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Electric Vehicles Charging Loads in Residential Areas of Private Houses

School of Electrical Engineering

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Abstract

Number of electric vehicles (EV) is increasing all over the world due to their driving performances and lower environmental impact in comparison with conventional combustion engine cars. Finland, as one of the leading countries in adopting new technologies, is interested in the development of infrastructure for battery electric vehicles (BEV) as the number of such automobiles is growing every year.

Growth of electric vehicles inevitably causes a growth of energy demand needed for their charging. Talking about privately owned cars, it is important to ensure that their charging at home is possible. That is why it is necessary to estimate if electric grid is able to meet new electricity demands dictated by increased number of EVs.

In this work charging loads of electric cars in residential areas of private houses in Finland are studied. Models represent different charging scenarios, uncontrolled and price-optimized, at four power levels – 1.84 kW, 3.68 kW, 11.1 kW, 22.2 kW. Houses were divided into groups of 5, 10, 50 and 100.

Main findings indicate that highly coincident fast charging at price-optimized scenario will significantly overload the grid. Poorly dimensioned electric network can suffer even during slow charging. Most of the grid stress in uncontrolled charging happens at the same time with evening peak load of households. Also, according to results of the simulation, slow charging causes the least amount of stress to the grid, while providing enough energy to charge all the cars during night time.

Preface

This Master Thesis was undertaken at the request of Aalto University, department of Electrical Engineering. My research question was formulated together with my supervisor, professor Matti Lehtonen. I would like to thank him for providing a topic related to electric vehicles, because this sphere is interesting to me. I am grateful for prof. Lehtonen's guidance and support during the process.
I am very thankful to Oula Lehtinen, Aalto student and author of the article about EV charging loads in apartment houses in Finland, for his advices and help with modelling. Also, I want to thank John Robert Millar, University lecturer, for consultations regarding LV network.

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Symbols

A	ampere
c	coincidence factor
d	distance
I	current
km	kilometers
kW	kilowatt
kWh	kilowatt hours
m	average daily distance
μ	lognormal mean
P	power
P_i	individual peak
P_{max}	observed peak power of the group
σ	lognormal standard deviation of the probability density function
TW	terawatt
U	voltage
V	volt
υ	standard deviation

Abbreviations

|	
AC	Alternating current
BEV	Battery electric vehicle
DC	Direct current
DIY	Do it yourself
EV	Electric vehicle
FTIA	Finnish Transport Infrastructure Agency
ICE	Internal combustion engine
LV	Low Voltage
pdf	Probability density function
RES	Renewable energy source
SESKO	National Electrotechnical Standardization Organization
SOC	State of charge

1 Introduction

This thesis will present electric vehicles (EVs) charging loads in residential areas of private houses. This work was developed from an earlier project done at the Project Work course ELEC-E8004 at Aalto University. In that project a group of students made several scenarios on how EV charging influences total load of apartment houses in Finland. Two houses with 27 and 91 apartments were investigated to meet demand of electric cars charging at 100% EV penetration level. The group of researchers used three different scenarios: uncontrolled charging, load-limiting charging and price-optimized charging at four different power rates 1.84 kW, 3.68 kW, 11.1 kW and 22.2 kW. Results of the work showed that in uncontrolled scenario only 1.84 kW and 3.68 kW charging powers are not causing overloading. Price-optimized scenario leads to highly simultaneous demand, with slow 1.84 kW charging fuses of houses are not overloaded, however, with higher charging powers connections are heavily overloaded. Load-limiting scenarios showed promising results for all power levels without overloading an example grid of apartment houses.

As the number of electric vehicles increases in Finland, issues associated to the grid arise. In this work residential areas of private houses will be investigated for load flows when electric cars charging is implemented. Based on real-life data for electricity consumption in Finnish detached houses, total loads will be estimated for different groups of houses assuming one electric vehicle per household. Houses of the following types are used in the work: non-electrically heated, electrically heated, electrically heated price controlled. New total demands will be checked to match with fuse sizes of houses and maximum allowed loads. The main goal of this thesis is to see how EV charging at four different powers 1.84 kW, 3.68 kW, 11.1 kW and 22.2 kW influences electrical load of private houses in Finland. Another purpose is to see how coincidence factors behave during charging. This is achieved by processing consumption data of Finnish detached houses and adding electric cars loads to it. The modelling software used in this thesis is MATLAB, as in the previous work. Separate models are made for price-optimized and uncontrolled charging. The results of this work are compared with the results of the similar work for apartment houses mentioned above made by the group of Aalto University students.

2 Background

Electric cars are the trend of the recent years. In the last decade, electric vehicles (EVs) have received lots of global attention due to their high driving performance, high total energy efficiency and lower environmental impact in comparison with conventional internal combustion engine (ICE) cars (Aziz, 2019). Sales of EVs are growing worldwide, more car manufacturers introduce electric models. The most popular ones currently are Tesla Model 3 and Nissan Leaf with Teslas dominating in Finland in the year 2018 (Traficom, 2019). Figure 1 represents growth of electric cars in Finland in the last years and Figure 2 shows projected growth.
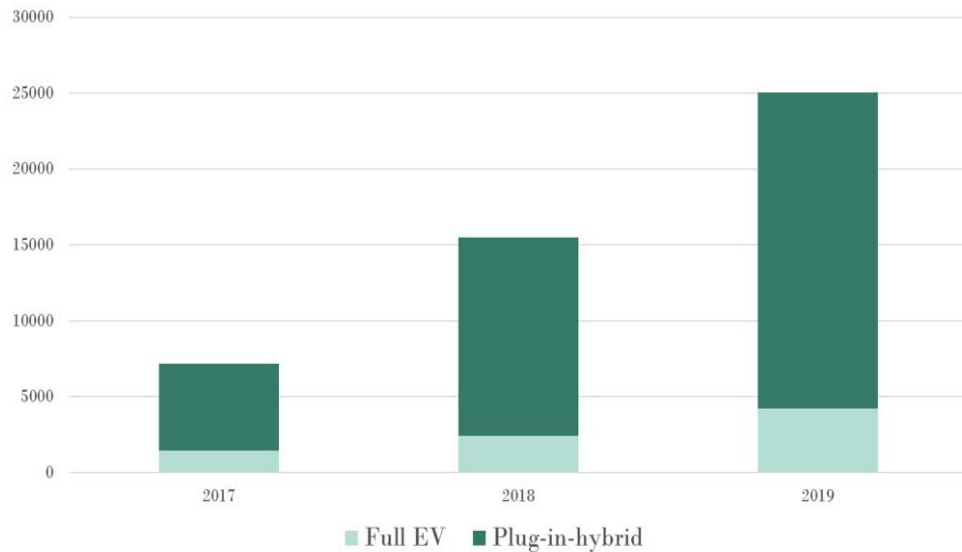
Figure 1. Growth of electric cars in Finland (Traficom 2019, modified)
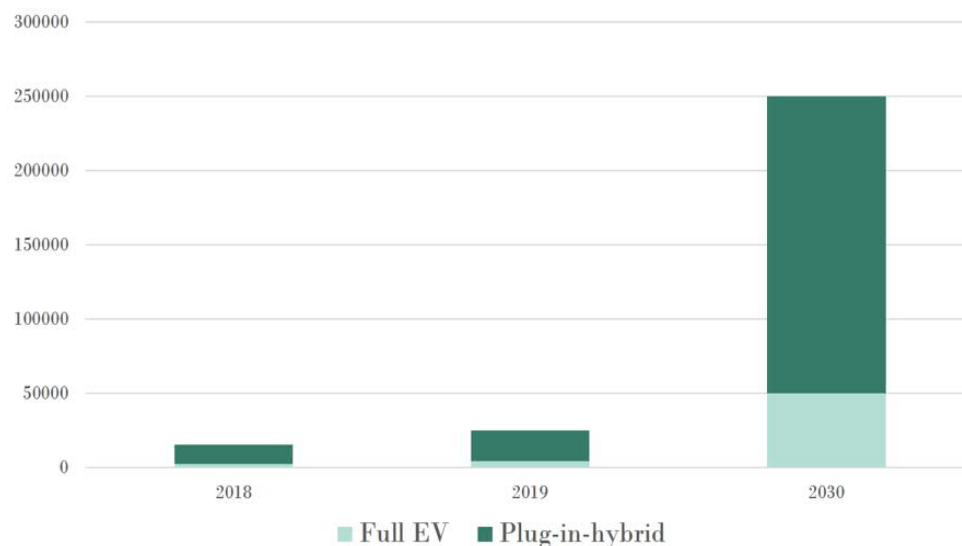
Figure 2. Projected increase of electric cars in Finland (Traficom 2019, modified)

Massive adoption of EVs can cause serious problems to the grid and have a negative impact on power quality, for example, huge energy consumption for charging, big gap between peak

and non-peak loads, flicker, phase imbalance and other. The coordination of EVs becomes an important topic. A large amount of EVs connected to the grid can be considered as a huge battery storage, which is also beneficial for a network with large penetration of renewable energy sources (RES). The high fluctuation of RES (for example, wind and solar) leads to the imbalance of the electrical grid – when demand can not meet production. It results in poor power quality characterized by frequency and voltage fluctuations (Aziz, 2019).

Electric vehicles have the potential for controllable charging, which can support the grid and improve the economic value of EVs. But before planning an intelligent charging it is important to determine how uncontrolled charging influences electric loads. It will be demonstrated in the fifth chapter of this thesis.

2.1 EV charging options

Roughly, charging can be divided into rapid, fast and slow. Charging speed depends on power output (kW).

- Ultra-rapid chargers with powers from 100 kW up to 350 kW use only direct current (DC). More conventional rapid chargers can provide 50 kW of DC power and also 43 kW alternating current (AC) is available
- Fast charging is considered to be from 7 kW to 22 kW
- Slow charging with up to 3,7 kW is good for overnight battery filling. Different sources name power from 3,7 kW to 7 kW as slow or medium power charging.

Classification of charging modes is based on power output as well on the devices used for charging.

- Mode 1. Slow AC charging mostly for light vehicles, with low current (like mopeds). It is not suitable for EVs and even forbidden in some countries.
- Mode 2. Slow charging mainly done from a household outlet, but the long-term charging current is limited to 8 A based on standard SFS-EN 62752. Charging cable is equipped with in-cable control box, which includes control and safety related functionalities.
- Mode 3. Recommended AC for daily charging. It has extended control possibilities and safety functionalities. The plug switches are mechanically or electrically locked in their sockets while charging. The charging system includes data bus to ensure that vehicle is properly and securely connected to charging station. The bus can control the load and power supply in both directions.
- Mode 4. Fast DC charging from an external (off-board) charger with fixed cable in a charging station. Enables flexible and controllable charging. The current supplied to the BEVs by devices is hundreds of amps and capacity may be up to 350 kW (and will increase in future). (Falvo, 2014)

SESKO – electrotechnical standardization association in Finland made recommendation for EV charging. According to them, slow charging solutions of Mode 2 are temporary or transitional solutions before other advanced methods become more common. The most recommended for EVs is mode 3, which can provide three-phase AC with maximum current of 63 A (Vesa, 2016). It requires type 2 socket, represented on Figure 3 below.

Figure 3. Type 2 socket (known also as Mennekes) (Vesa 2016)

European Commission decided that all electric vehicles in Europe should have Type 2 charging plug (Virta, 2017). Other types of connectors presented in the market can be found in Appendix 1.

2.2 Energy market

Nordic electricity market consists of three major components: day-ahead, intraday and balancing markets. The day-ahead market «Elspot» provides market participants with the possibility to trade electricity for the following day. Most of the trading occurs here. After estimation of the energy amount required it is possible to purchase it 24 hours in advance with the price [€/MWh], which is established on the market for every hour of the following day. In the intraday market «Elbas» it is possible to trade electricity 1 hour before the delivery time when forecasts are more accurate. Quantities of energy here are much smaller than on the day-ahead market and prices are higher. The balancing market is different from the ones described above. On the day-ahead and intraday markets, electricity is traded for the future and the goal is to make as precise forecast as possible in order to reach the equilibrium between production and consumption (Fingrid, 2019). However, it is quite hard to predict the situation for energy load for each hour, so real time control is required. Here balancing markets join the game.

In Finland it is possible to make electricity contract based on Elspot prices, meaning that price of electricity a person is using will differ every hour. Group of houses in this research have price-controlled electricity usage and heating. This principle of price incentivized electricity usage for EV charging will be applied to estimate loads in Chapter 4.

2.3 Distribution system, impact on electric grid

When planning the development of electrical network, not only number of electric cars should be taken into account but also characteristics of charging infrastructure. New loads will add stress to the electric grid and generating plants if not managed properly. According

to estimation of private German company «Energy Brainpool» if all 28 countries of European Union will change towards electric cars by 2050, required total power will be 830 TW (EEA Report, 2019).

Not all networks are ready for load raise. Promising locations for chargers installation are crowded public places such as shopping centers, stadiums, theatres, hotels, municipal institutions. Chargers are also needed on highways between cities, for apartment buildings and private houses. But transformer substations are different everywhere.

Research made in USA in 2013 showed that public chargers connected to the grids in highly populated locations do not cause serious impact on the network, because transformers and other equipment are designed with a margin for heavy loads. The problem appears when EV owners install chargers in their private houses in regions of up to 10 houses. In such areas networks are not designed for significant increase in the load. (Jiang, 2016).

Several studies show the problem of overloading in low-voltage networks due to uncontrolled EV charging, especially in apartment house areas with district heating. Depending on charging powers used, network characteristics and customer type, one result by Tapani Tikka demonstrates overloading of 35% of distribution transformers at EV penetration level of 25%, while study made by Antti Alahäivälä shows that only 2 out of 15 transformers will be overloaded at 100% penetration of EVs (Pitkäniemi, 2019). Both of the estimations are done for Finnish areas, in the research of Tikka cars were charged at power of 10 kW and in the research of Alahäivälä charging power was limited to 3.7 kW.

Another work conducted by group of students from Aalto University found that slow charging at 1.84 kW would be acceptable even in uncontrolled charging for apartment houses at 100% penetration of EVs. However, faster options of 11 kW and 22 kW would lead to serious overloading, especially, in case of price-optimized charging, because simultaneous charging is highly likely to happen. Results of the same study prove that load-limiting charging allows to avoid exceeding transformers connection size even for 11 kW and 22 kW powers (Lehtinen, 2019).

3 Finnish households

3.1 Private households

In this work the focus is on private houses in Finland. According to the survey conducted in Sähköautoilijat Ry's Facebook-group, more than 60 % of people who own a battery car live in private houses (Figure 4). This fact shows the importance of investigating EV charging loads for free-standing private houses in Finland.
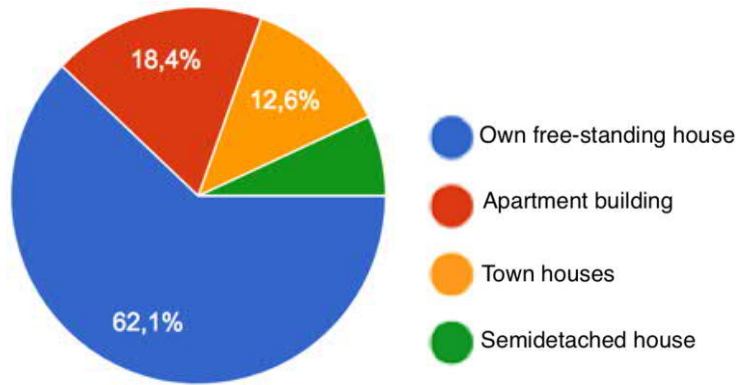
Figure 4. Types of houses of battery car owners in Finland (online questionnaire in Sähköautoilijat ry's Facebook-group, 2020). Blue – omakotitalo, red – kerrostalo, yellow – rivitalo, green – paritalo.

There are few companies in Finland, which provide ready solution for charging in private houses with full chain of services including initial inspection, device, installation and taking charger into use. The companies are PlugIt, Virta, Fortum Charge&Drive, Helen and Tesla. All of them can provide chargers with power up to 22 kW if condition of the electrical network allows it. However, in most of the cases maximum power of home chargers is not exceeding 11 kW (Vuori, 2020).

However, many people out of this 62,1 % living in detached houses did not address to any company providing ready solutions. Almost 80% did installations themselves or use household socket. Results from the same questionnarie are represented in Figure 5.
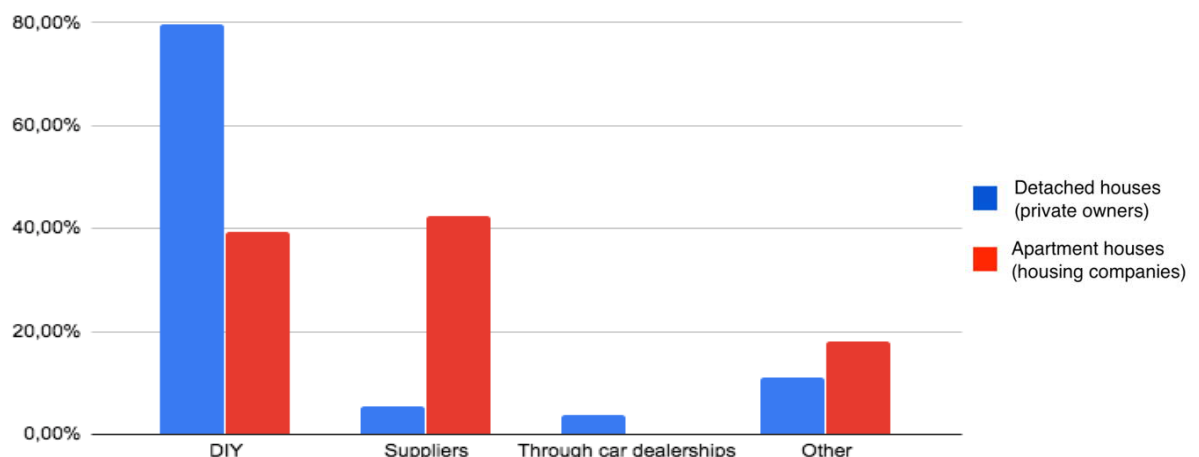
Figure 5. Where do people take charging devices from (online questionnaire in Sähköautoilijat ry's Facebook-group, 2020, DIY – Do It Yourself)

On the x-axis of the graph DIY stands for Do It Yourslf and it includes usage of household socket. A device for home charging can be purchased from such providers as EV Lataus Oy, Webasto, Garo, Defa and others. It is easy to buy device with type 2 socket, attached cable and get 22 kW power if fuses in installation place are suitable. If a person doesn't have necessary skills for installtion, any electrician can help with it. By «suppliers» companies providing charging solutions are meant. And as seen from the graph only small share of people order chargers from official providers.

From the results of questionnarie it can be concluded that private sector needs attention, since uncontrolled installation of chargers in some regions can lead to overloadings. Even though nowdays people who are buying battery cars are «early adapters» who are interested in new technologies and ready to keep DIY style, need for ready-to-go charging solutions in private houses will increase. In order to be ready for changes load estimation in deached houses areas is important.

3.2 Household data

Real life data for electricity consumption of detached houses is used in this work to estimate the total loadings. One set of data is price-controlled electricity consumption based on Elspot prices, other data belongs to general houses somewhere in Finland, the locations are unknown for privacy reasons. It is known that approximately 40% of general houses have electrical heating. According to the electricity consumption data, houses are divided into the following types: non-electrically heated, electrically heated and price-controlled electrically heated. For each of these types loads are estimated for groups of 5, 10, 50 and 100 houses.

Since residents of houses use electricity at different times and amount of appliances in use is random, maximum coincident load from all of them is not equal to the sum of maximum loads of all of the houses. In order to describe a probability of coincidence of peak loading between different households, coincidence factor is used. Formula 1 shows how to find it. Basically, it shows a ratio of the simultaneous maximum total load of all houses to the sum of maximum loads of individual houses during the same time period.

$$c = \frac{P_{max}}{\sum_{i=1}^{n} P_i} \tag{1}$$

Where:
c – coincidence factor
P_{max} – observed peak power of the group, kW
P_i – individual peak, kW

Working days during the coldest week were used to calculate coincidence factors, as well as for modelling loads. In uncontrolled charging scenario with electrically and non-electrically heated houses the coldest period was from 06.01.2012 till 11.01.2012. For the scenario with price-controlled electricity usage data for year 2016 is provided, so the coldest week from this year is used 04.01.2016 – 09.01.2016. Graph on Figure 6 demonstrates behavior of coincidence factors as the number of houses increases.
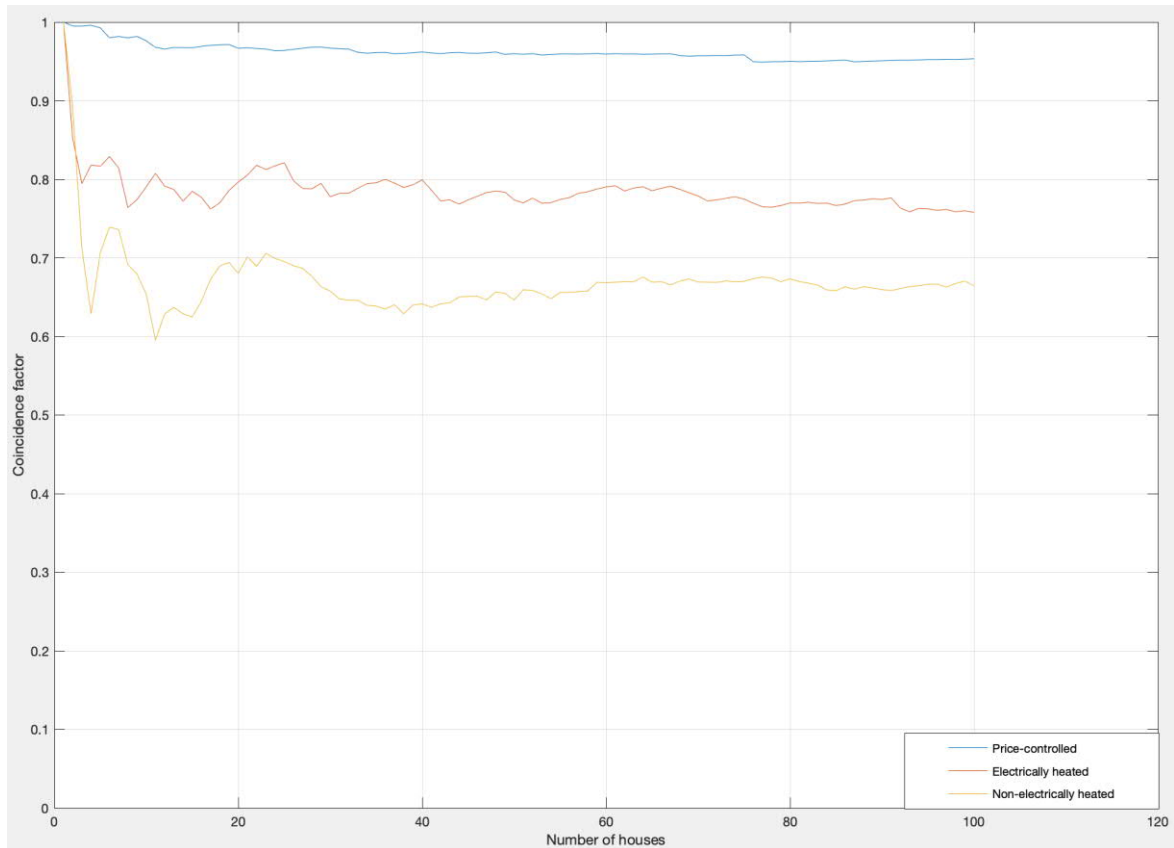
Figure 6. Coincidence factors of houses during five working days on the coldest week of the year.

As can be seen, coincidence factors are rather high for all types of houses, especially for price-controlled reaching minimum value at 0.95. It is expected results, since the purpose of price-incentivized electricity usage is to consume most of the needed energy during the cheapest hours. It makes electricity usage simultaneous, because everybody wants to use it during the cheapest hours. In case of uncontrolled energy usage coincidence factors are also high. Saturation point can be observed starting from 40-50 houses approximately. After this point coincidence factors are almost leveling out at values 0.78-0.79 for electrically heated houses, and 0.66-0.67 for non-electrically heated. Such high numbers can be explained by a short sample period during the coldest week. Weather is a common factor for all of the households, which forces people to use more power. Even non-electrically heated house-holds might have used additional electronic heating devices.

Figure 7 represents the example of a realistic low voltage (LV) network for detached free-standing houses in Finland. It consists of 85 nodes and gives an image of how houses can be grouped. Typically, Finnish detached houses have 3 phases and fuse size 25A, 35A or 63A. In our case uncontrolled charging is utilizing 25A, and for price controlled 63A is used. This assumption was made based on raw data of electricity consumption.
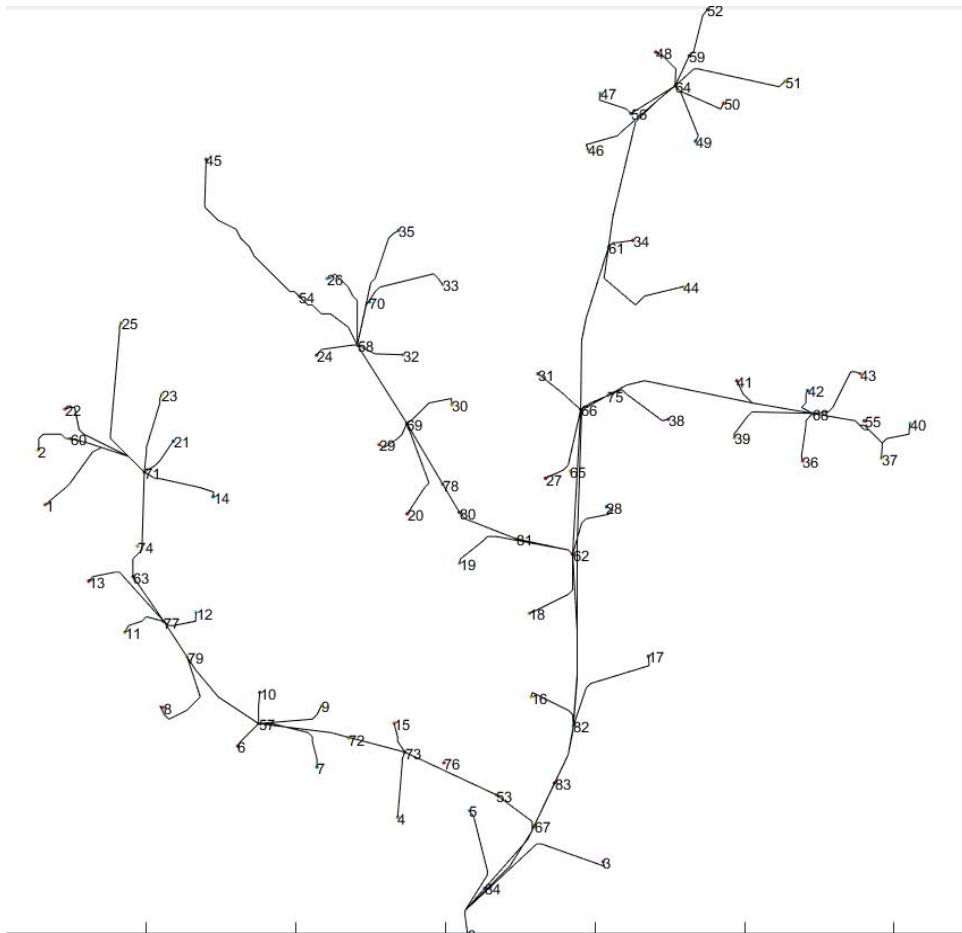
Figure 7. Example of LV network of detached houses in Finland (Millar John, 2020)

Scheme on the figure illustrates a plan of a regular allotment of private houses in Finland and their cabling. The following arrangement is considered for modelling the loads in this work. Every single house is connected to a cable box, several cable boxes are later linked with secondary transformers. One cable box can group up to 10 houses with coincidence factor 1, meaning that they are rated enough to meet demand of a coincident load of small group of houses. Larger groups of 50 and 100 houses have different coincidence, because probability of simultaneous load in larger groups is smaller. They may vary depending on grid specifications. Based on the discussion with Aalto University lecturer, John Millar, co-incidence factor of 0.6 was chosen for groups of 50 and 100 houses in this work.

4 Characteristics of electric vehicles

It is assumed that one household owns one electric vehicle. Modelling is done for working days (Monday - Friday). Battery capacity of different models may vary a lot, also amount of energy used during a day depends on driving distance and driver's behavior. It is expected that a car is fully charged by the morning and initial state of charge (SOC) is a random number. Since the data for the coldest weeks is taken for simulation, average winter consumption of EV is used. Tekniikan Maailma conducted a test to see how six common EV models behave in Finnish winter conditions. According to the test, average consumption on a highway was 0,25 kWh/km (Pitkäniemi, 2019). Since in this work private houses are analyzed, it is acceptable to use highway consumption, because detached houses are usually located beyond the main city area. Also, during winter times heating is used in cars. According to the available data from EV-database heating requires 0,025 kWh/km and pre-heating of the car is approximately 0,5 kWh (Pitkäniemi, 2019).

It is known that probability distribution of driven distances is following lognormal distribution (Qian, 2011) and can be described, by the following Formula 2

$$f_1(d|\mu,\sigma) = \frac{1}{d\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln d - \mu)^2}{2\sigma^2}} \tag{2}$$

Where:
d − distance, km
μ − lognormal mean
σ − lognormal standard deviation of the probability density function (pdf)

According to Trafi, average daily driven distance of a private car in Finland is 46 km and standard deviation is 20 km (Traficom, 2019). These arithmetic values need to be converted into μ − lognormal mean and σ − lognormal standard deviation using relations in Formulas 3 and 4.

$$\mu = \ln(m^2/\sqrt{v + m^2}) \tag{3}$$

$$\sigma = \sqrt{\ln(v/m^2 + 1)} \tag{4}$$

Where:
μ − lognormal mean
σ − lognormal standard deviation of the probability density function (pdf)
m − average daily distance, km
v − standard deviation, km

Parameters mentioned above allow to plot the probability density function of daily driven distances in Finland. From the graph on Figure 8, it can be noticed that most of the driving in Finland lays within 20 and 70 km per day.
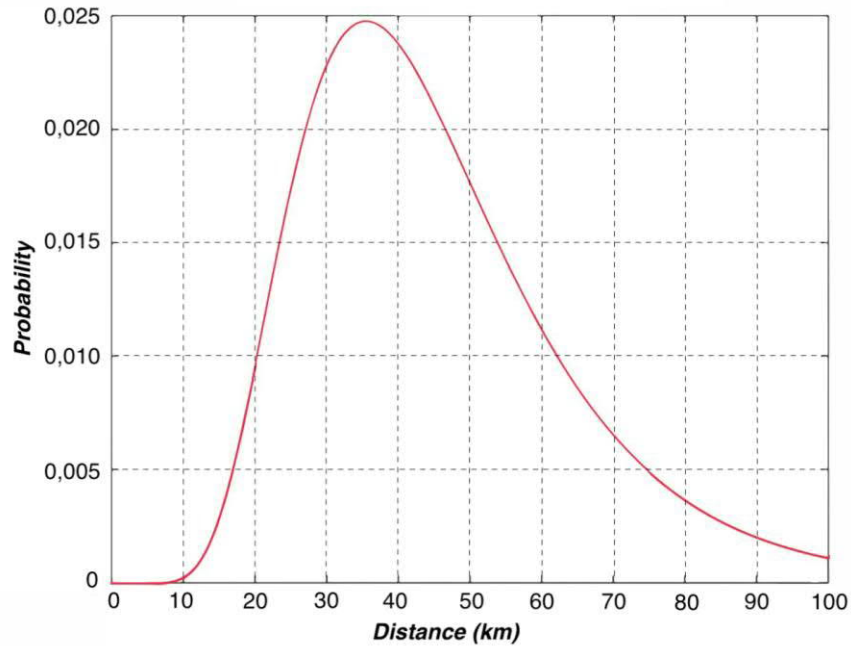
Figure 8. Distribution of daily driven distances in Finland

Another factor, which should be taken into account while modelling charging loads is arrival times – the moment when people come home and plug their electric car into the network. For this work it is assumed that all cars are charged at home during overnight parking. Finnish Transport Infrastructure Agency (FTIA) provides open data about amount of traffic on roads of Finland in different regions, at different times (Väylä, 2020). In other words, it shows how many cars are located on roads at specific hour of the day. Taking average distribution of number of cars on public roads during winter time Mon-Fri in Uusimaa region and adding 1 hour in order to estimate arrival times, we can see that most of the cars arrive home between 16 and 19 o'clock (Figure 9). Here the assumption was made that average travel time from work to home is 1 hour for Uusimaa region.
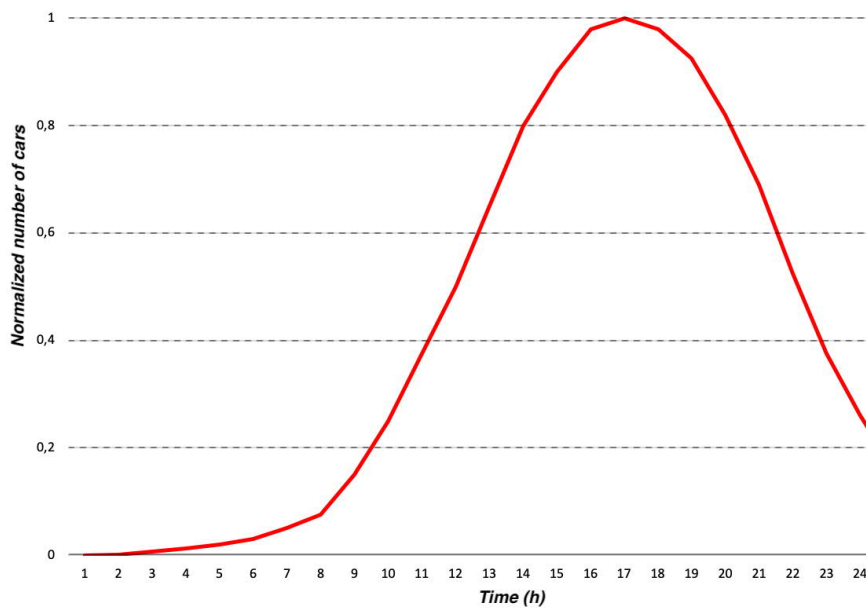
Figure 9. Distribution of arrival times

Charging powers used in modelling correspond to 8A, 16A and 32A currents. Table 1 shows all charging options used in this work.

Table 1. Charging powers used for modelling

	1-phase	1-phase	3-phase	3-phase
Current	8A	16A	16A	32A
Power	1.84 kW	3.68 kW	11.1 kW	22.2 kW

5 Modelling results

This chapter demonstrates modelling of charging loads for different groups and types of houses, as well as total consumption of households when electric vehicles charging is added to their raw consumption. In every subsection there are graphs, where connection limit is shown. This limit was calculated using Formula 5.

$$P = \sqrt{3}UI \cos\varphi * n * c \qquad (5)$$

Where:
P – power (connection limit), W
U – line voltage, V
I – current (fuse size of the house), A
$\cos\varphi$ – power factor
n – number of houses in a group
c – coincidence factor

5.1 Uncontrolled charging

Raw data of hourly household electricity consumption in year 2012 was provided for general houses. It was known that approximately 40% of those houses were electrically heated. According to the total electricity used during the coldest week from Monday 6th January till Friday 10th January it was easy to separate manually the ones who are using electrical heating and the ones who are not. These types of houses use 25A fuses and were analyzed separately.

From the raw data every time 5, 10, 50 and 100 houses were randomly taken. House load, depicted with red line on the graphs, was calculated by summing loads of single houses at each hour of the day. Blue line illustrates loads of electric vehicle charging, which was simulated with the help of Matlab according to the parameters listed in the previous Chapter 4 Characteristics of electric vehicles. Yellow line shows total loads, which was obtained by adding together house loads and EV charging loads.
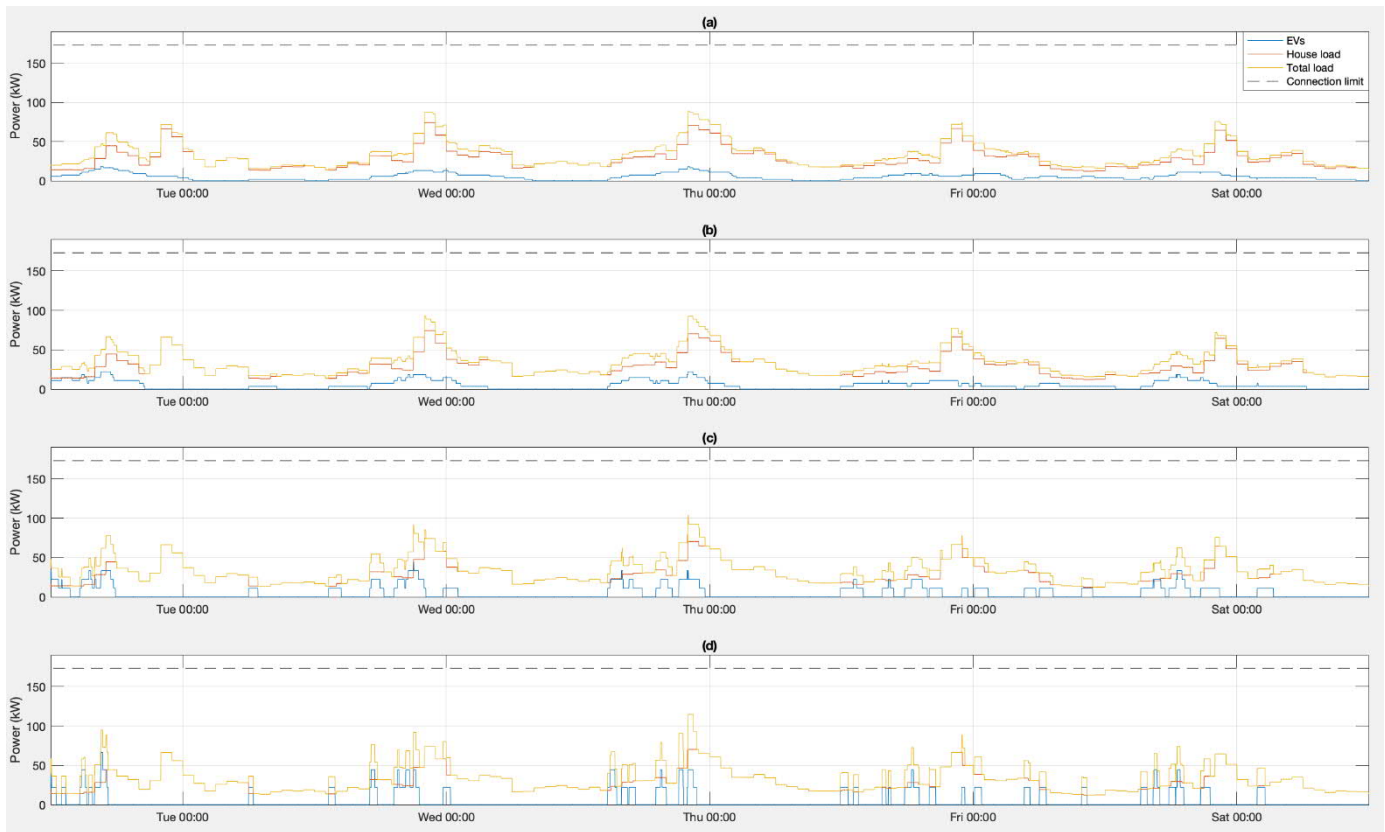
5.1.1 Without electrical heating

Figure 10 demonstrates a group of 5 houses and load distribution during the mentioned period.
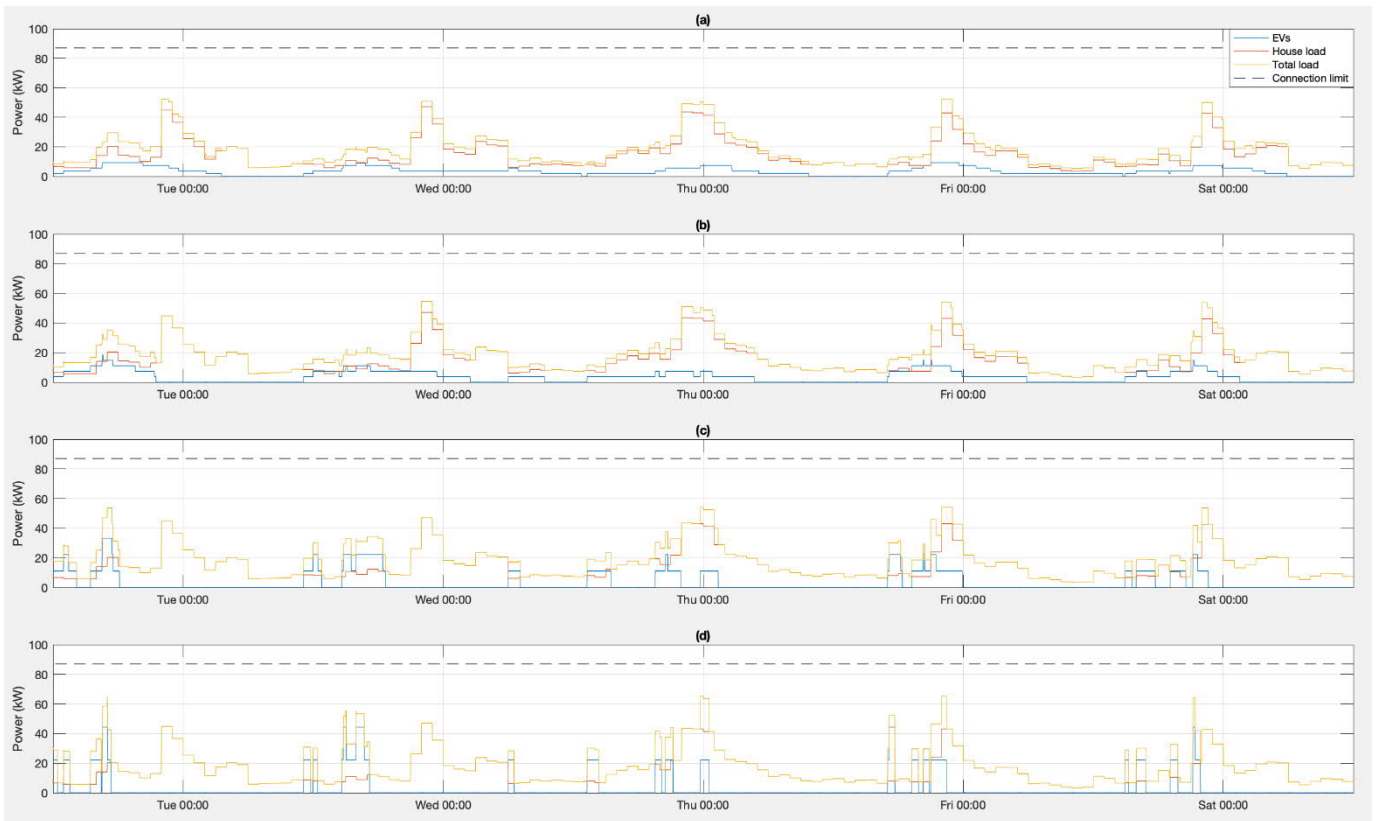
Figure 10. Uncontrolled charging of 5 houses without electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

Five houses are connected to a cable box, which is scaled to match coincident load. As can be seen from the graph, electric cars increase total loads and create peaks at 11.1kW and 22.2kW, however, the grid stays very safe.

Next graphs on Figure 11, 12 and 13 are showing uncontrolled charging in houses without electrical heating for groups of 10, 50 and 100 respectively.

Figure 11. Uncontrolled charging of 10 houses without electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW).

10 houses can be connected to the same type of cable box as a group of 5 houses, therefore, the limit load is scaled so that it can meet coincident demand from all 10 houses. From the graphs it is seen that most of the charging starts in the evenings, when everyone arrives home and plugs cars to the network. With slow charging the load is smoothly distributed over the evening and night time, while fast charging with 11.1 kW and 22.2 kW creates evening peaks which overlap with other household electricity consumption. It is clearly seen that most of fast charging is completed before night time. Even though fuses are not overloaded, sharp peaks, which occur at the same time with other electricity consumption, is something what should be avoided if possible.
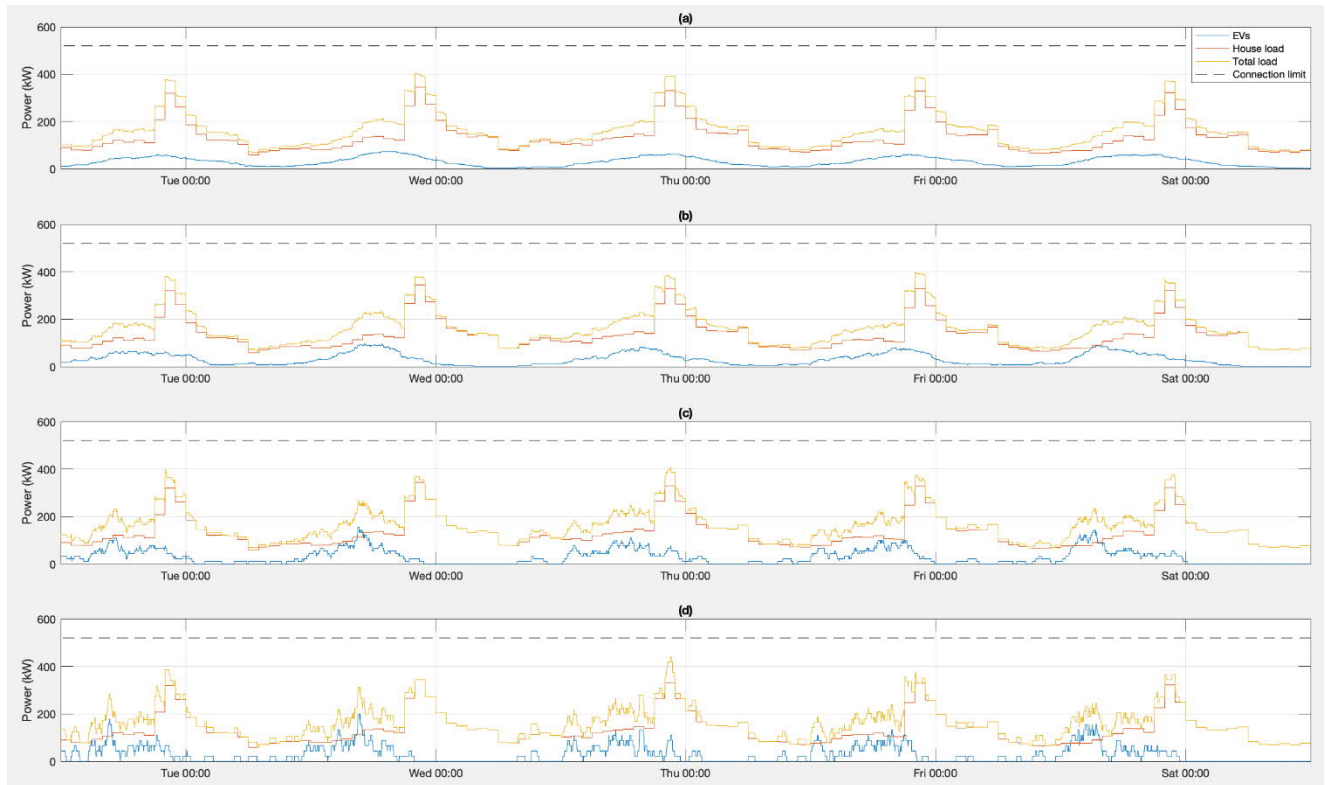
Figure 12. Uncontrolled charging of 50 houses without electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

Maximum load available for the group of 50 houses is calculated taking into account coincidence factor 0.6. Models show that none of charging powers cause grid overloading. At slow rates of 1.84 kW and 3.68 kW charging happens very smoothly never exceeding house load, while faster charging just occasionally exceeds it. Demand for charging happens mostly in the evening when cars arrive home.
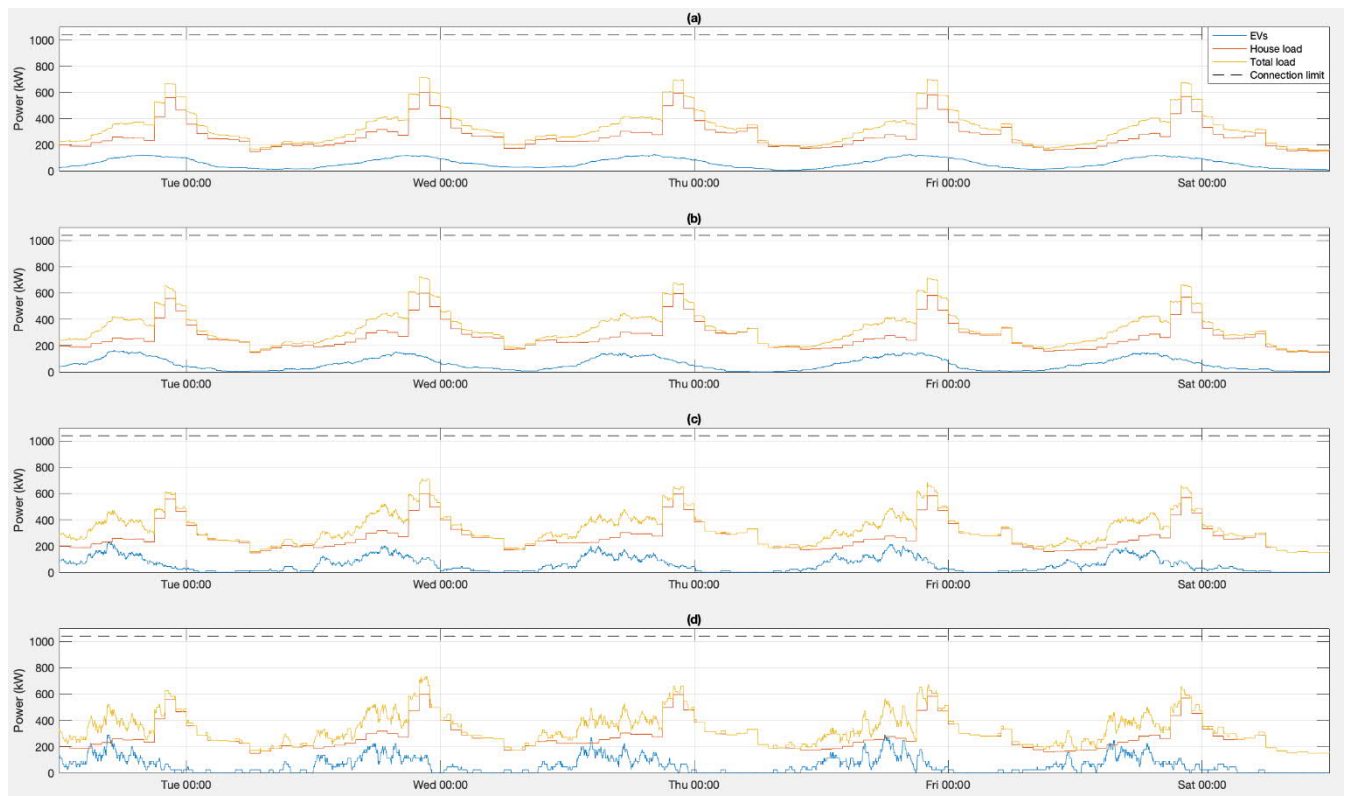
Figure 13. Uncontrolled charging of 100 houses without electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

As graphs on Figure 13 demonstrate, allotment with 100 non-electrically heated houses and uncontrolled charging will not suffer from grid overload in this example simulation. Total load is obviously increased and charging overlaps with evening electricity consumption, however, no harm for fuses is done.

It can be noticed that few hours before midnight house load raises significantly, which might lead to a conclusion that these houses are electrically heated in fact. But it should be noted that the coldest week is used for analysis and extra appliances for heating can be used. Analysis of raw household consumption show that these houses on average use much less electricity than the ones defined as electrically heated and described in the next section.

5.1.2 With electrical heating

Uncontrolled charging in electrically heated houses is taken separately since it is interesting to see how differently EV charging influences the grid in this situation.
Figure 14 shows a group of 5 houses and their electrical load for 4 different charging powers.
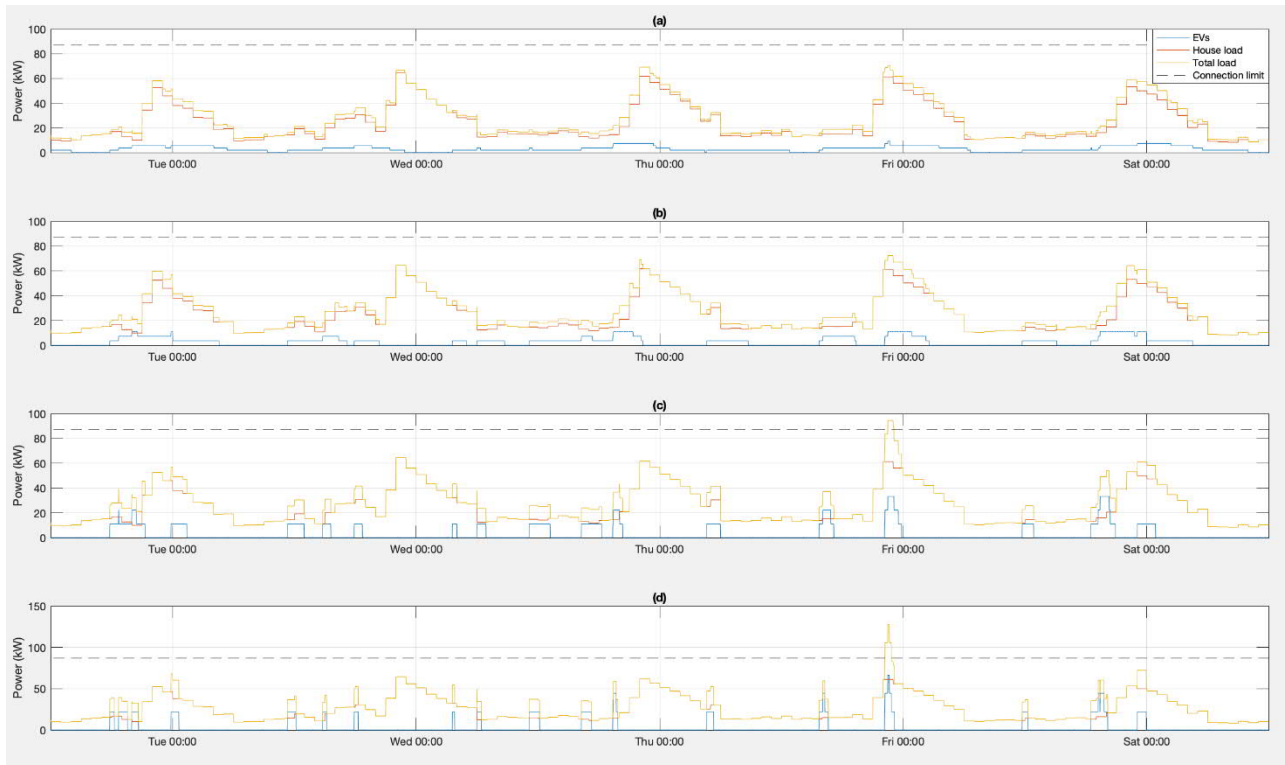
Figure 14. Uncontrolled charging of 5 houses with electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

For easier comparison of non-electrically heated and electrically heated houses, network and fuses characteristics are kept the same. The first thing which attracts attention is fuses over-loading at fast charging. Basic house load stays within the limit, but it can be also noted that total load of this group of houses is larger in comparison with non-electrically heated ones described in the previous section.
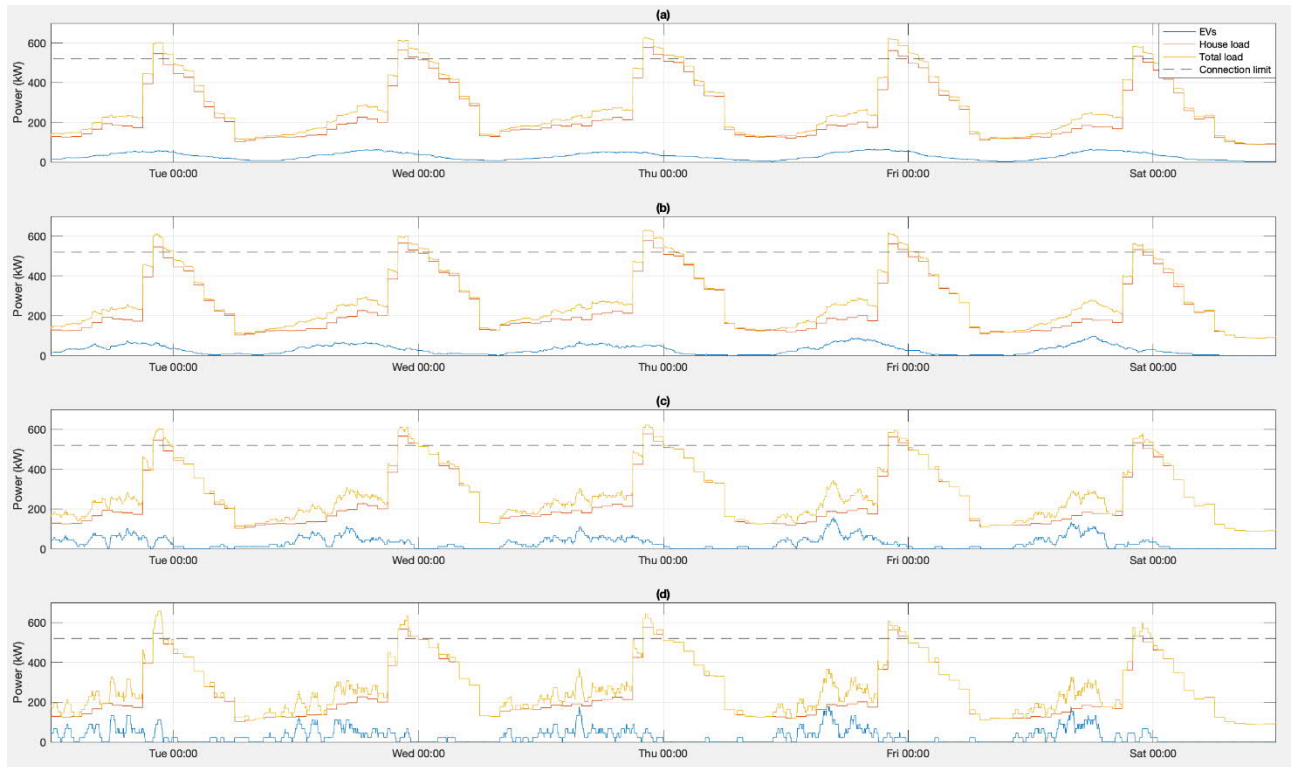
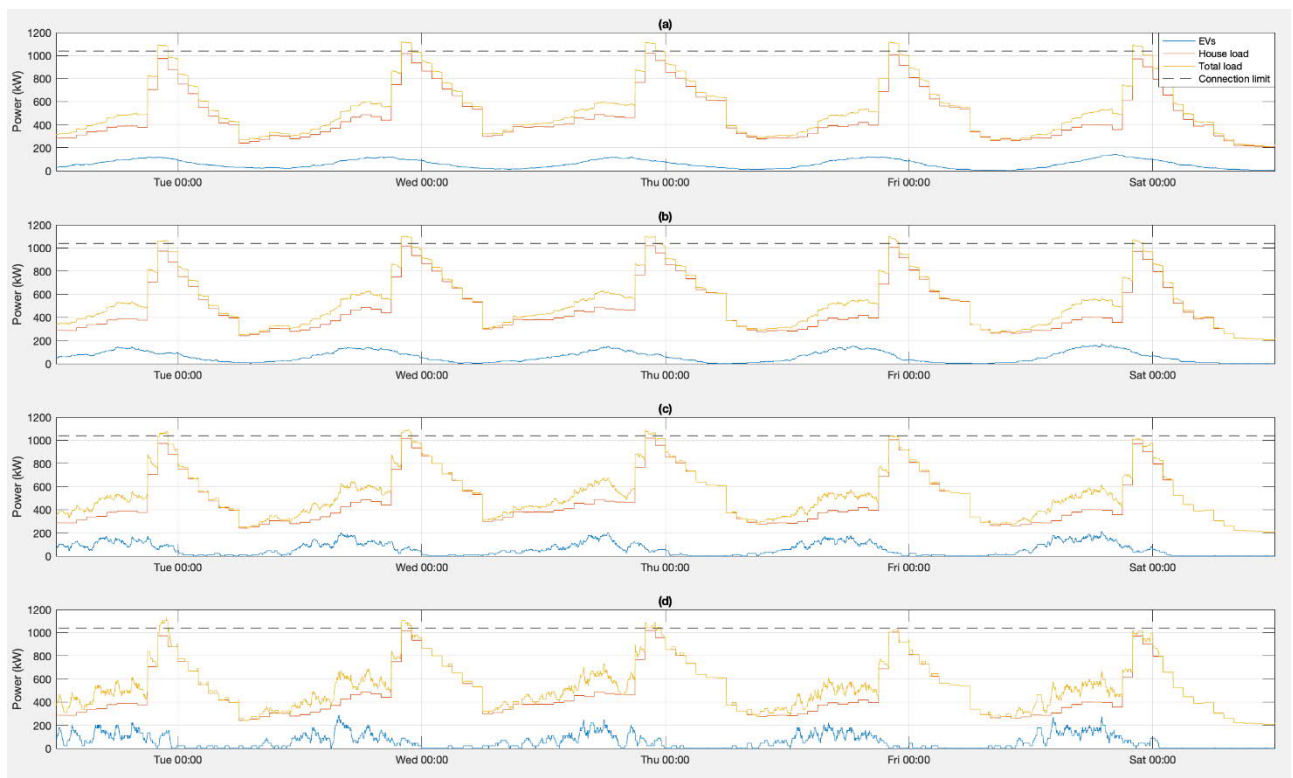Next Figure 15 shows electric load of a group of 10 houses.
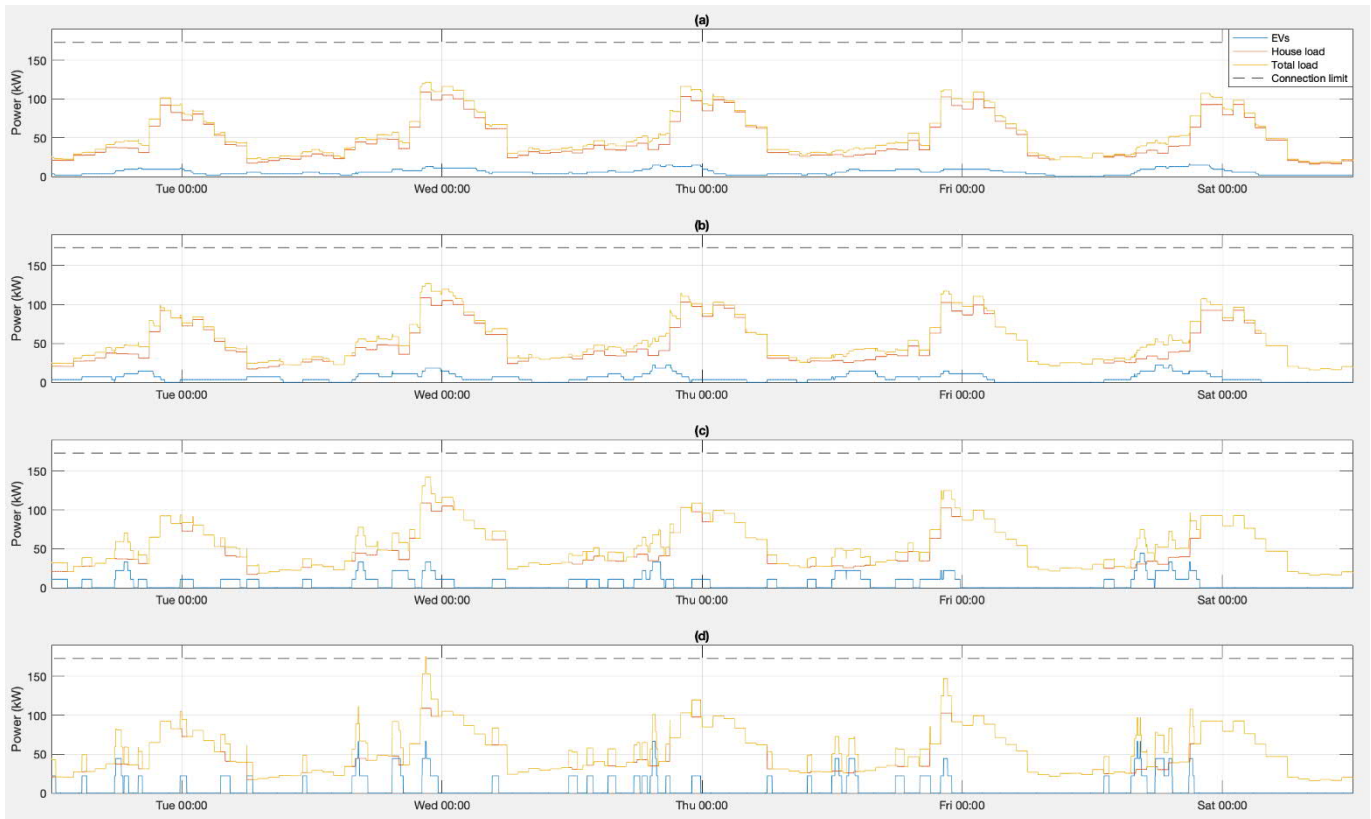
Figure 15. Uncontrolled charging of 10 houses with electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

The same trend as in a group of 5 houses can be traced. Overload and most of the peaks happen at fast 22.2 kW charging. The highest demand happens in the evening when cars arrive home and charging can be completed even before night time in case of 11.1kW and 22.2 kW.

The following graphs on Figures 16 and 17 illustrate loads in a group of 50 and 100 houses, where maximum demand for the group was established using coincidence factor 0.6.

Figure 16. Uncontrolled charging of 50 houses with electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

Figure 17. Uncontrolled charging of 100 houses with electrical heating (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

The first thing to notice is overloading of the grid at all power levels. Even without EV charging added to the total load, house load comes either very close to the limit or exceed it. It means that in reality, network in this kind of residential area would not have characteristics set in the model. However, for comparison it is better to keep some of the parameters constant.

Unlike in groups of 5 and 10 houses EV charging demand never exceeds house loads in groups of 50 and 100. Very clearly seen that most of the electricity demand comes at the end of the day and beginning of the night between 22:00 and 3:00 when heating is actively used. Interesting, that when number of houses is getting as large as 50 and 100 houses, EV charging demand even at high power levels as 11.1 kW and 22.2 kW doesn't add so much stress to the grid in case of electrically heated houses, which are already using lots of energy. The blue line on the graphs, which shows EV demand never reaches red line indicating house load. It means that houses, which are already using electrical heating, are ready to meet even fast EV charging demand.

5.2 Price controlled

Raw data of household electricity consumption in year 2016 was provided for private houses. It was known that electricity usage is price-optimized meaning that smart system was choosing the most economically beneficial hours for heating and other background electricity usage. It was based on day ahead Elspot electricity prices. The exact location as well as arrangement of houses, fuse types and family sizes were unknown, therefore some assumptions for modelling have been made.

As was mentioned earlier, simulation models assume one electric vehicle per house. According to the data, the most appropriate fuse size for price-controlled electrically heated houses is 63A. Figure 18 represents loading of the coldest week of 2016 from Monday 4th January till Friday 8th January in a group of 5 houses.
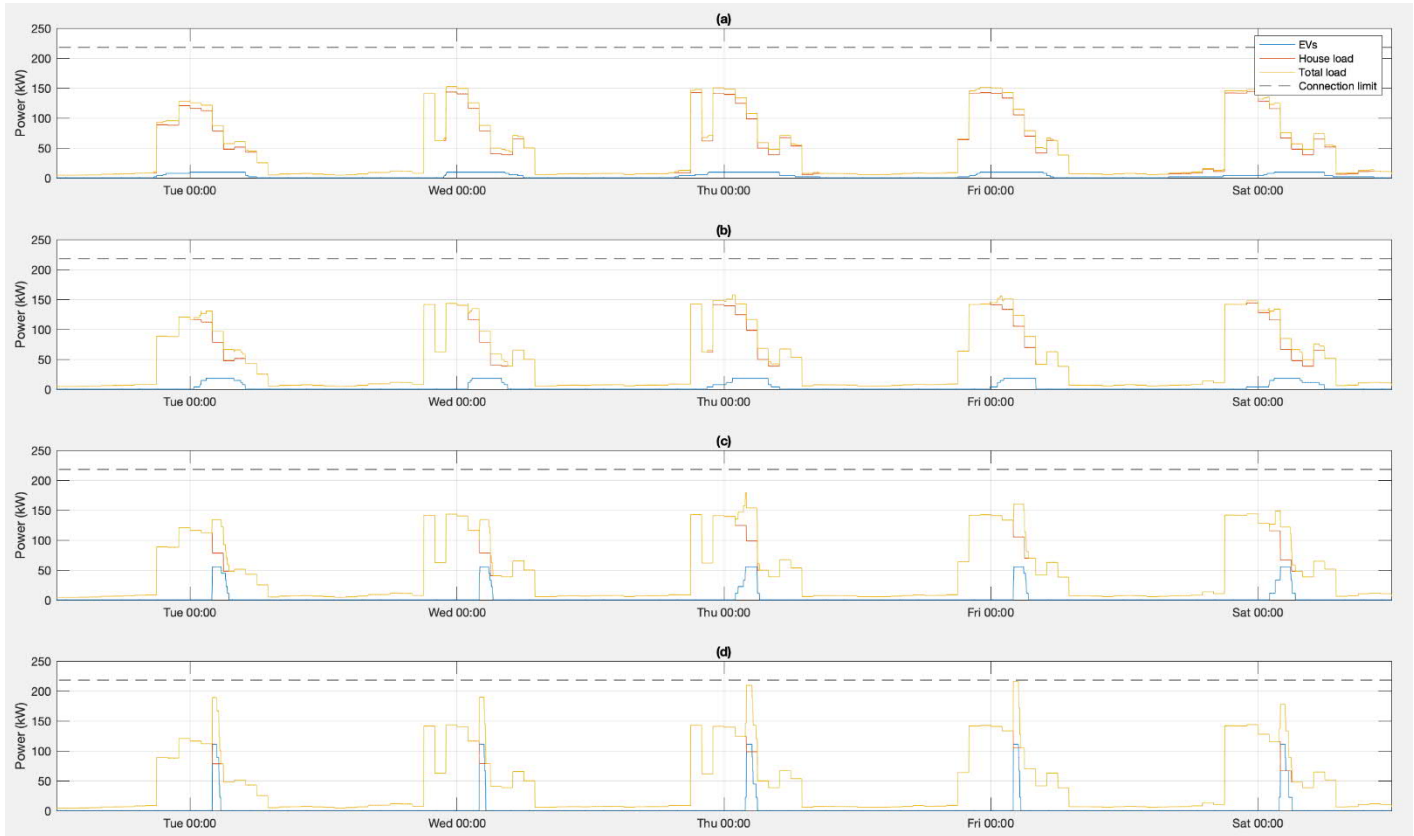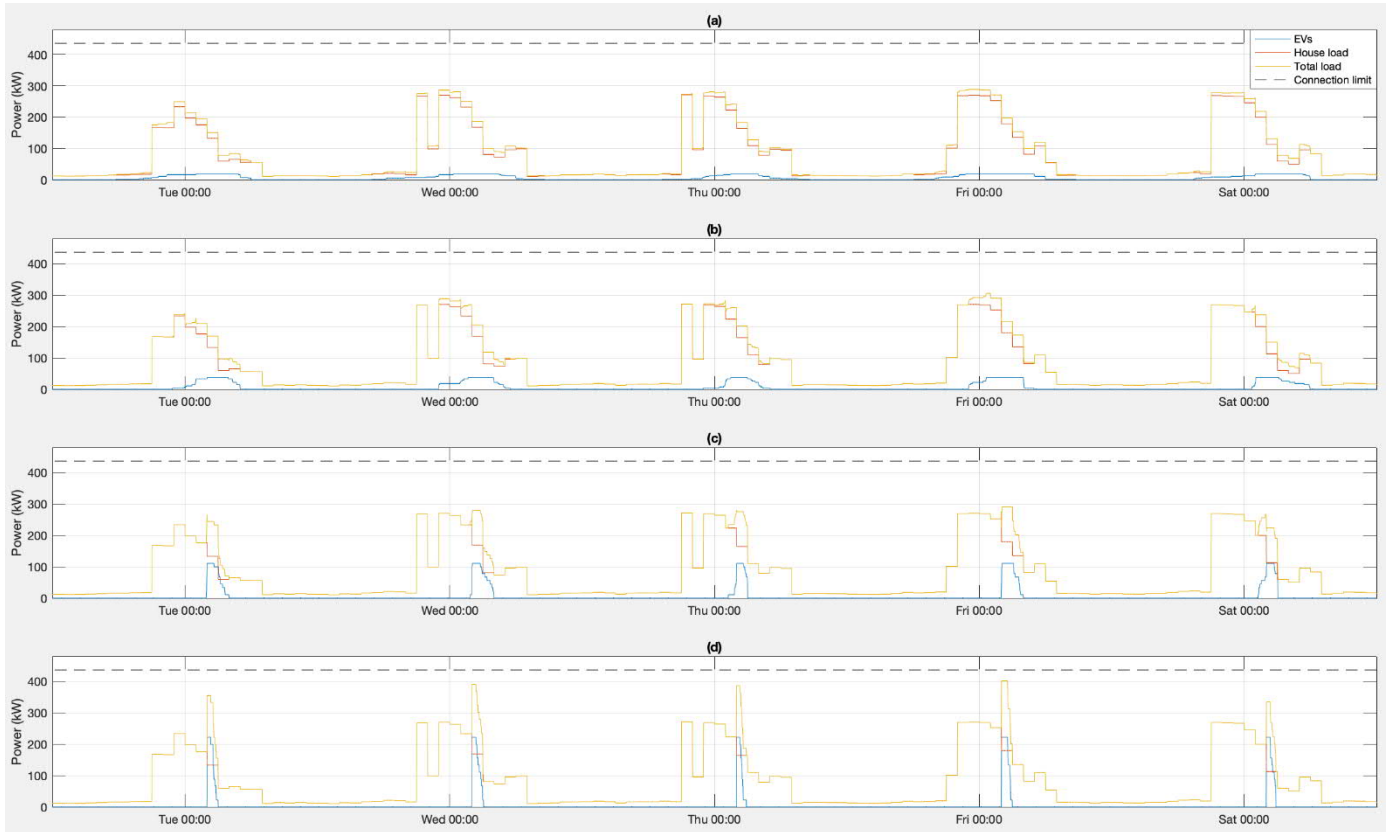
Figure 18. Price controlled charging of 5 houses (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

At low power rates like 1.84 kW and 3.68 kW there is no significant impact. However, noticeable peaks at powers of 11.1 kW and 22.2 kW happen during night time. In case of 11.1 kW fuses are still safe from overloading, but in case of 22.2 kW it can be noticed that charging peaks make total load almost exceed the limit value.

Next Figures 19, 20 and 21 are showing loads of 10, 50 and 100 houses respectively.

Figure 19. Price controlled charging of 10 houses (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

With 10 houses situation is similar as with 5 houses. Fuses are not overloaded and stay very safe at lower charging powers, while fast charging at 22.2 kW creates serious danger for specific night hours. Should be noted that the risk of cable box overloading happens already with coincidence factor 1, which was used to set the limit for groups of 5 and 10 houses.
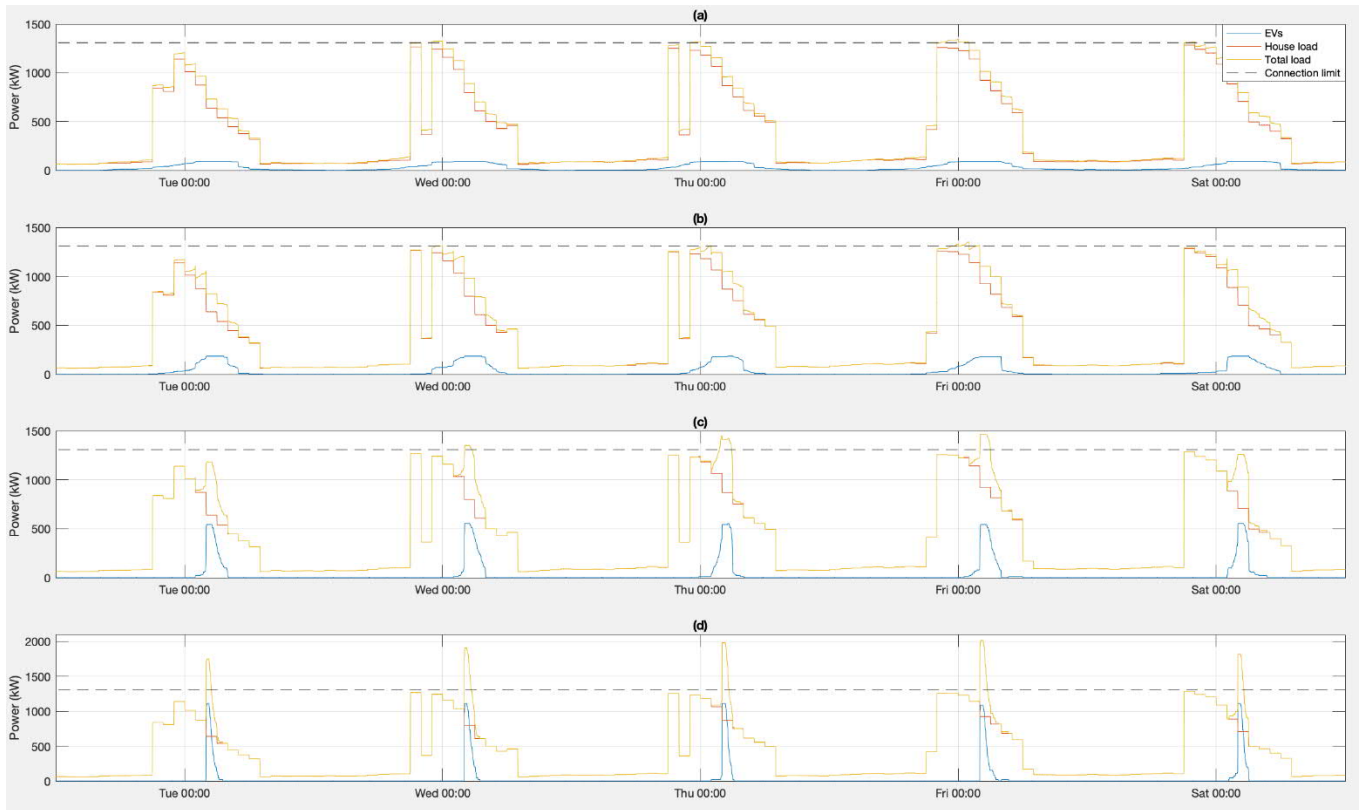
Figure 20. Price controlled charging of 50 houses (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

In case of 50 houses, as well as in the other cases of large house groups, coincidence factor of 0.6 was chosen to set up the limit. Looking at household load only, indicated with red line on the graphs, it is clear that even without EV charging load comes very close to the limit, however, never exceeds it. It is worth to remember about low winter temperature makes people use more heating. Here adding electric car charging is fatal for the grid and slight overloading happens even at 1.84 kW and 3.68 kW charging. While 22.2 kW creates almost double overloading.
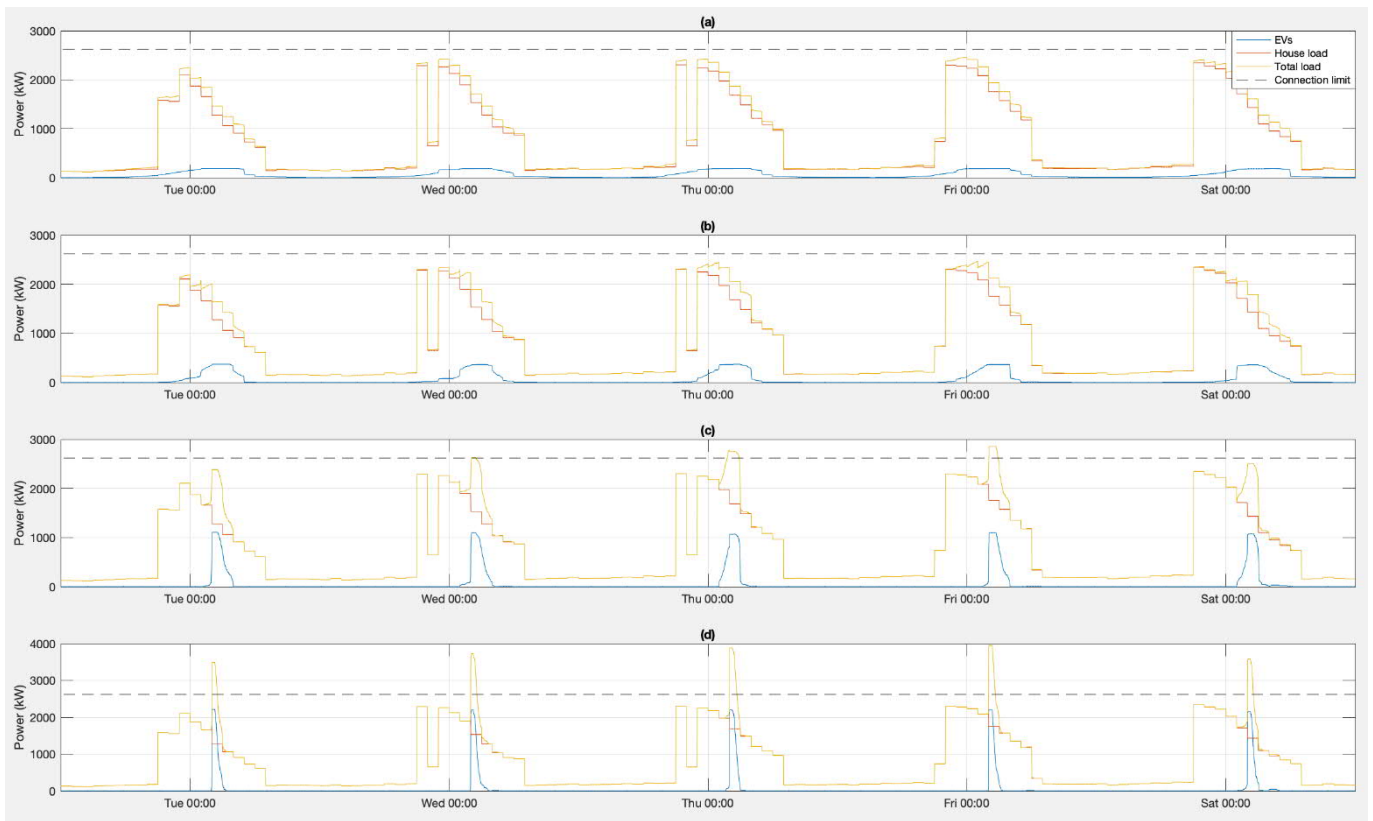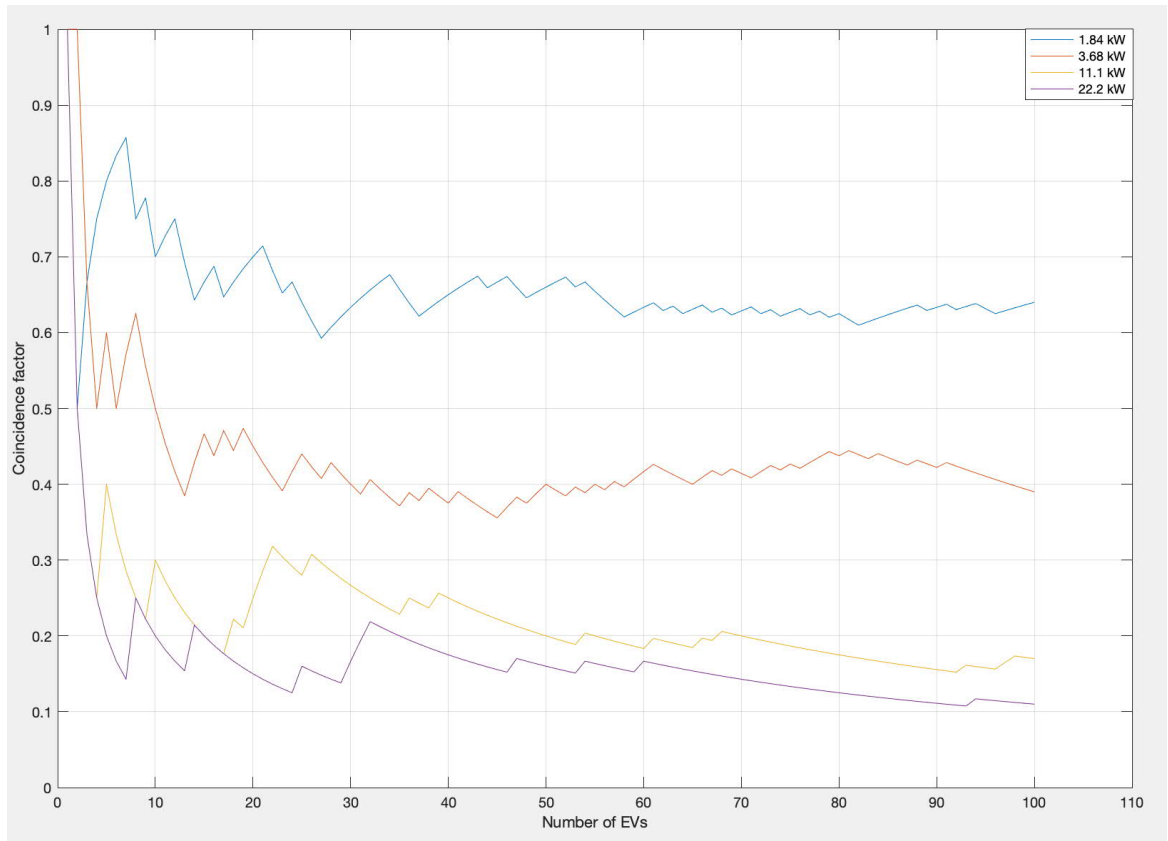
Figure 21. Price controlled charging of 100 houses (a – 1.84 kW, b – 3.68 kW, c – 11.1 kW, d – 22.2kW)

The limit for 100 houses was also set using coincidence factor of 0.6. From the graphs can be easily seen overloading at 11.1 kW and especially at 22.2 kW charging.

5.3 Coincidence factors of electric vehicles

Figure 22 demonstrates coincidence factors of EV charging without household loads. The highest coincidence corresponds to slow 1.84 kW charging. It stays between 0.6 and 0.7 starting from approximately 30 electric cars. The lowest coincidence happens for the fastest 22.2 kW charging. It fluctuates between 0.1 and 0.2 starting from 45 cars.

On Figure 23 coincidence of price-controlled charging is demonstrated. It can be noticed immediately that values are extremely high. At 1.84 kW power the result shows 100% simultaneous charging no matter how many cars are taken. Even fast charging does not reach value lower than 0.9.

Figure 22. Coincidence factors of EVs, uncontrolled charging.
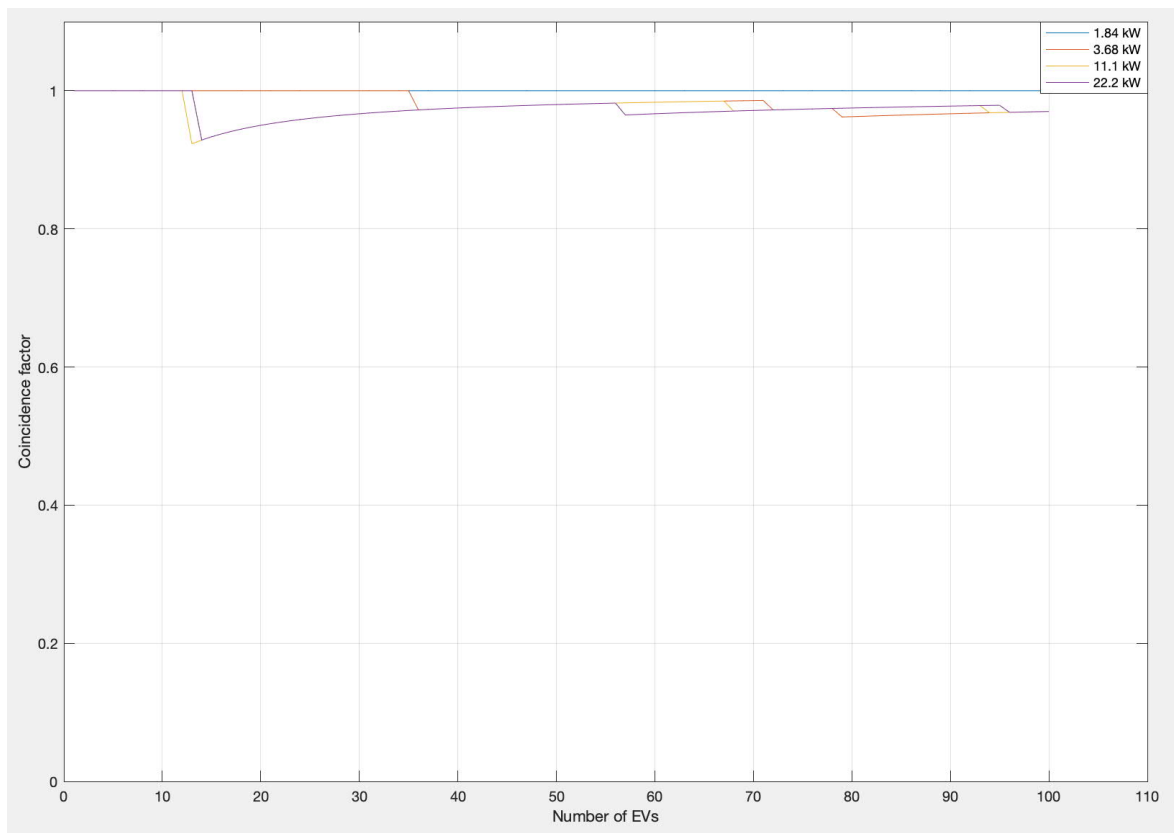
Figure 23. Coincidence factors of EVs, price-controlled charging

6 Discussion

The main point, which could be noted from load modelling is that price-optimized charging can be very coincident at low and high charging powers. 11.1 kW and 22.2 kW overload an example grid greatly creating sharp peaks in demand during cheap night hours. Table 2 below shows maximum demands (household and EV combined) observed during studied period. Red background of a cell means that maximum available capacity of the grid was exceeded.

Table 2. Maximum demands observed for uncontrolled charging (06.01.2012 – 11.01.2012) and price-controlled charging (04.01.2016 – 09.01.2016)

Number of houses in a group	Non-electrically heated	Electrically heated	Electrically heated price-optimized
5	65 kW	128 kW	216 kW
10	115 kW	175 kW	401 kW
50	441 kW	657 kW	2010 kW
100	731 kW	1128 kW	3951 kW

Maximum demands of electrically heated houses were exceeded in all charging scenarios and sometimes even at small power rates. However, these overloadings are very slight. It should be reminded that specifications of houses with and without electrical heating in uncontrolled charging are kept the same for easier comparison. Their fuse sizes were set to be 25 A. Of course, houses with electrical heating tend to consume more energy. Even from the graphs in section 5.1.2, it can be seen that own loads of houses (without electric vehicles) are coming very close to the established limit. It means that in reality area with such houses would have larger fuse size to keep more flexibility for increased load. While houses without electrical heating appliances, where the same 25A fuses are installed, are ready to meet electric vehicles charging needs, following from the results of the modelling. Though, I was expecting an opposite result, thinking that electrically heated houses have bigger margin for additional electrical loads rather than houses not designed for it. It is worth to mention again that the coldest weeks from Monday to Friday were chosen for modelling since in these dates electricity usage should be more intensive in comparison with other days, which lets to estimate worst case scenario.

Uncontrolled charging usually starts in the evening and overlaps with evening peak load hours of households. At 11.1 kW and 22.2 kW peaks are especially high and dangerous for small groups of 5 and 10 houses. Charging is usually completed before night time, creating bigger gap during night off-load hours.

7 Conclusions

Reviewing electricity consumption of private houses in Finland we can see that adding one electric vehicle for each household will influence total loads differently depending on the types of houses and charging scenario.

Loads from electric cars charging create the largest stress for the grid at high power levels, such as 11.1 kW and 22.2 kW, exceeding maximum available capacity of the example grid. One of the results of the other work done by Oula Lehtinen indicated heavy overloading of the grid in apartment houses in Finland during price-optimized charging. This work showed the same result for private houses. Charging only during the cheapest hours may overload the grid 2 times more above the limit. Another expected outcome from the modeling shows that uncontrolled charging adds extra stress during evening peak hours. In small groups of houses EV charging peaks are noticed better during uncontrolled charging, while price-based charging has huge peaks even at large groups of 100 houses.

Lehtinen's work states that the only way to use fast charging in apartment buildings requires application of intelligent load-control. While in this work we can see that correct dimensioning of a grid in private houses allows uncontrolled fast charging without danger for the grid. Usually the smallest fuse size used in free-standing houses in Finland is 25A. In case of non-electrical heating the potential of household load is not utilized fully, that is why adding electric car doesn't bring any harm. In this case load of electric cars can exceed other domestic loads, however, the grid will stay safe.

In conclusion, it was interesting to investigate behavior of coincidence factors of EV charging. The highest coincidence happens at smaller charging power and, vice versa, there is less coincidence when fast charging is used. In general, coincidence during slower charging reaches saturation a little bit sooner, 30-35 cars, than charging at higher powers, 45-50 cars. In case of uncontrolled scenario, the only common factors for electricity usage are time of arrival home and outdoor temperature. When in price-incentivized scenario additional dominating factor is electricity price. That is why coincidence of price-based EV charging stays very high all the time.

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Appendixes

Appendix 1. Types of connectors and plugs. 1 page.

Appendix 1. Types of connectors and plugs

Source: EnelEx, 2019. Different EV Charging Connector Types. Online source: https://evcharging.enelx.com/eu/about/news/blog/552-ev-charging-connector-types Accessed: 14.03.2020