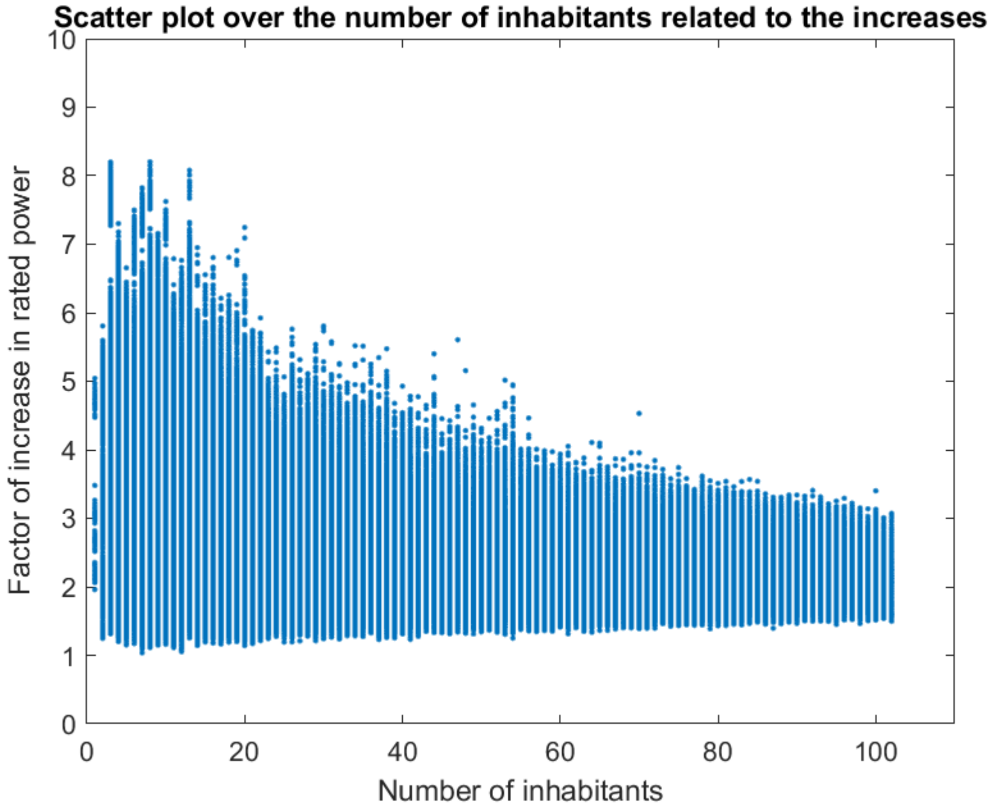

Figure A.8: Scatter plot showing factor of increase in rated power demand for All Households and Rural vehicles.

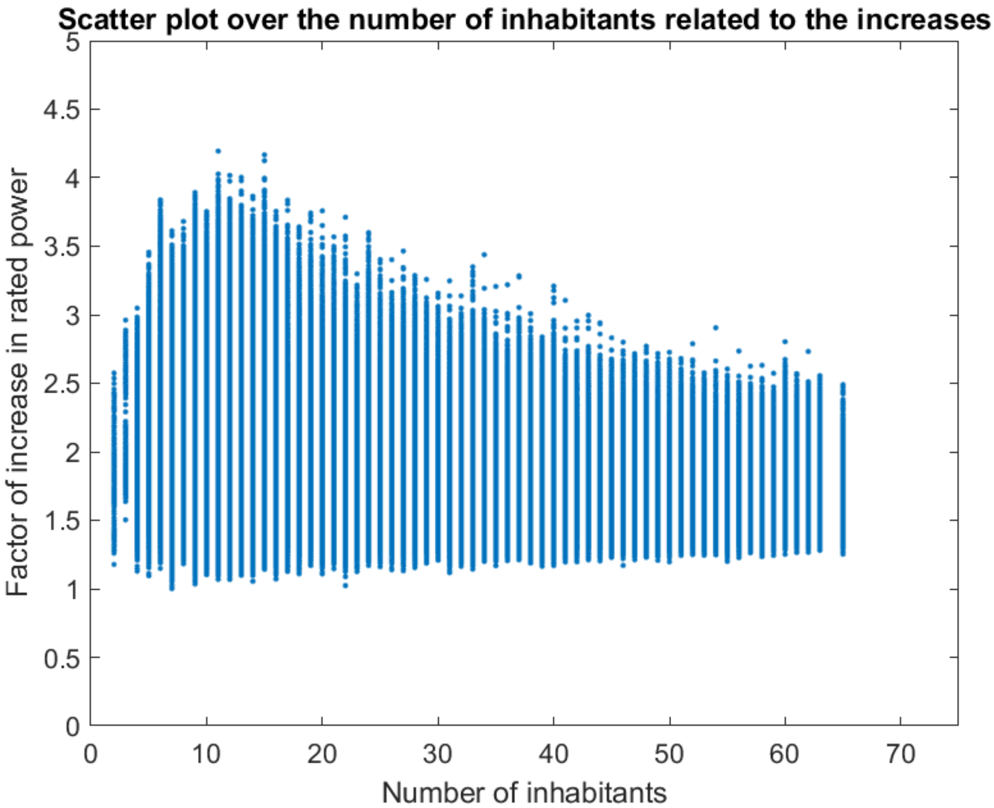

Figure A.9: Scatter plot showing factor of increase in rated power demand for Villas and Urban vehicles.

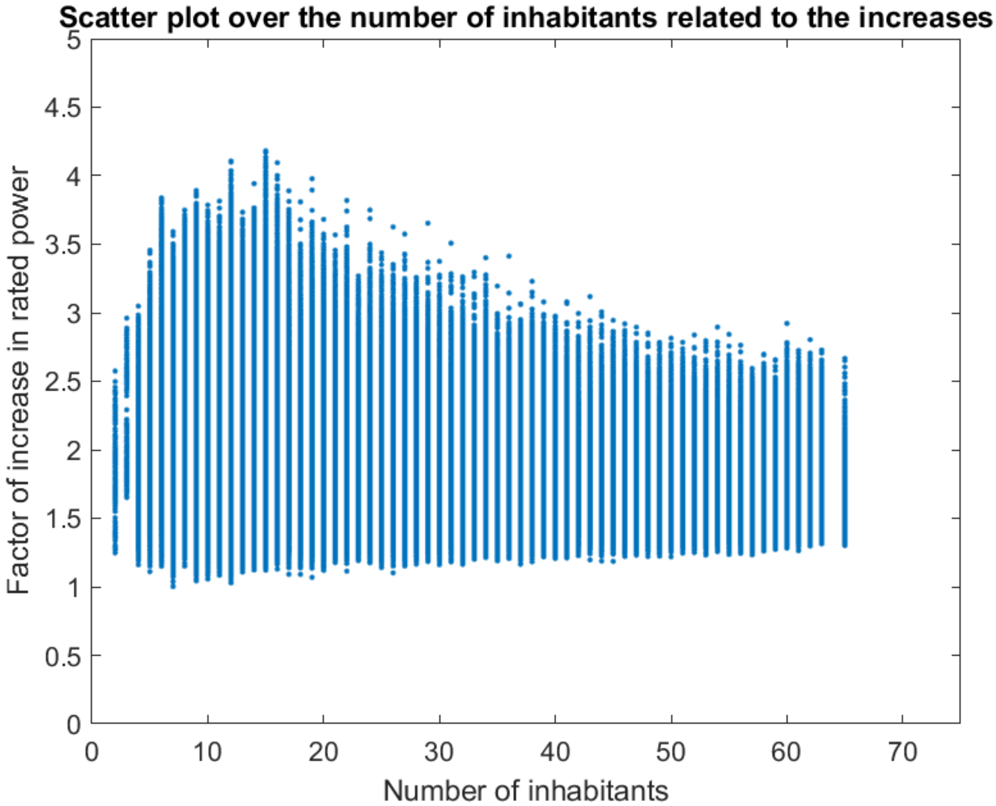

Figure A.10: Scatter plot showing factor of increase in rated power demand for Villas and Rural vehicles.

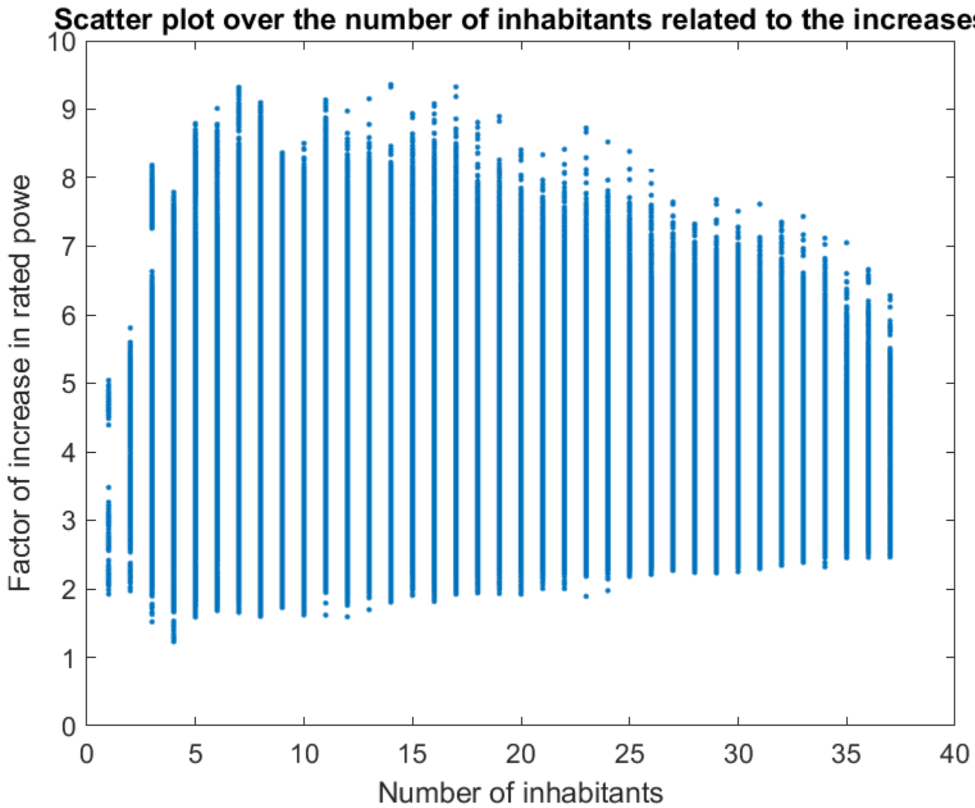

Figure A.11: Scatter plot showing factor of increase in rated power demand for Apartments and Urban vehicles.

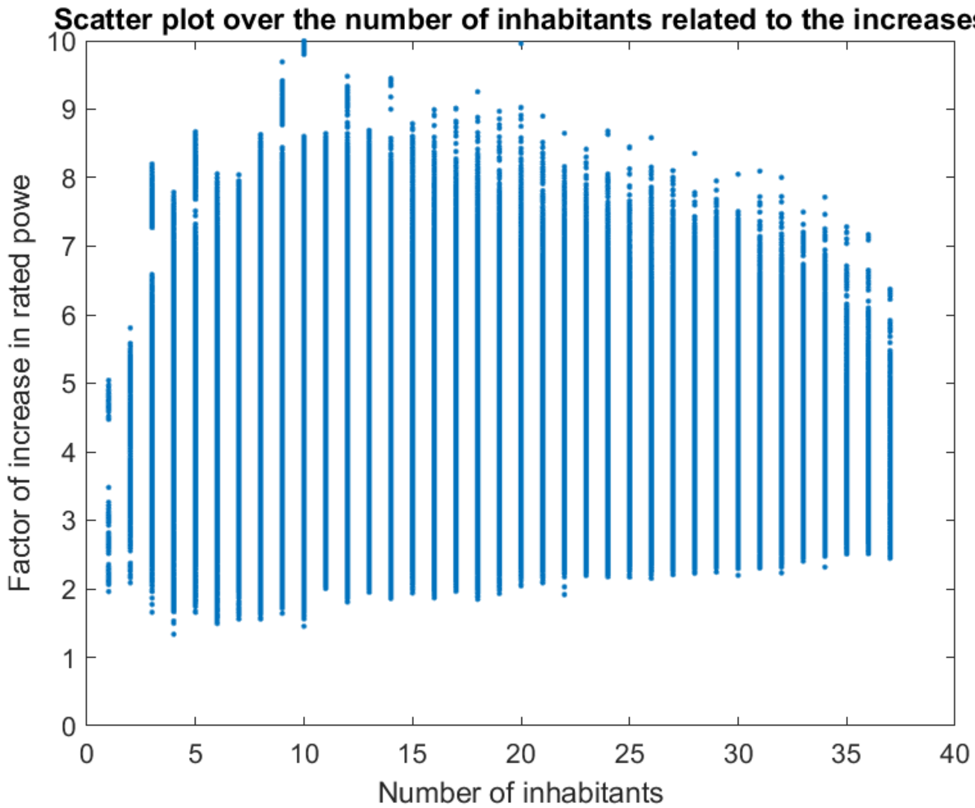

Figure A.12: Scatter plot showing factor of increase in rated power demand for Apartments and Rural vehicles.

A.2 Real increase

A.2.1 Histograms

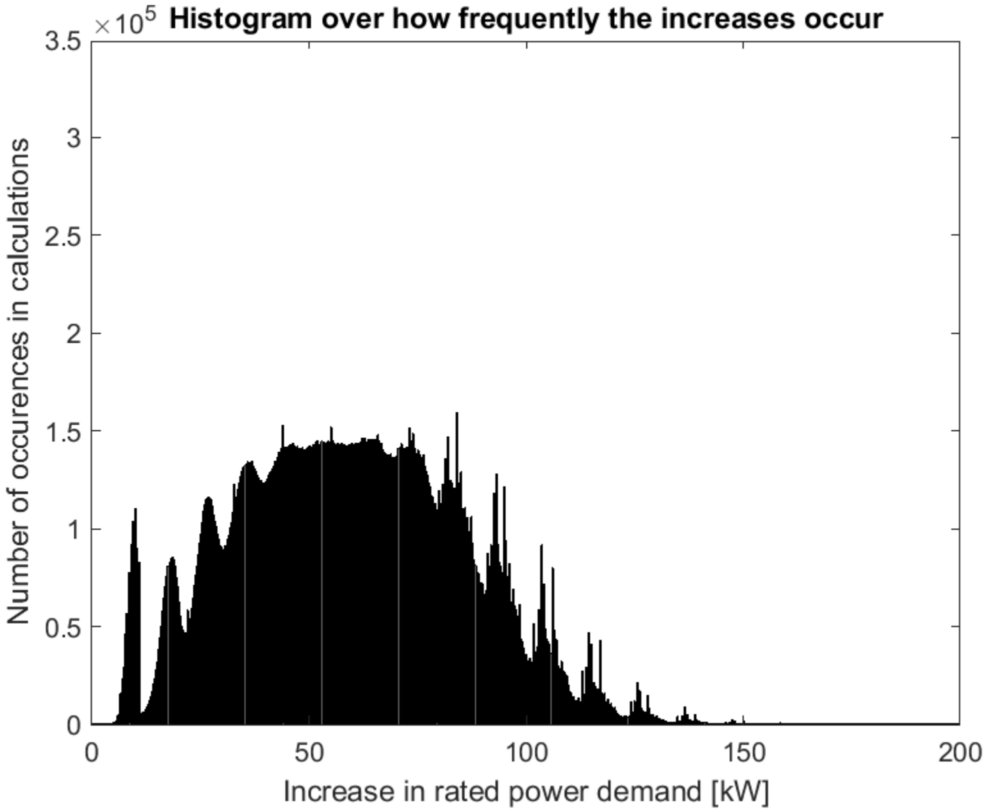

Figure A.13: Histogram for All households and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

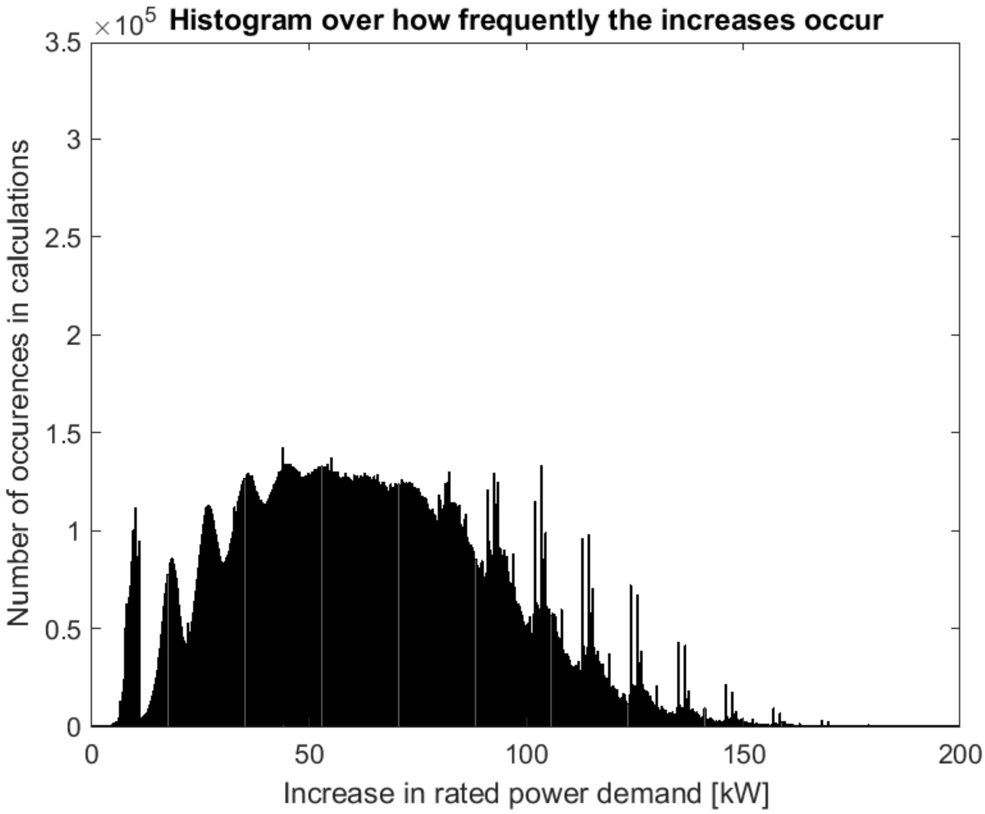

Figure A.14: Histogram for All households and Rural vehicles. The graph shows how common certain increases are, independent of how many households are combined.

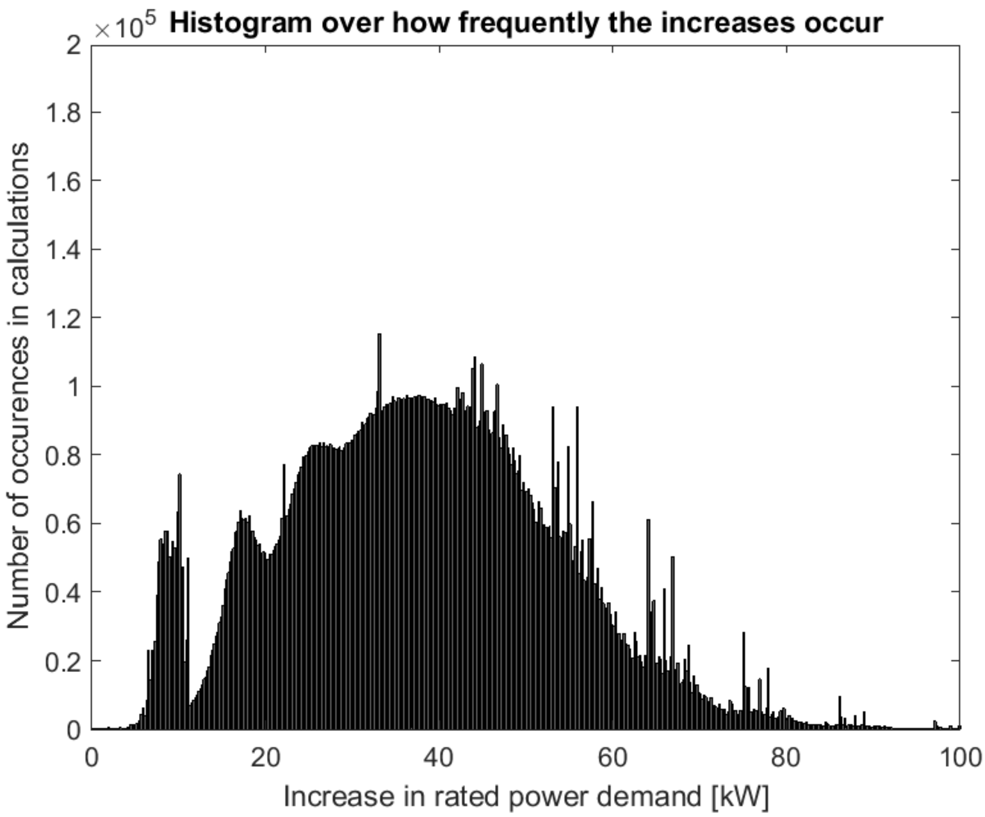

Figure A.15: Histogram for Villas and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

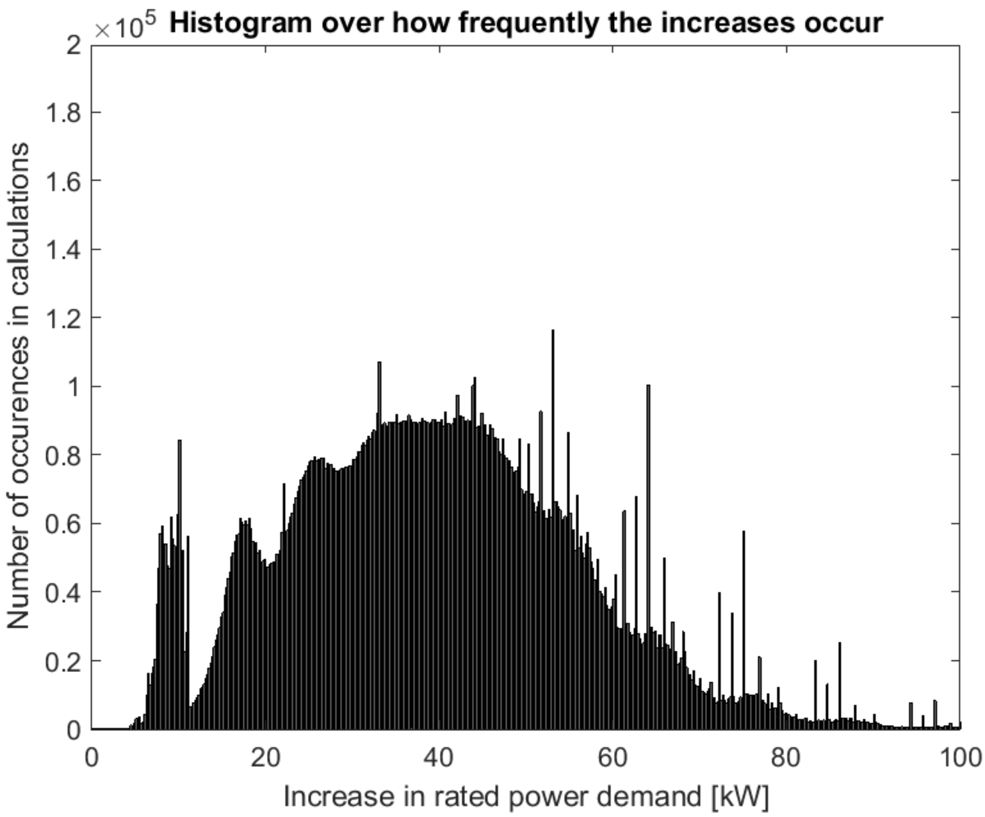

Figure A.16: Histogram for Villas and Rural vehicles. The graph shows how common certain increases are, independent of how many households are combined.

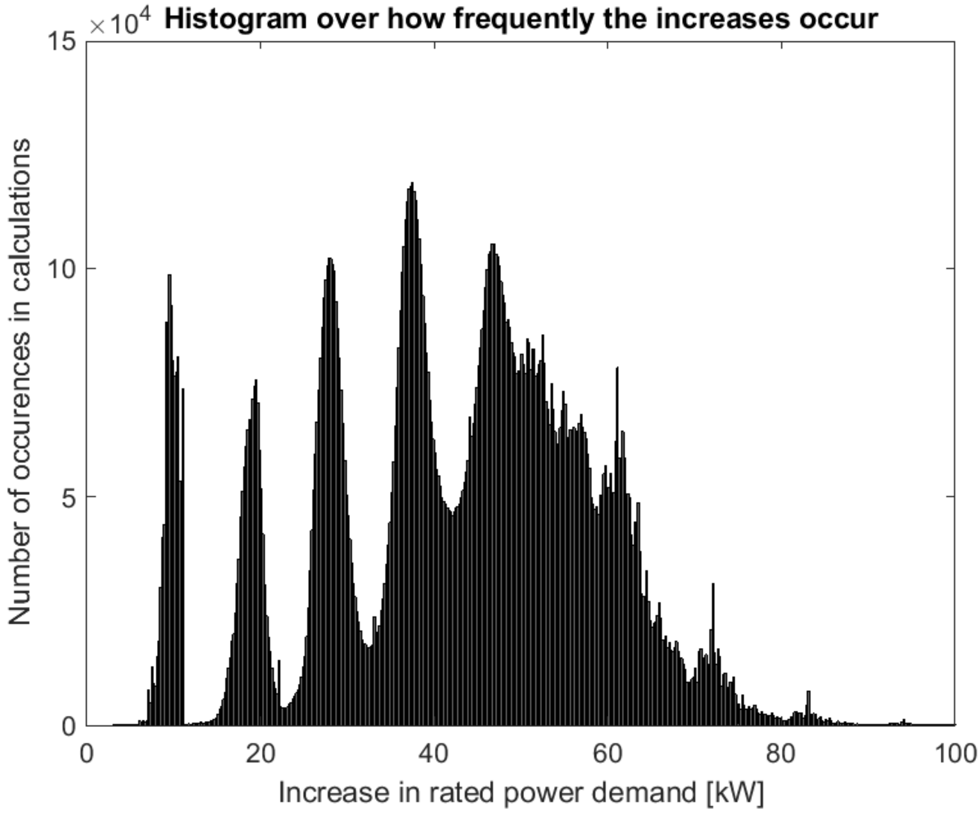

Figure A.17: Histogram for Apartments and Urban vehicles. The graph shows how common certain increases are, independent of how many households are combined.

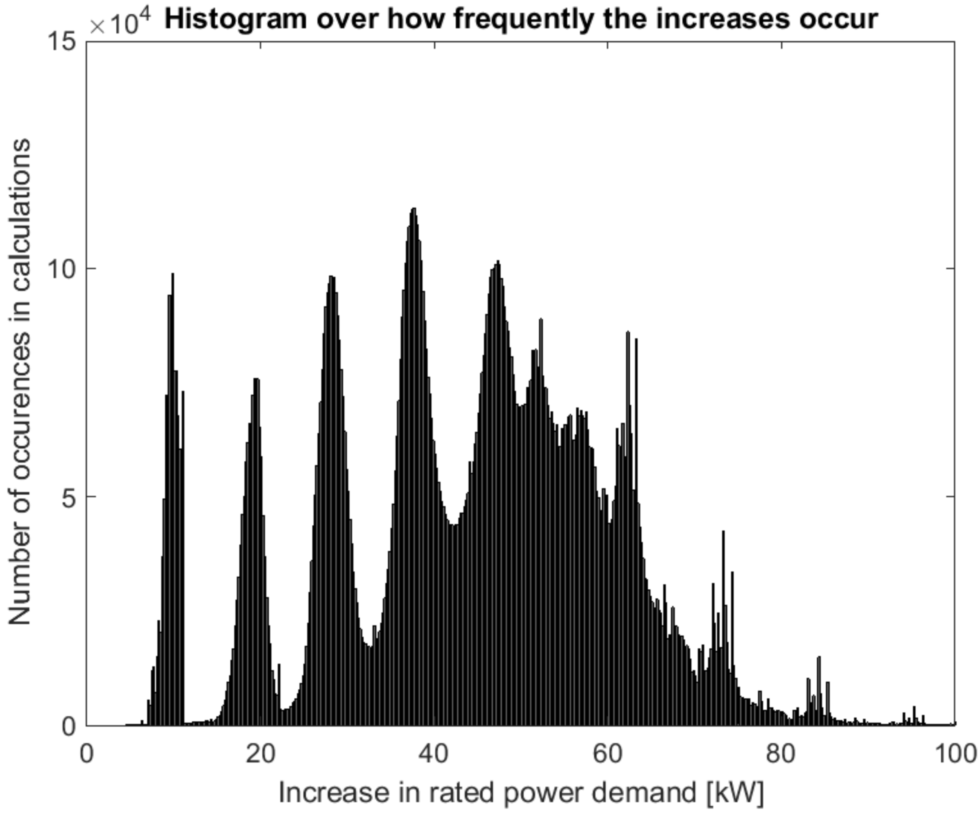

Figure A.18: Histogram for Apartments and Rural vehicles. The graph shows how common certain increases are, independent of how many households are combined.

A.2.2 Scatter plots

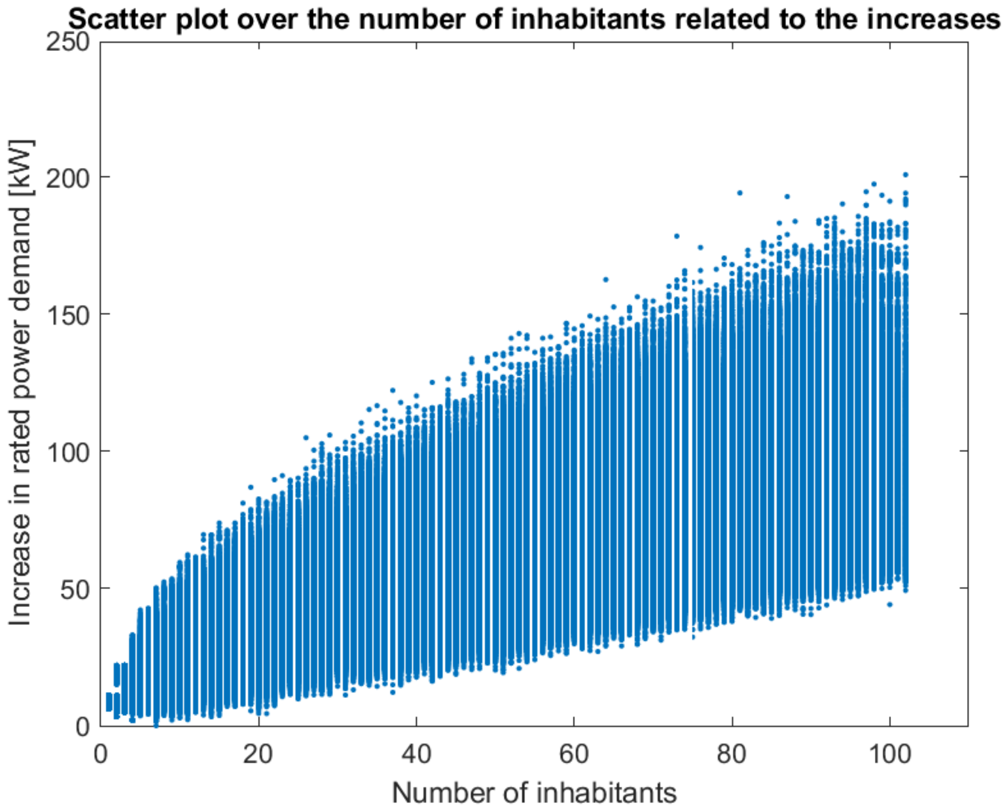

Figure A.19: Scatter plot showing rated power demand increases in kW for All Households and Urban vehicles.

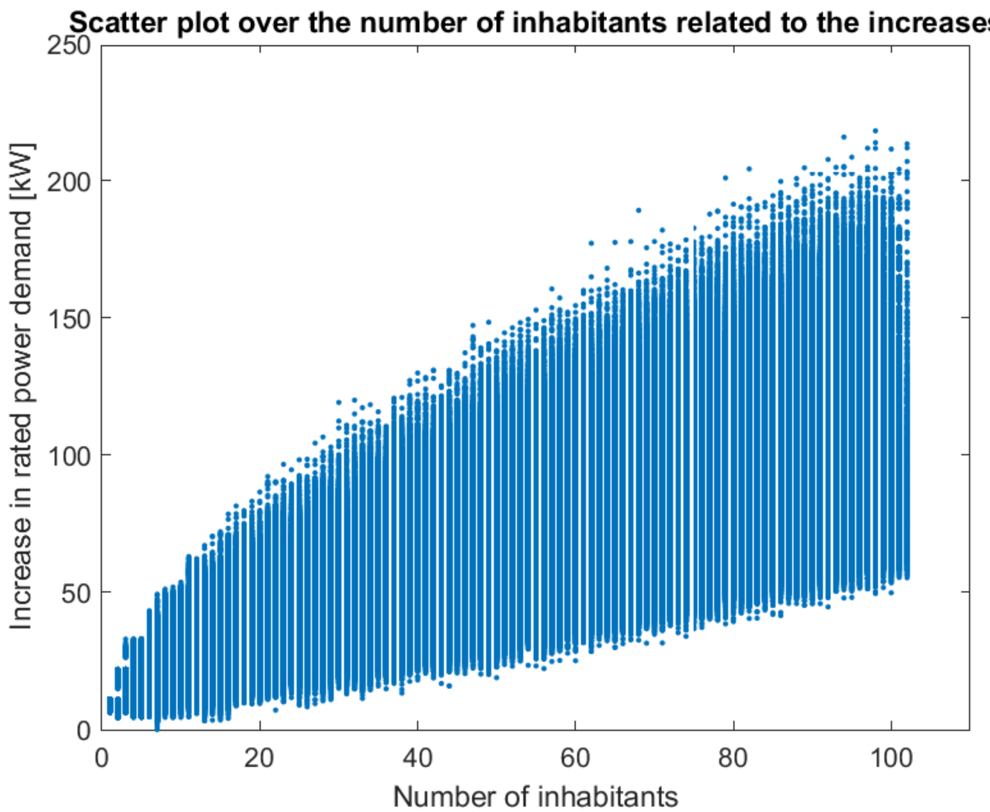

Figure A.20: Scatter plot showing rated power demand increases in kW for All Households and Rural vehicles.

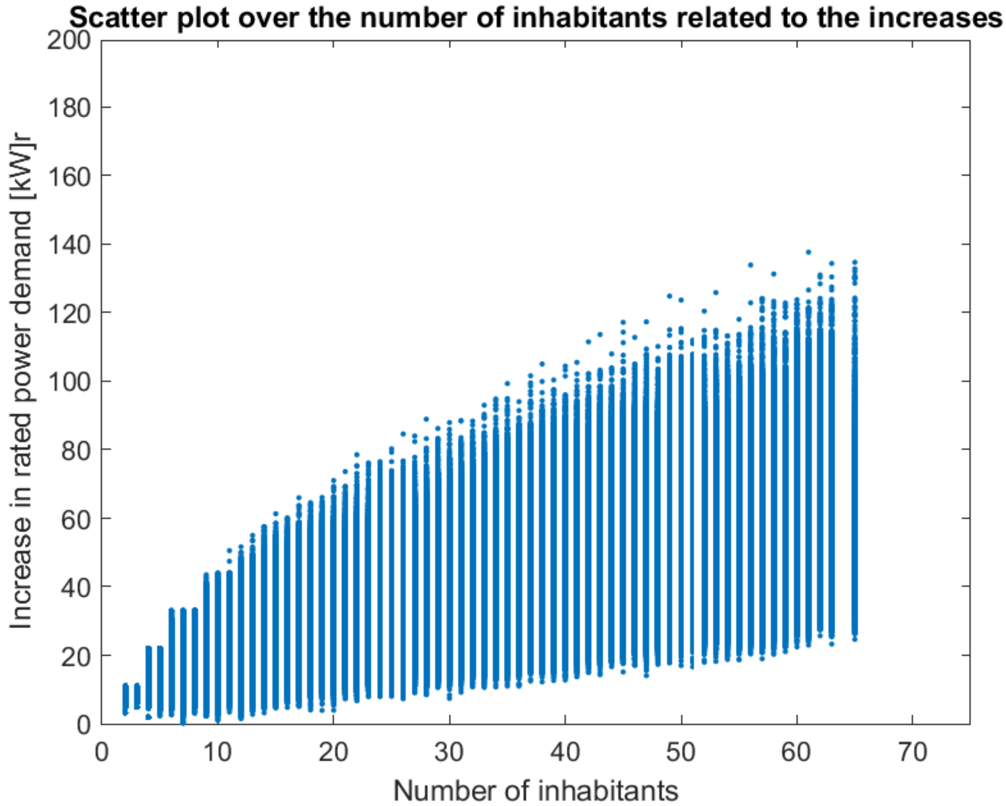

Figure A.21: Scatter plot showing rated power demand increases in kW for Villas and Urban vehicles.

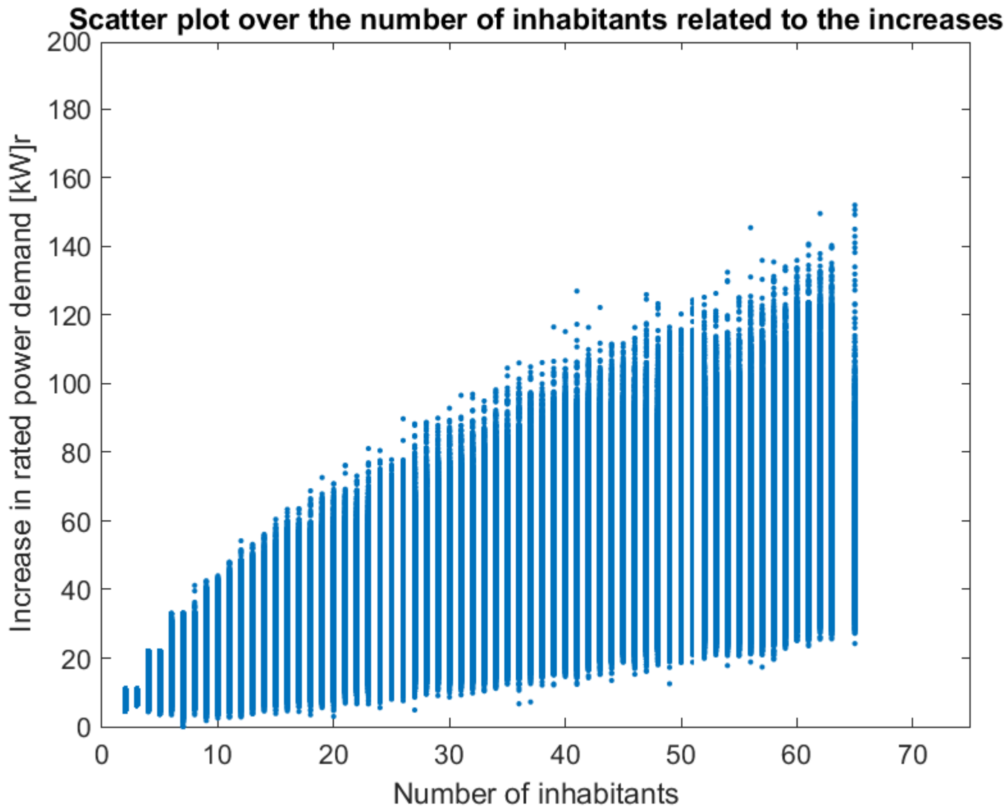

Figure A.22: Scatter plot showing rated power demand increases in kW for Villas and Rural vehicles.

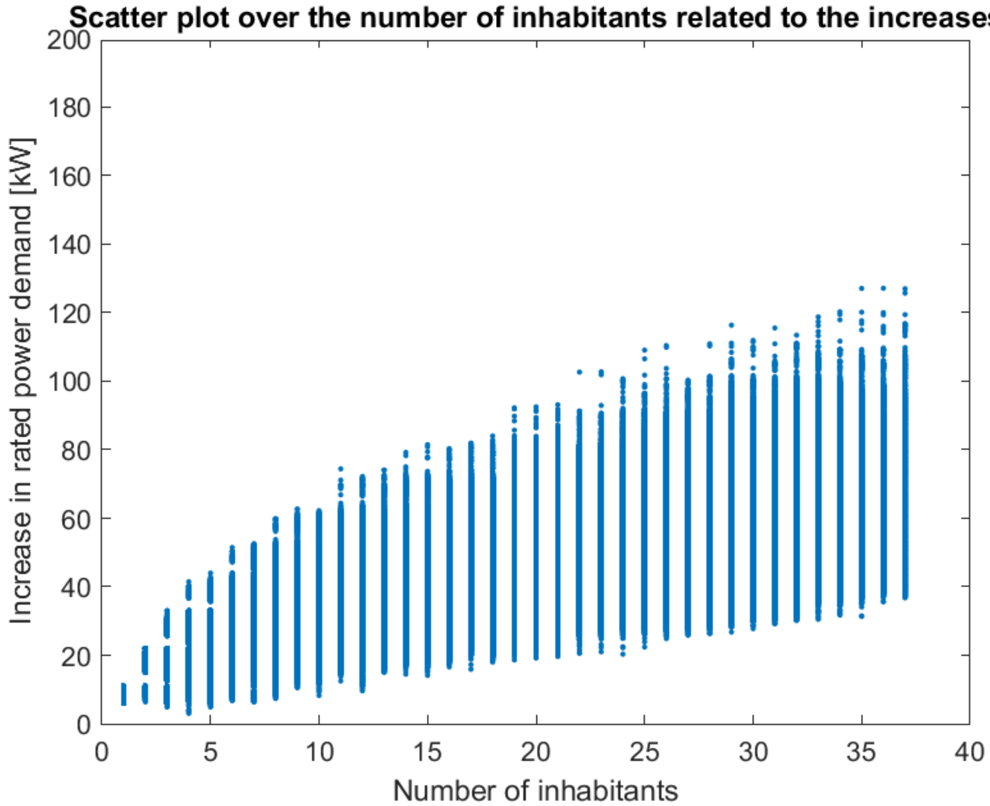

Figure A.23: Scatter plot showing rated power demand increases in kW for Apartments and Urban vehicles.

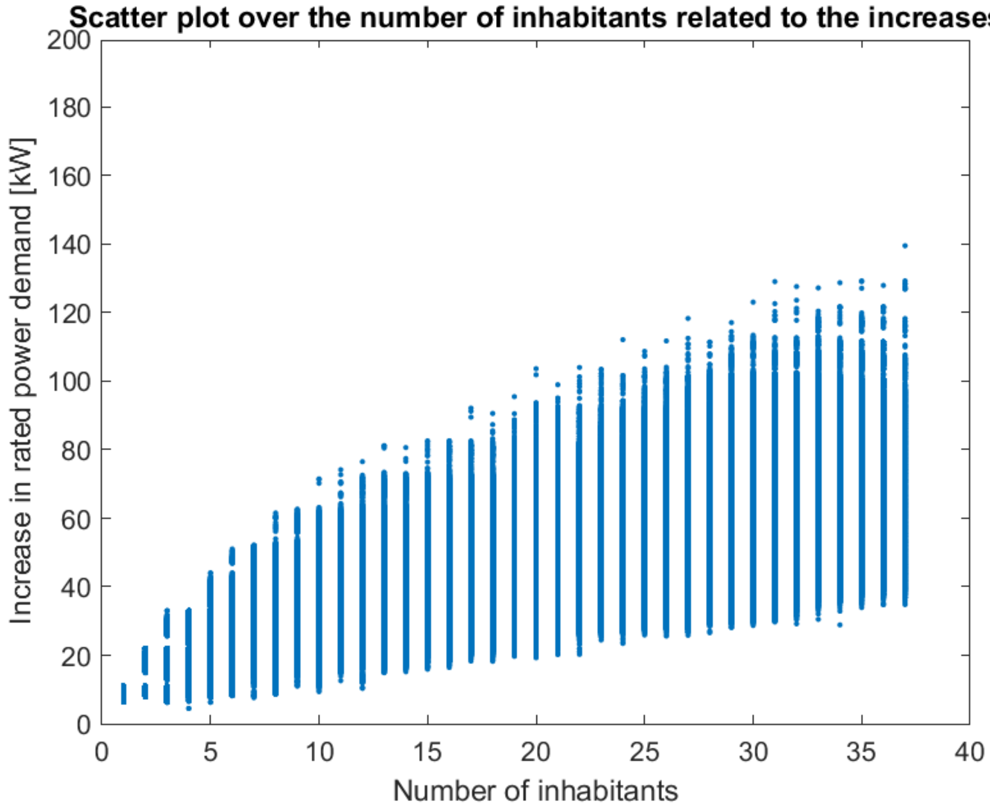

Figure A.24: Scatter plot showing rated power demand increases in kW for Apartments and Rural vehicles.

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