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September 21, 2023

[redacted]

[redacted]

RE: Your Access to Information Request Number SPC1 -23G

Your access to information request was received in this office on January 23, 2023 requesting access to the following information:

> "Please Provide documentation to the province's electricity system and ratepayers due to the federal government's decisions to require 100% of all passenger cars and trucks sold by 2035 to be zero emission. Please be sure to include any estimates or analysis or changes necessary to power generation needs, transmission requirements, local distribution infostructure, household upgrades and the cost to consumers."

On Feb 27, 2023, you amended the request to cover just reports and analysis of data

On March 1, 2023 we agreed to place this request on hold pending the release of an upcoming report on electric vehicle impact on SaskPower distribution system. We have recently received the finalized report and reactivated your request.

Your request for access to the above has been granted. Please find enclosed:

- "EV Charging project report – Final Apr 8, 2023"

Yours truly,

Conlin Mckay
Access Officer

Enclosures

Integration of Electric Vehicles into the Power Distribution System

Brief Final Report of the project
April 8, 2023

Intern: Mohamed Ahmed

Academic Advisors: Zhanle Wang, Raman Paranjape
Industrial Advisors: Shea Pederson, Darcy Kozoriz, James Fick

Acknowledgment

- We are thankful for the sponsorship of SaskPower and Mitcas to the project.
- We are truly grateful to Mr. Shea Pederson, Mr. Darcy Kozoriz, and Mr. James Fick for feedback and advice in our biweekly meetings.
- Without the sponsorship and advice from our partner, the completion of this project would not be possible.

Summary of the Project

- Electric vehicles (EVs) have become increasingly popular because of their high efficiency and sustainability.
- However, EVs represent an intensive electric load. Their penetration to the power system poses significant challenges to power distribution system operation and control, such as voltage drop and transformer overload.
- This study evaluates the impact of EV penetration on Saskatchewan's urban residential power distribution system and develop plans to cope with the EV load growth.

Summary of the Project

- Actual EV charging profiles have been analyzed to understand the characteristics of the EV charging.
- Individual and aggregated EV charging models based on Saskatchewan's local situations is developed.
- In this study, we used the actual AMI data in Saskatchewan, Canada, to determine the base load profile of each household.
- The data source contains the actual load profiles of 98 houses in Saskatchewan province from June 1st to July 18th, 2022.
- The EV charging profiles, and the base demand are embedded into the load flow model to evaluate the impact of EV penetration on the power distribution systems.
- The impact of uncontrolled EV charging load is evaluated based on transformer loading and voltage drop at each bus.

Summary of the Project

- Furthermore, we developed a model that is able to identify the critical number of EVs that can be added to the distribution system such that the transformer loading does not exceed the standard ratings.
- Finally, a highly efficient optimal EV charging model was developed.
- This model considers EV charging as an elastic demand and is used to optimally schedule and control EV charging.
- By aggregating controlled EV charging, this model helps to shift the load away from peak demand periods and reduce peak demand.
- The model produces a day-ahead or hours-ahead plan for EV charging control, which can be utilized by utilities or EV aggregators.

Summary of the Project

- The optimal charging model's output, in the form of scheduled and controlled EV charging load profiles, can serve as a control policy for charging EVs.
- The model aims to not only reduce peak demand but also enhance energy efficiency and defer infrastructure investment.

- This is a brief report of this study. More detailed methods and research results can be found in the intern’s PhD thesis and publications.
- The thesis defense is schedule on April 12, 2023.
- At the moment of finalizing this report. One journal article is published. Two journal articles and one conference paper are under preparation.

Report organization

- This report includes three sections, and each section describes one objective.
  - Objective 1: EV charging data analysis and EV charging model development (starting from slide #8)
  - Objective 2: Load flow models to evaluate the impact of EV charging load on urban power distribution systems (starting from slide #45)
  - Objective 3: Optimal EV charging model to mitigate the negative impact of the growth of EV charging on on urban power distribution systems (starting from slide #126)

Objective 1

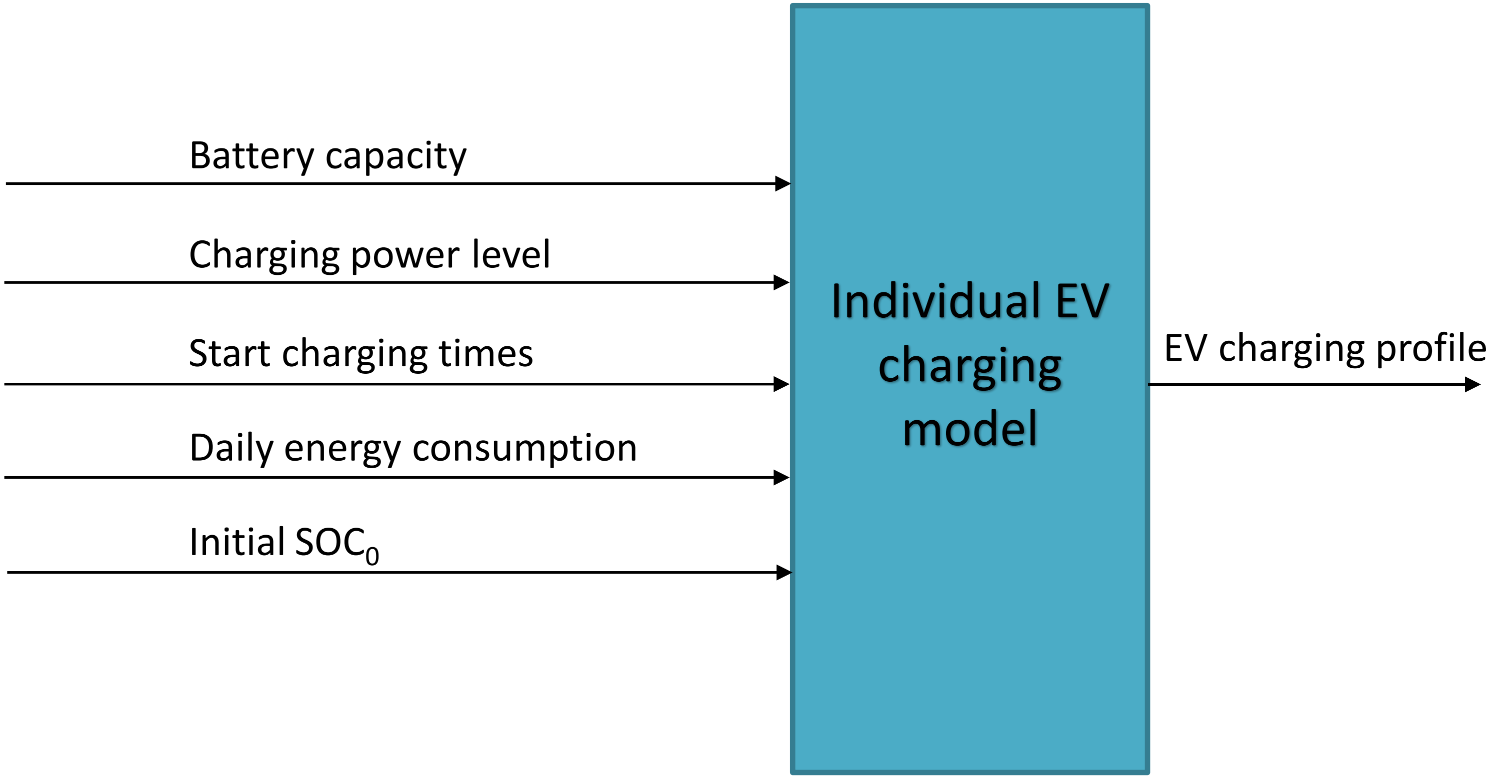
- This section presents the individual and aggregated EV charging models, which is the first step of the project.
- The model parameters are tuned based on the actual EV charging profiles in Saskatchewan.
- The models can be used to predict individual and aggregated EV charging profiles of various types of EVs in Saskatchewan.
- For more detailed information, please see the full report.

Outline

- Parametrized EV charging model
- Analysis of the actual EV charging profiles in Saskatchewan
- EV model parameter tuning
- Simulation results
- Summary

Individual EV charging model

- The diagram below shows the important parameters that affects the EV charging profile.



Model parameters

- The model parameters are tuned based on actual EV charging profiles in Saskatchewan, which is retrieved from the FleetCarma dashboard.
- The data source contains the actual EV charging data in Saskatchewan from April 2021 to October 2021.
- We used the September charging data as an example to model and tune the parameters.
- There were 74 EVs' charging data available in September.

Data preparation

- Since this project focuses on EV charging impact on the residential sector, only the residential charging data was considered.
- The raw data includes the EV charging data from all the sectors (e.g., residential, commercial, camping area, etc.)
- Therefore, the first step was to extract the residential charging data by labeling the residential locations.
- In addition, bad data was removed.

Data preparation

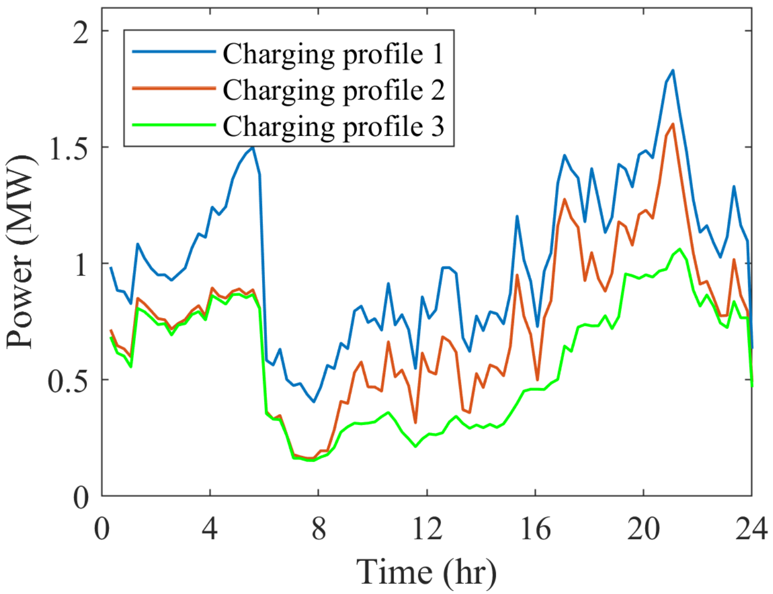
- There are geofence data indicating charging locations in the raw data; however, the geofence data are missing for many charging instants.
- Therefore, we mapped the Latitude and Longitude of all the charging locations for all the charging instant to identify whether they are residential or non-residential.

Identify residential EV charging profile based on charging location

- The charging data contains 22926 charging instants in September.
- From these charging instants, we identified **149** charging locations.
- We mapped these locations to Google map and manually identified if these locations are residential or non-residential.
- We essentially created a lookup table to label each location as residential or non-residential.
- We then used this lookup table to label the 22926 charging instants as residential or non-residential.
- The charging in the following locations were removed: out of territory, farms, camping areas, hotels, and malls.
- Finally, we removed all the charging labeled as non-residential.

Comparison before and after removing those locations

- The figure below represents the actual aggregated daily charging profiles.
- Charging profile 1 shows the charging profile of all charging data.
- Charging profile 2 shows the charging profile after removing the following locations: out of territory, farms, camping areas, hotels, and malls.
- Charging profile 3 shows the charging profile of residential sector only.



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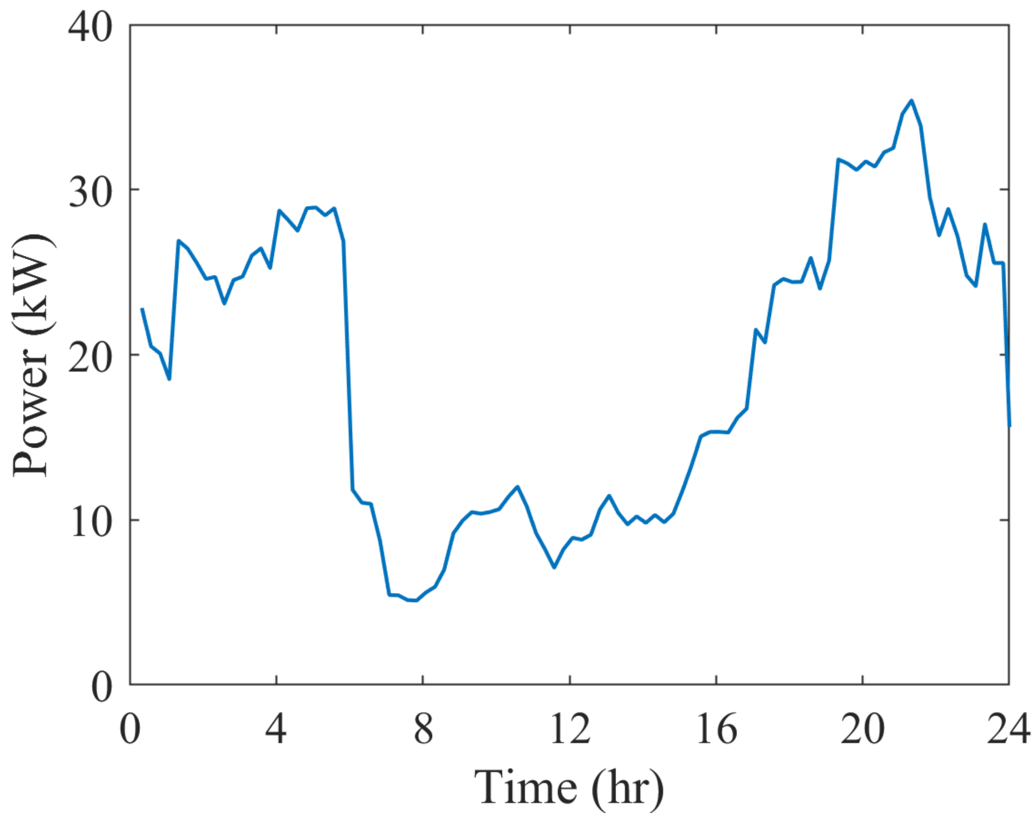
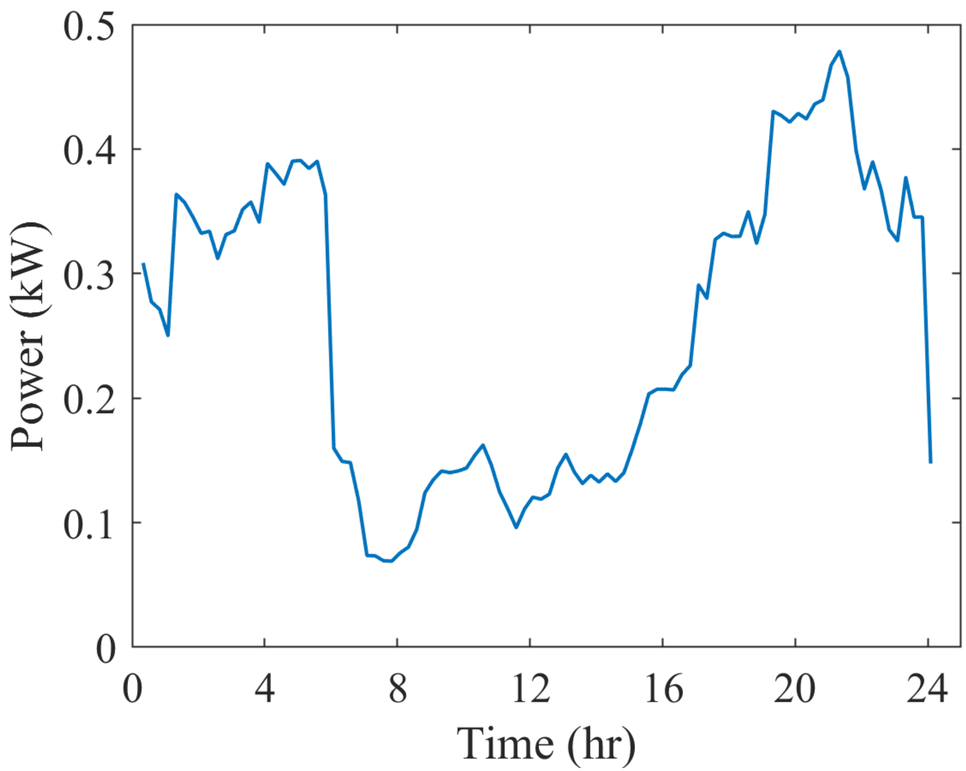
Average daily EV charging profile

- The figure below shows the average daily EV charging profile of all the 74 vehicles in the residential sectors in September 2021.



Average daily EV charging profile per vehicle

- The figure below shows the average daily charging profile per vehicle in the residential sectors in September 2021.



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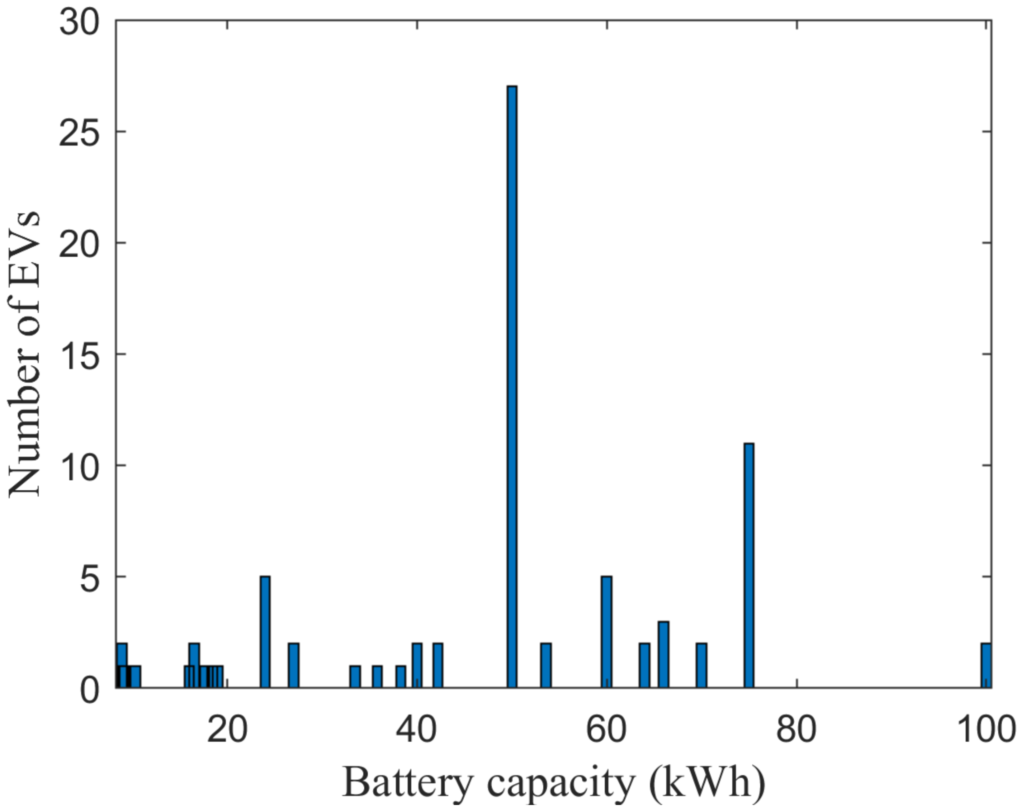
Model parameters

- The extracted residential EV charging profile was analyzed.
- Statistic methods were used to model the parameters, which include battery capacity, charging power level, start charging time, daily EV charging energy and initial state of charge.
- More specifically, the distribution of each parameter was identified from the actual data.
- In the following slides, the method to model each parameter is presented in turn.

Actual data of EV battery capacities

- There were 74 EVs registered in the FleetCarma program in Saskatchewan in September 2021.
- The figure below shows the histogram of the EV battery capacities.



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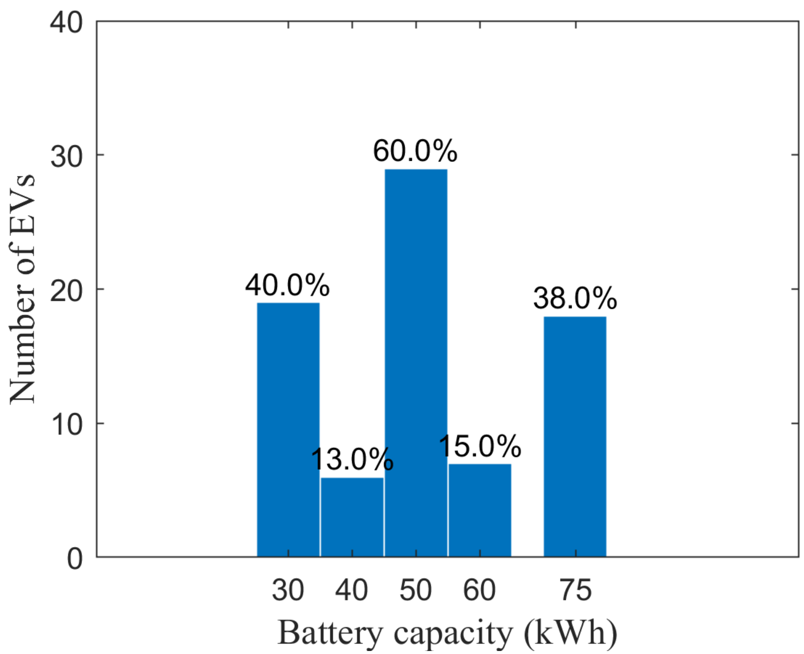
Modeling method for the battery capacity

- We clustered those battery capacities to 30 kWh, 40 kWh, 50 kWh, 60 kWh and 75 kWh, as shown in figure below.
- We then obtained the percentage of EVs having those battery capacities, e.g., 60% EVs have battery with the capacity of 50 kWh.

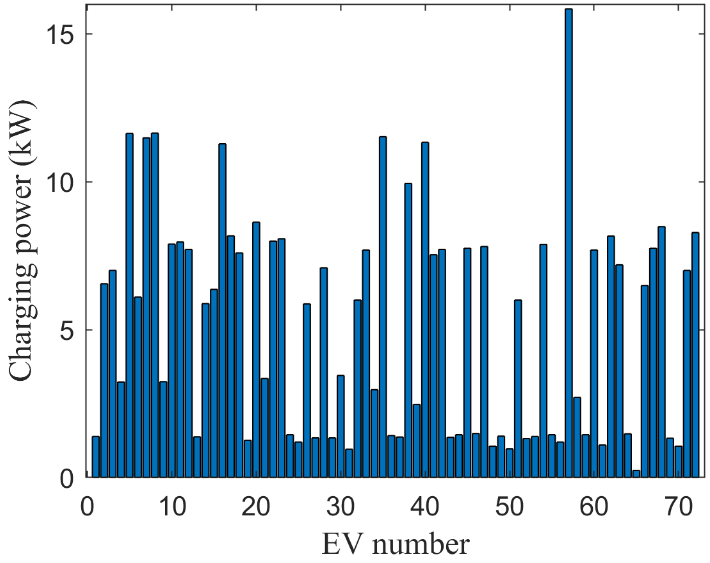


Actual data of rated charging power

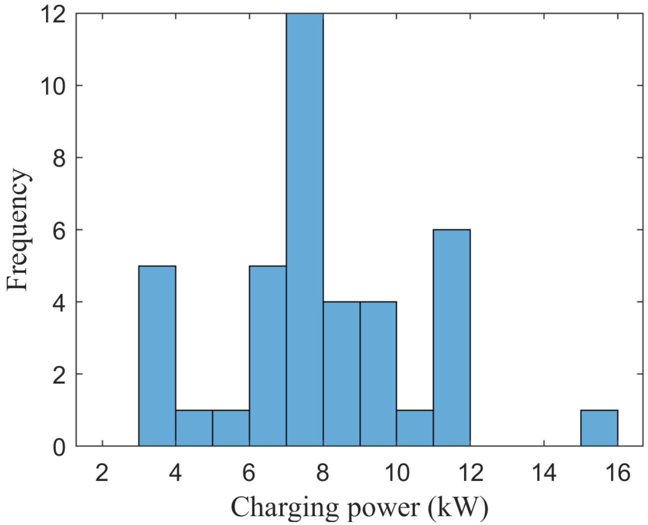
- At the residential sector, there are two EV charging levels; Level-1 charging (1.4 kW - 1.9 kW) and level-2 charging (2 kW – 19 kW) **.**
- We started by analyzing the actual EV charging power data in September 2021.
- The daily charging data is not fixed at one charging value.
- Therefore, we chose the most frequent charging value for each EV.

Actual data of rated charging power

- We found that 28% EVs had Level-1 charger, and 72% EVs had Level-2 charger.
- The following figures shows the most frequent charging power of each EV and the histogram of level 2 charging power.



(a) Most frequent charging power of each EV



(b) Histogram of level 2 charging power

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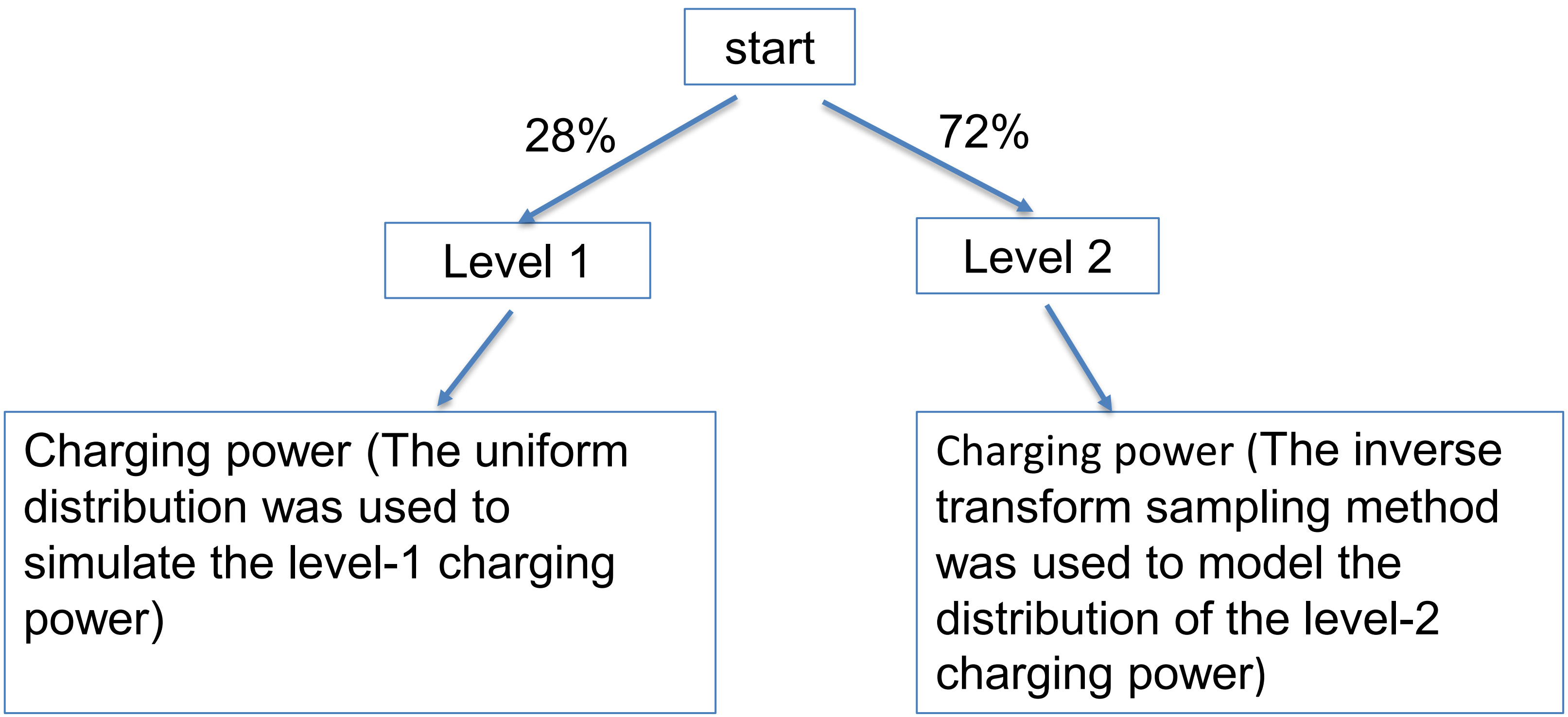
Modeling method of rated charging power

- From this analysis, the EV charging power in the simulation can be determined as follows.



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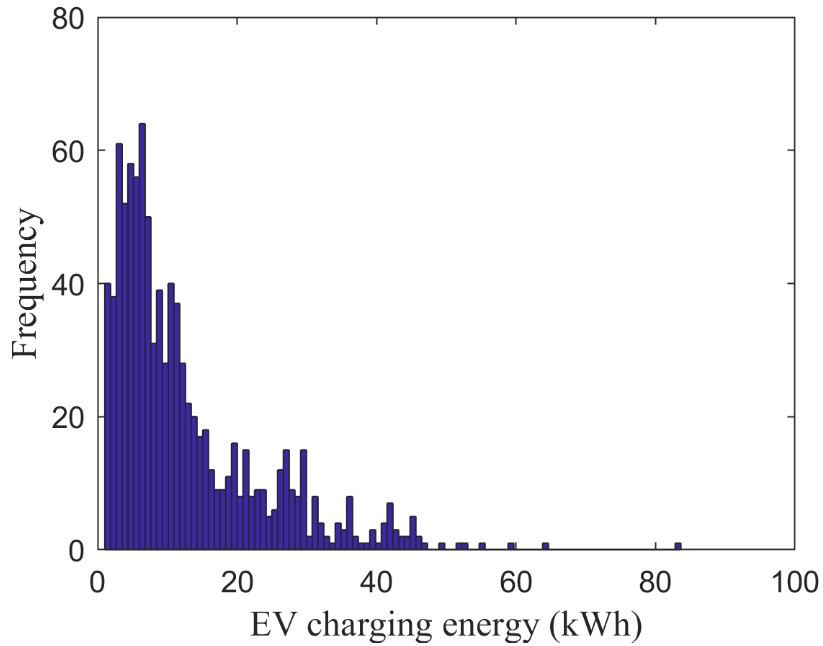
Actual daily EV charging energy at home

- The daily EV charging energy should equal to the daily EV energy consumption to design the simulation model.
- The figure below shows the histogram of the actual daily EV charging energy at home in September 2021.



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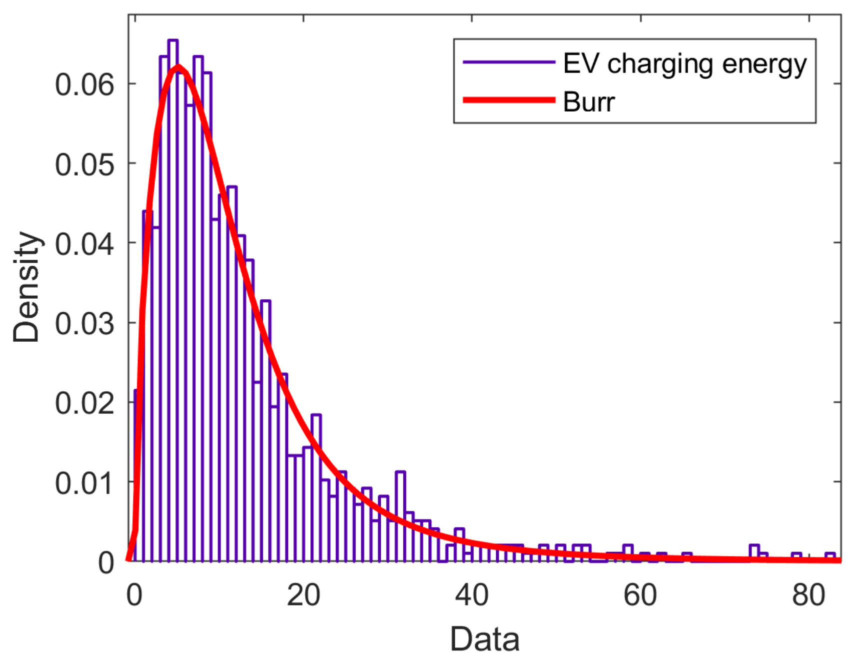
Modeling method of EV charging energy at home

- We used Burr distribution to model the distribution of the daily EV charging energy at home.



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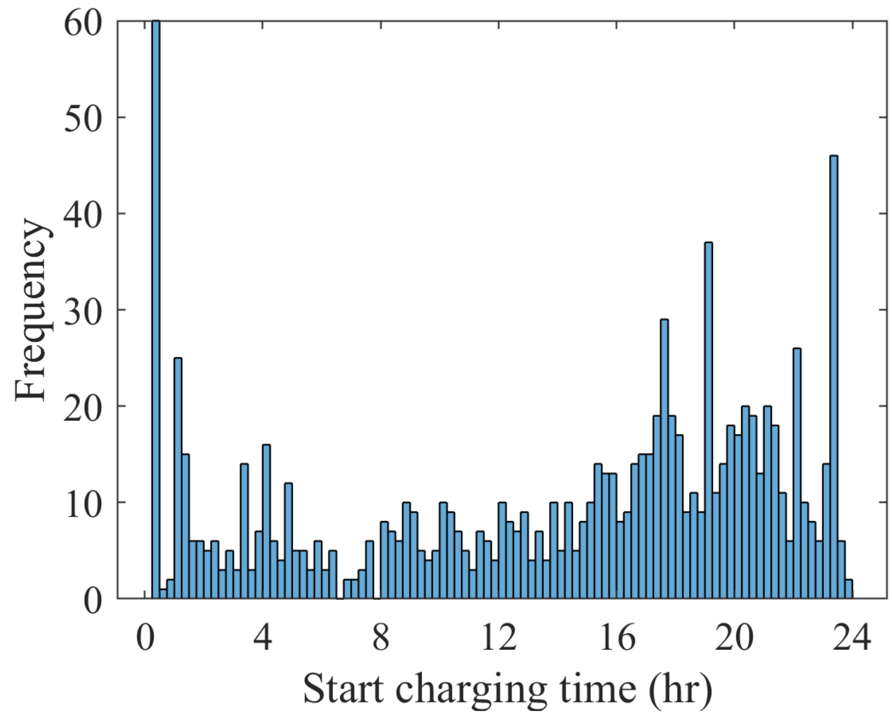
Actual data of start charging time

- The start charging time of EVs is an important parameter that may affect the peak of EV charging demand.
- Therefore, we analyzed the actual charging data and extracted the start charging time for each EV.
- The total start charging times were 937 and the number of days of charging were 893.
- Therefore, some EVs were charged multiple times in a day.

Actual data of start charging time

- The figure below shows the histogram of the actual start charging time for all EVs during September 2021.
- We used the inverse transformation method to model the distribution of the start charging time.



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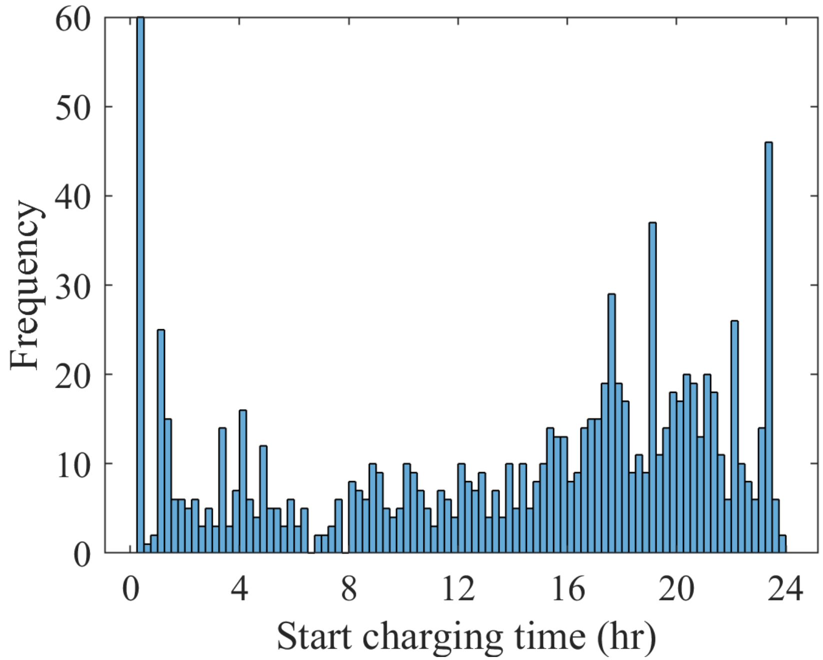
Modeling method of start charging time

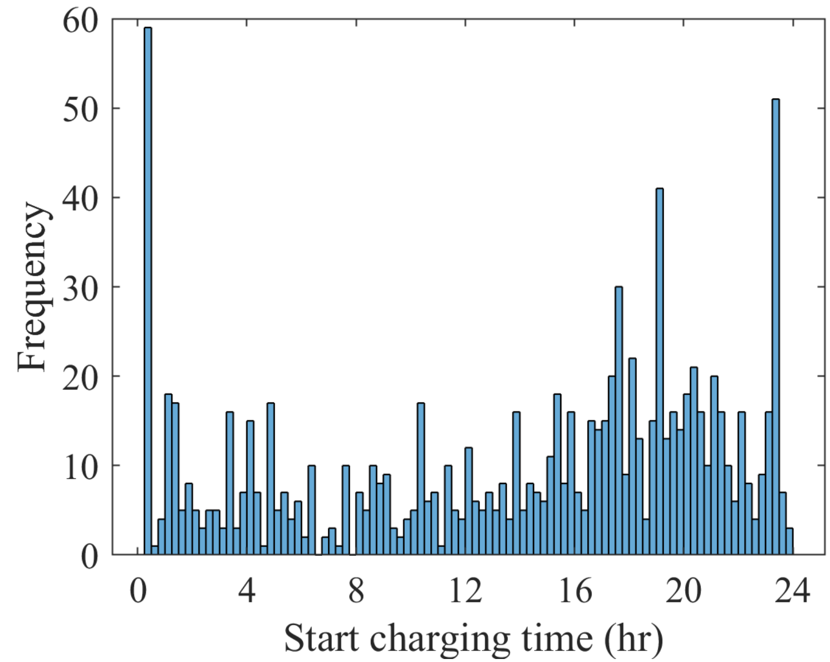
- We used the inverse transformation method to model the distribution of the start charging time.

Modeling method of start charging time

- We used the inverse transformation method to model the distribution of the start charging time.



(a) Actual start charging time



(b) Simulated start charging time using the inverse transformation method

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Modeling initial SOC (SOC_0)

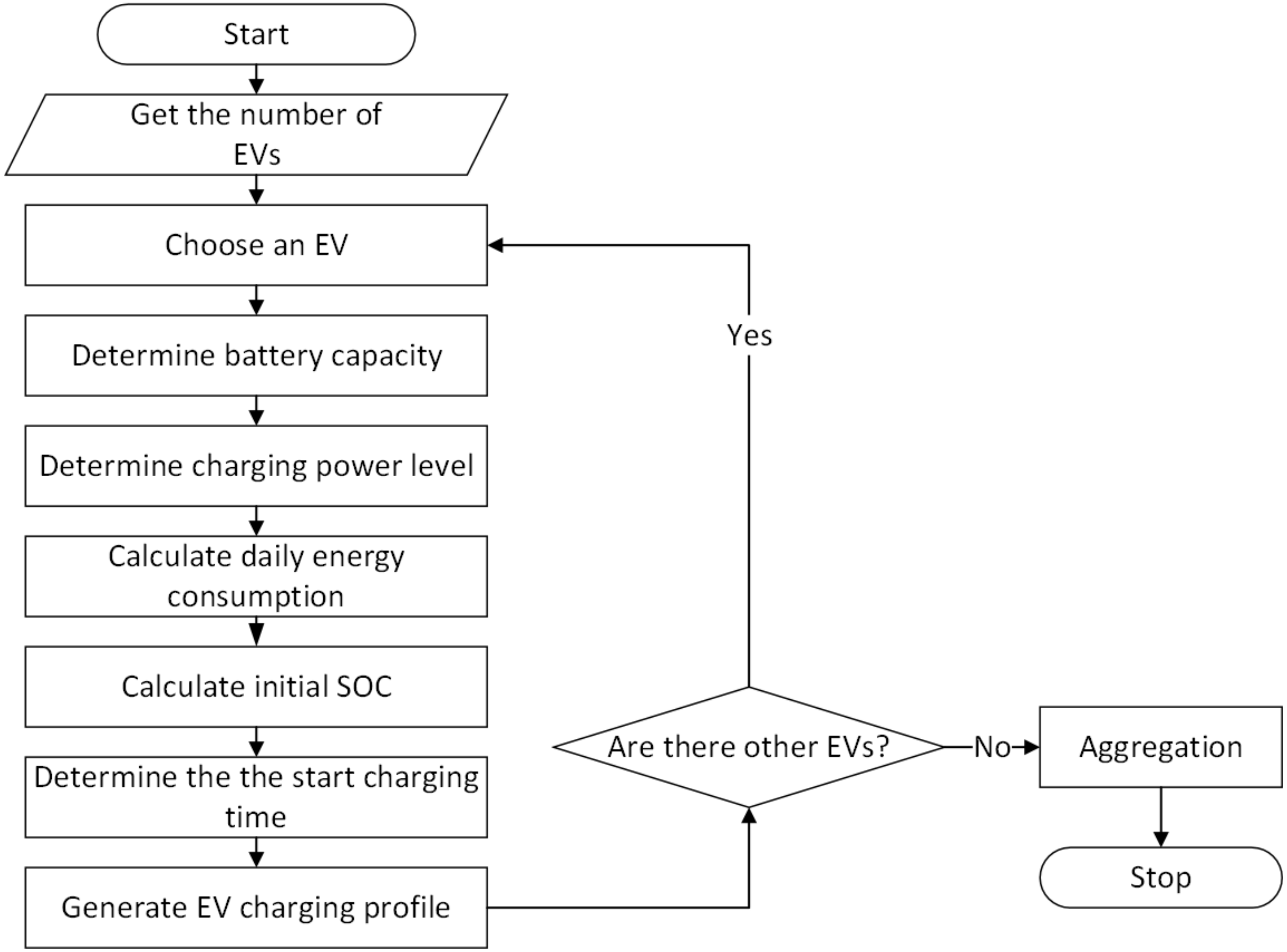
- The initial state of charge (SOC_{0i}) of EV represents the level of charge of the battery according to its full capacity.
- $SOC_{0,i}$ is a random number based on the distribution of EV battery capacity (C_i) and daily EV charging energy (E_i).

$$SOC_{0,i} = \left(1 - \frac{E_i}{C_i}\right) \times 100\%$$

The aggregated EV charging model

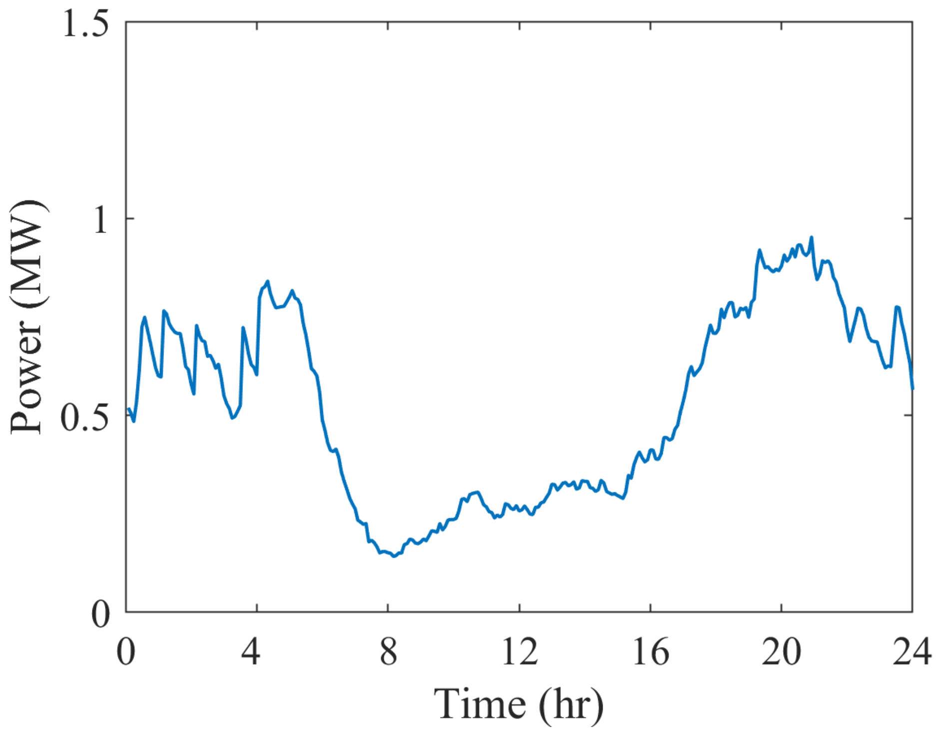
- The parameters of the individual EV model were captured by different type of statistic method (e.g., burr distribution, and inverse transformation method).
- Monto Carlo method was used to develop the aggregated EV charging model.

Flow chart of the aggregated EV charging model



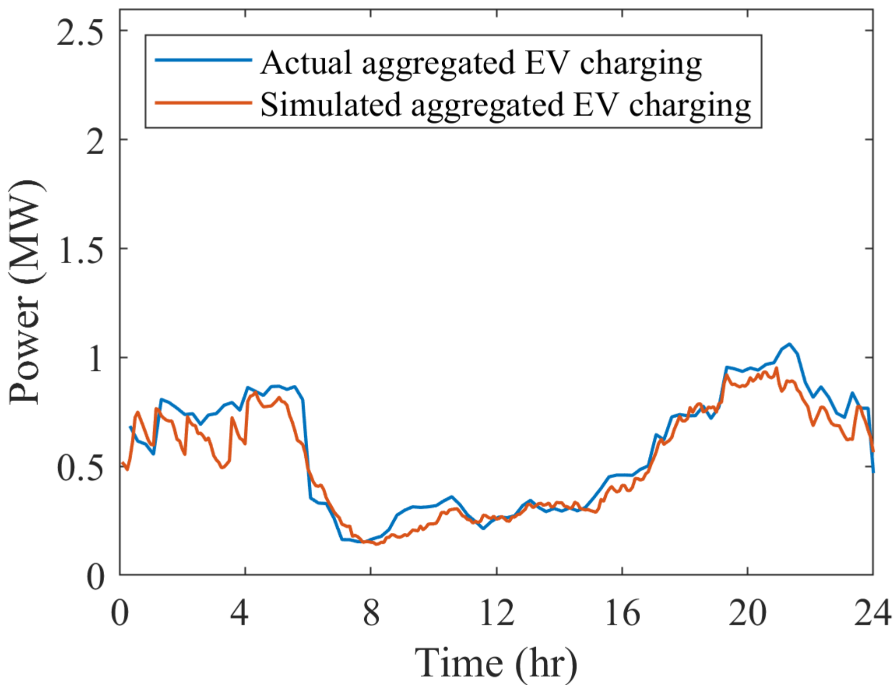
Simulation results

- The figure below shows the simulation results of aggregated EV charging profile of 893 EVs.



Validation of the EV charging model

- The blue curve represents the actual profile of 893 daily EV charging of 74 EVs.
- The orange curve represents the simulation results of aggregated EV charging profile of 893 EVs.

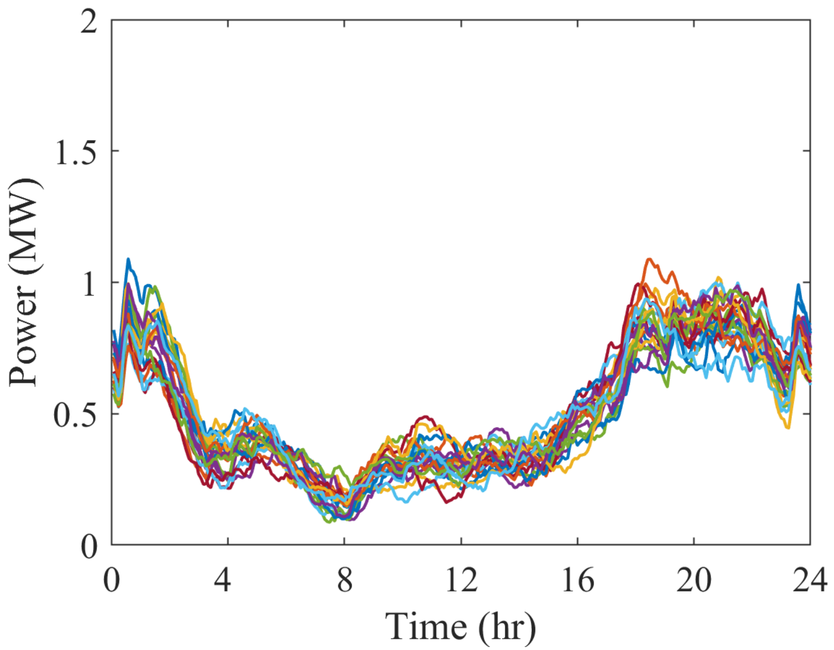


Validation of the simulation results

- The total charging energy of the actual EV charging profile is 13.6 MWh, while the total simulated EV charging energy is 12.6 MWh.
- The energy difference between the actual and the simulated results is approximately 7.3%.

Robust analysis

- To test the robustness of the simulation model, we ran the model 20 times as shown in the figure below.
- The similarity of each run shows that the model is robust, and the simulation results are reproducible.



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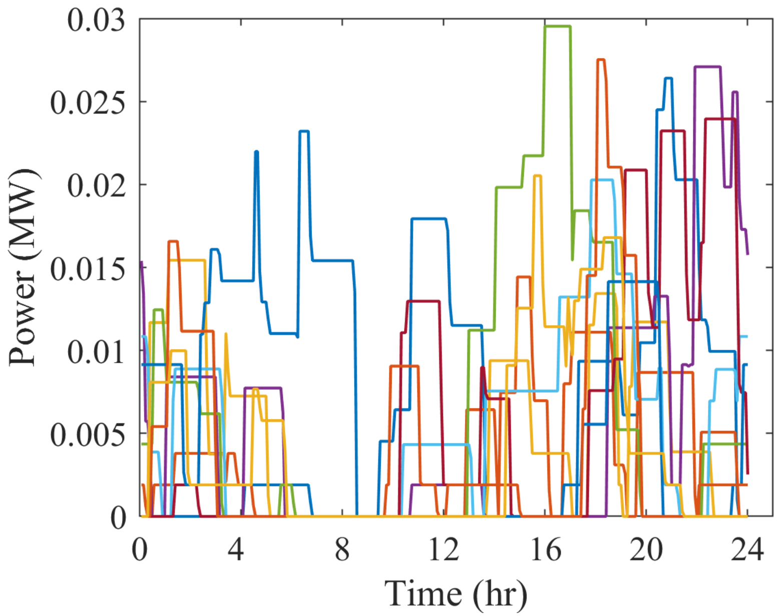
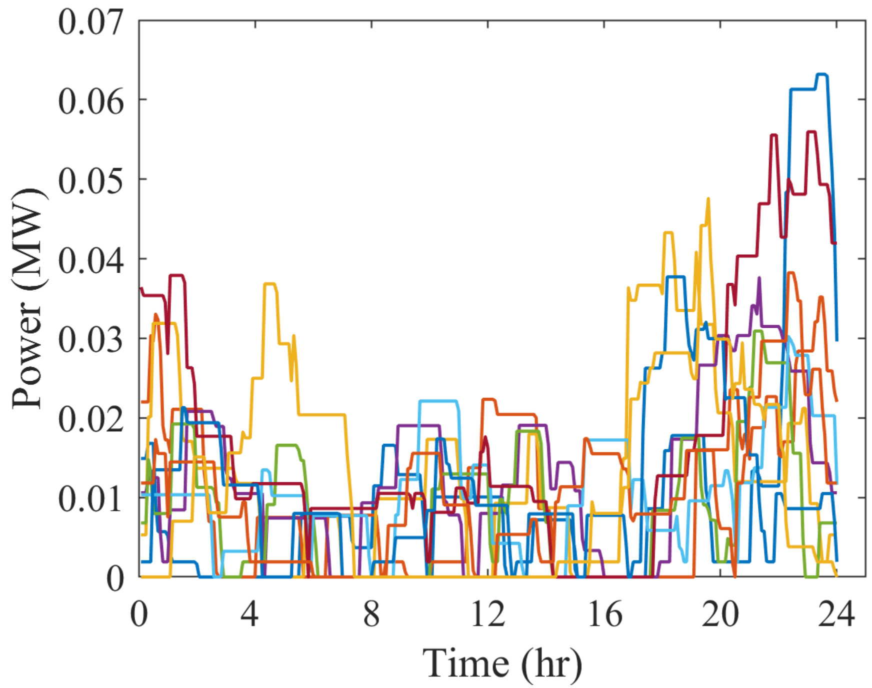
Charging profiles of aggregated 10 EVs

- The figure below shows aggregated EV charging profile of 10 EVs.
- There were 10 times of simulation, and each profile is the result of each run.
- We can see that, if the number of EVs is small, the charging behavior can be unpredictable.



Charging profiles of aggregated 20 EVs

- The figure below shows aggregated EV charging profile of 20 EVs.
- There were 10 times of simulation, and each profile is the result of each run.



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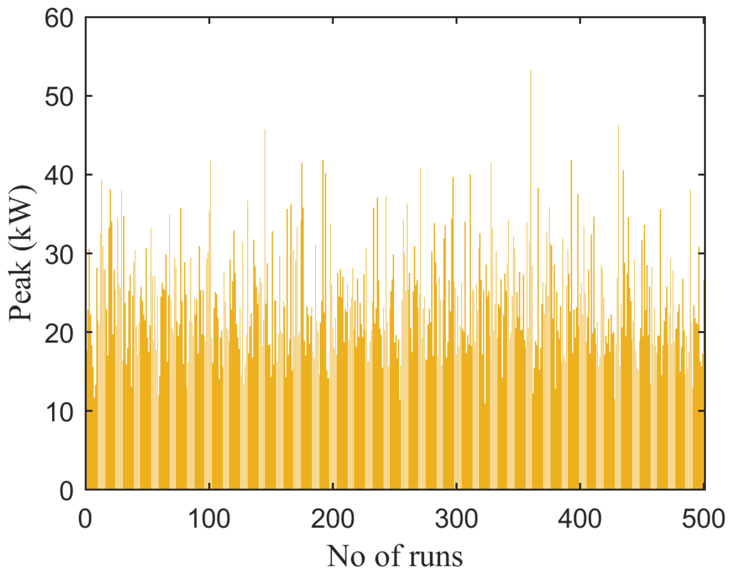
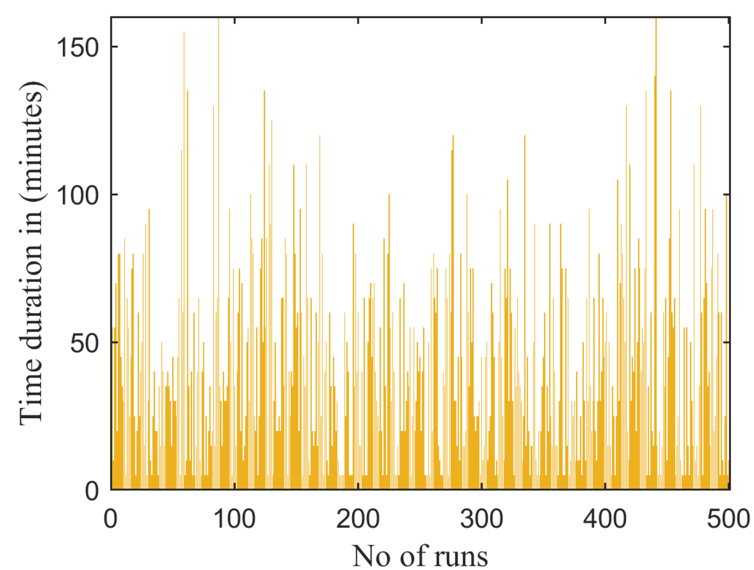
Peak demand of aggregated 10 EVs

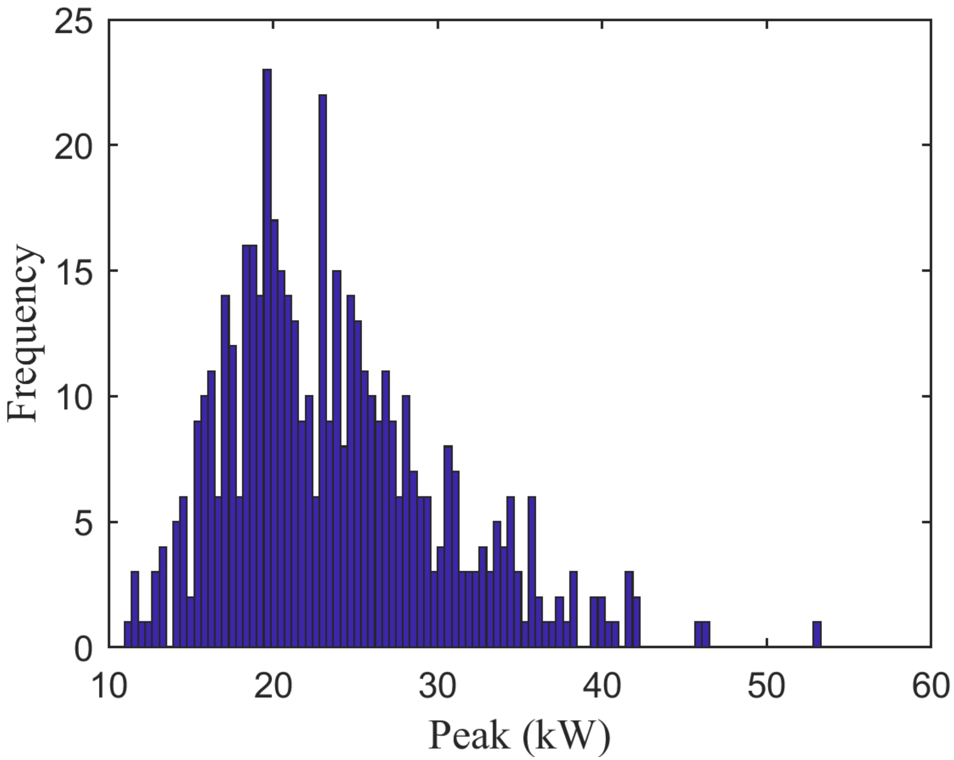
- We ran 10 EV simulation 500 times to find the peak demand of each time.
- The figures below show the bar chart of the peak demand and its duration of aggregated charging profile of 10 EVs.





Statistic information of the peak demand

- The figure below is the histogram of peak demand of aggregated charging profile of 10 EVs..



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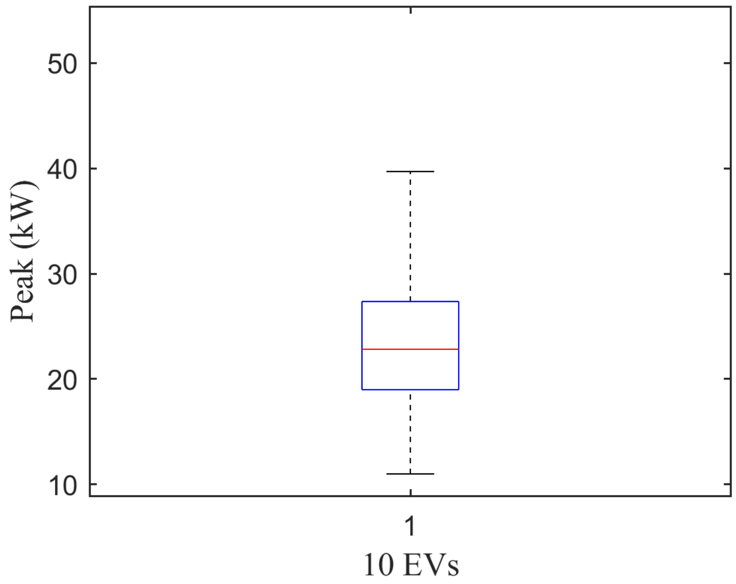
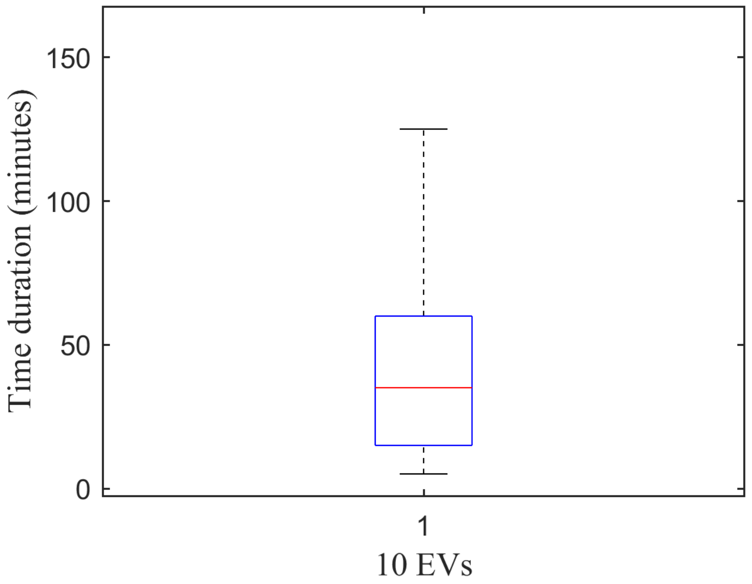
Statistic information of the peak demand of aggregated 10 EVs

- The peak demand
  - Mean value is 23.7 kW.
  - Standard deviation is 6.59 kW.
- The time duration of peak demand
  - Mean value is 41.3 minutes.
  - Standard deviation is 31.8 minutes.

Statistic information of the peak demand of aggregated 10 EVs

- The figures below show the box plot of peak demand and the duration of the 500 times of simulation.
- The red mark indicates the median. The bottom and top edges of the box indicate the 25th and 75th percentiles, respectively.
- The whiskers extend to the most extreme data points not considered.





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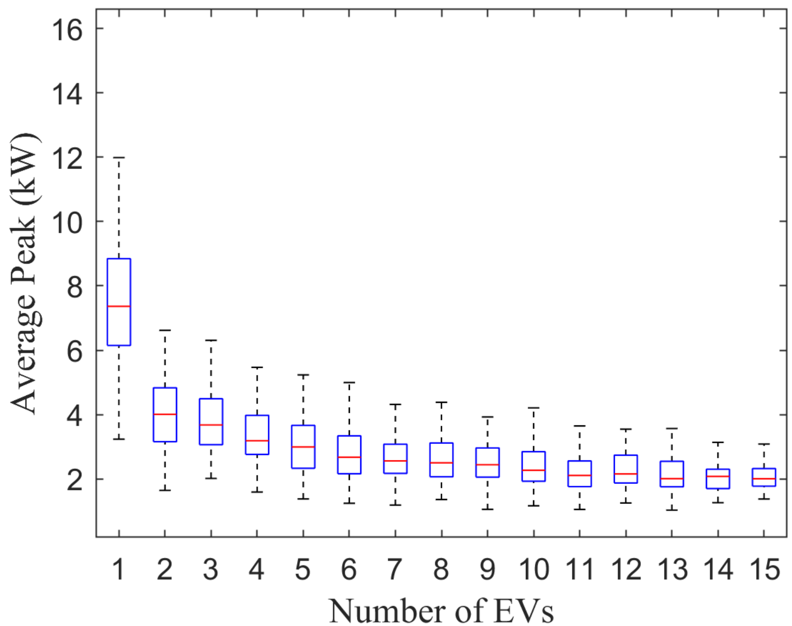
Statistic information of the average peak demand of various number of EVs

- The figure below shows the box plot of average peak demand of the 100 times of simulation of various number of EVs .
- The red mark indicates the median.
- The bottom and top edges of the box indicate the 25th and 75th percentiles, respectively.



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Summary of Objective 1

- We have developed data-driven and parameterized EV charging models.
- The EV charging models are robust and can accurately represent EV charging load in Saskatchewan.
- The EV charging models can be used for electricity load prediction, generation planning, and expansion analysis of power distribution systems.
- The EV charging models will be embedded into load flow studies to evaluate the impact of EV penetration on Saskatchewan's urban residential power distribution systems, such as voltage sag, line loss, and transformer overloading.

Objective 2

- This section evaluates the impact of EV penetration on Saskatchewan's urban residential power distribution system based on the transformer loading and the voltage drop value at each bus, which is the second step of the project.
- We modeled two distribution systems as follows:
  - 15-house distribution system.
  - 22-house distribution system.
- These two distribution systems are the samples for our study. They do not represent the overall power distribution in Saskatchewan.
- Load flow analyses applied at each model to determine the voltage value at each house, and transformer overloading after integrating various types and numbers of EVs to the distribution networks.

Objective 2

- The aim was to examine the transformer loading and voltage values at customer homes during on-peak demand periods.
- The on-peak demand was selected based on an analysis of AMI data from 98 households in Saskatchewan.
- The AMI data do not include EV charging load, which is defined as the base load in our study.
- The EV charging profiles, and the base load were incorporated into the load flow model to determine the effect of EV integration on transformer loading and voltage values.
- Furthermore, the threshold of power distribution system collapse (i.e., the transformer was overloaded, or the voltage dropped to below the threshold) was identified.

How to evaluates the impact of EV penetration

- The voltage at the customers' houses should be higher than or equal to 110 volt.
- The primary side of the transformers is represented by a slack bus and the voltage value equals 116 volt.
- In addition, the transformer loading should not exceed the standard rating.

The transformer standard rating

- According to the standard engineering practice, transformer Loading SaskPower supplied padmount transformers can be loaded to 144% of the nameplate rating for a 4-hour period at 40 ℃ ambient temperature after being loaded for the previous 12-hour at an average load of 75% of rating without significant loss of life to the winding insulation in Summer.
- Ambient temperature significantly affects the cooling process, such that in winter conditions the transformer can be loaded to 200% of the nameplate rating.

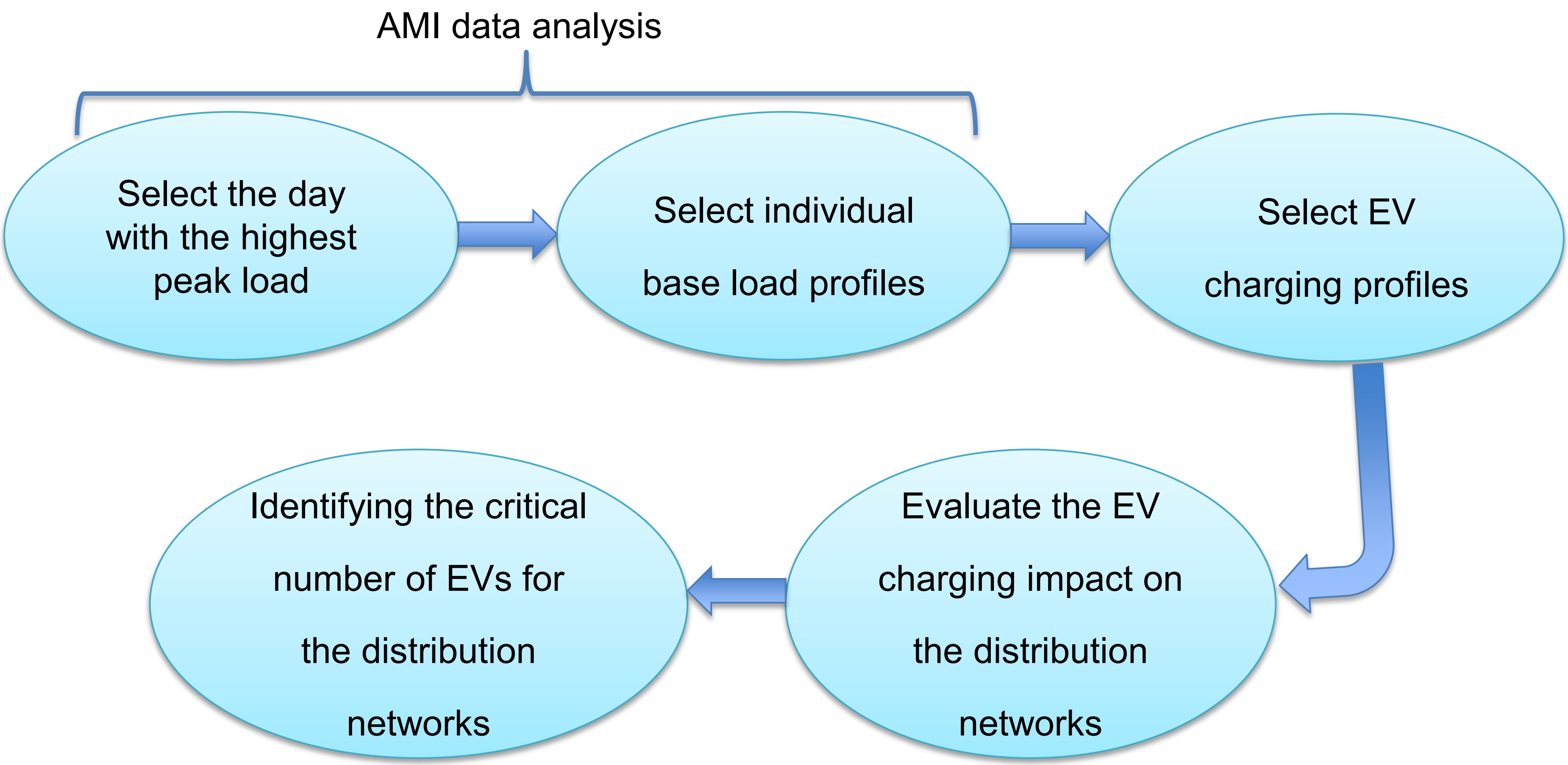
Outlines

- AMI data analysis
  - Select the day with the highest peak load.
  - Select household load profiles with a reasonable on-peak demand for the distribution systems as **on-peak** demand.
- EV charging data selection.
- Evaluate the EV charging impact on the 15-house distribution system under **on-peak** demand.
- Evaluate the EV charging impact on the 22-house distribution system under **on-peak** demand.
- Identifying the critical number of EVs for the distribution networks.

Important definitions

- Base load profile: the AMI data without EV charging
- Load profile: baseload + EV charging

Workflow



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AMI data analysis and selection

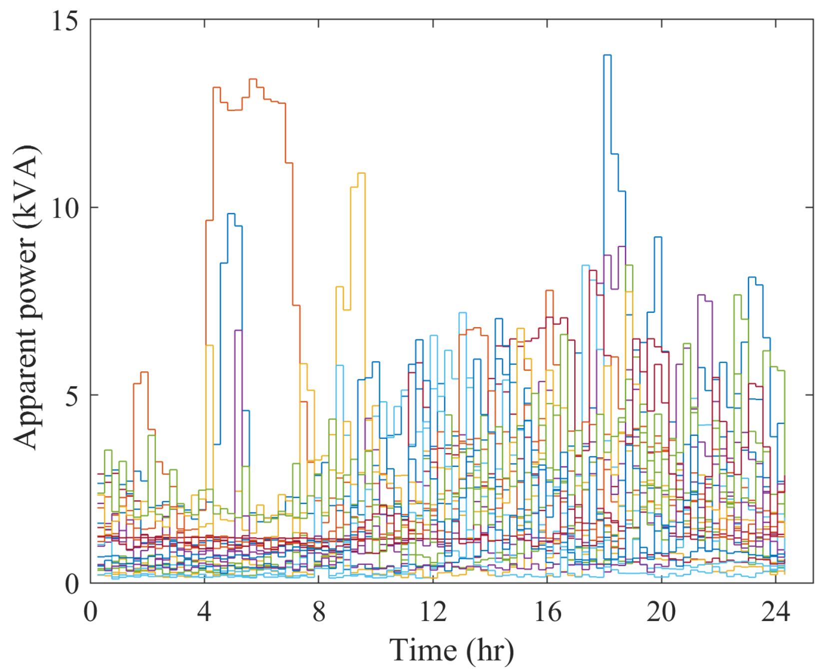
- In this project, we want to evaluate the impact of integrating EVs into the residential distribution system during on-peak demand.
- Therefore, the main reason for analyzing the AMI data is to determine which day has the highest peak load.
- Furthermore, the AMI data is used to select household base load profiles with reasonably high peaks. For instance, for 22 house distribution systems, we need to select 22 household load profiles that provide reasonable on-peak demand.

AMI data analysis

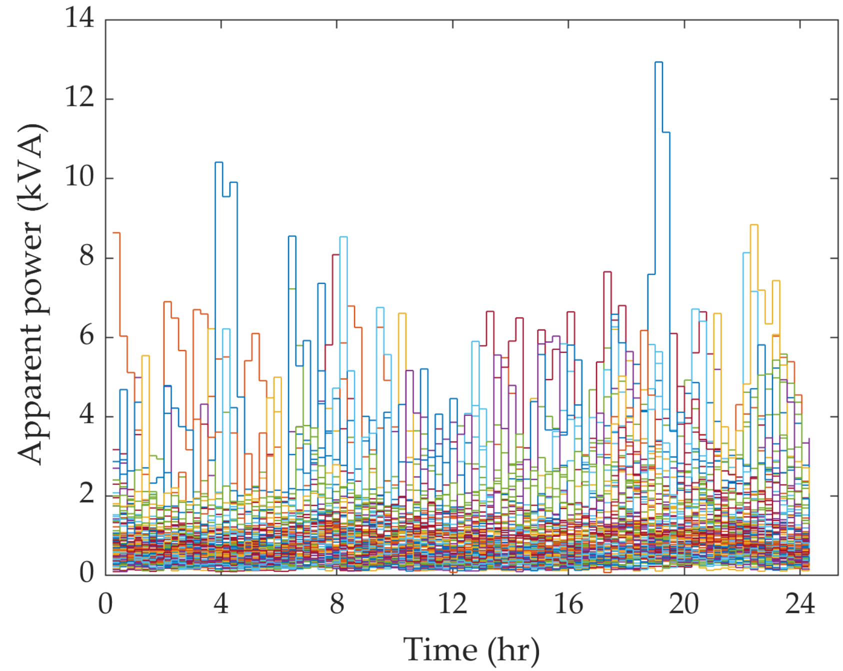
- We extracted and prepared the AMI data from the Excel file for June and July 2022.
  - 98 houses (smart meters).
  - 48 days From June 1st to July 18th
  - The data include meter number, kVA and kWh for every 15 minutes
  - The data prepared by deleting the repeated data and filling the missing data using the interpolation method.
  - The peak demand periods occur in summer when it is hot.
  - According to Environment Canada, the hot days in Regina in 2022 were on June 13 (Monday), June 17 (Friday), June 18 (Saturday), June 23 (Thursday), June 29 (Wednesday), July 16 (Saturday), and July 17 (Sunday).

Base load profile of hot days in Regina of 98 houses

- The figure below represents the base load profile of 98 houses on June 13th (Monday) and June 17th (Friday) 2022.
- The highest temperature on June 13th and June 17th was 28℃ and 30℃, respectively.



(a) June 13th (Monday)



(b) June 17th (Friday)

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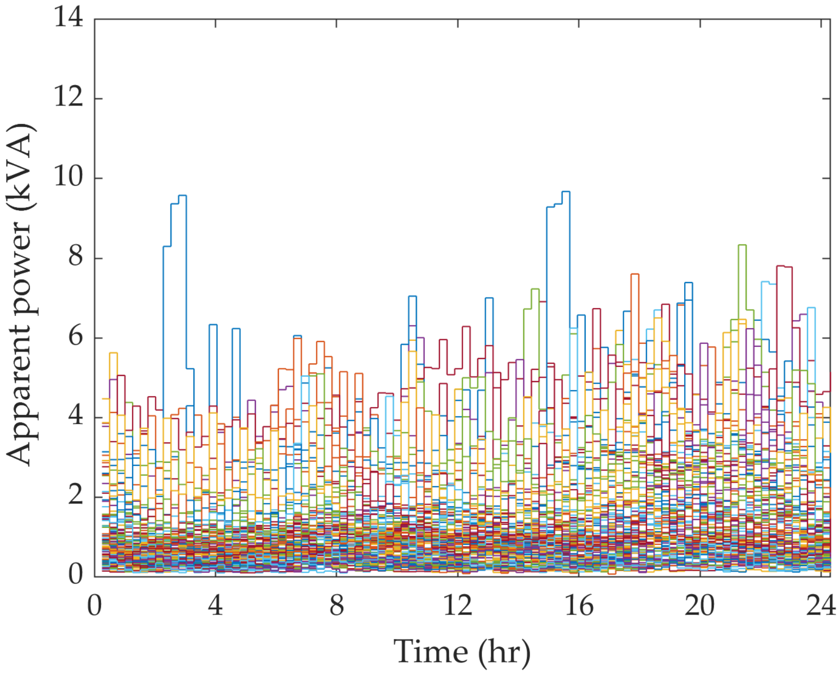
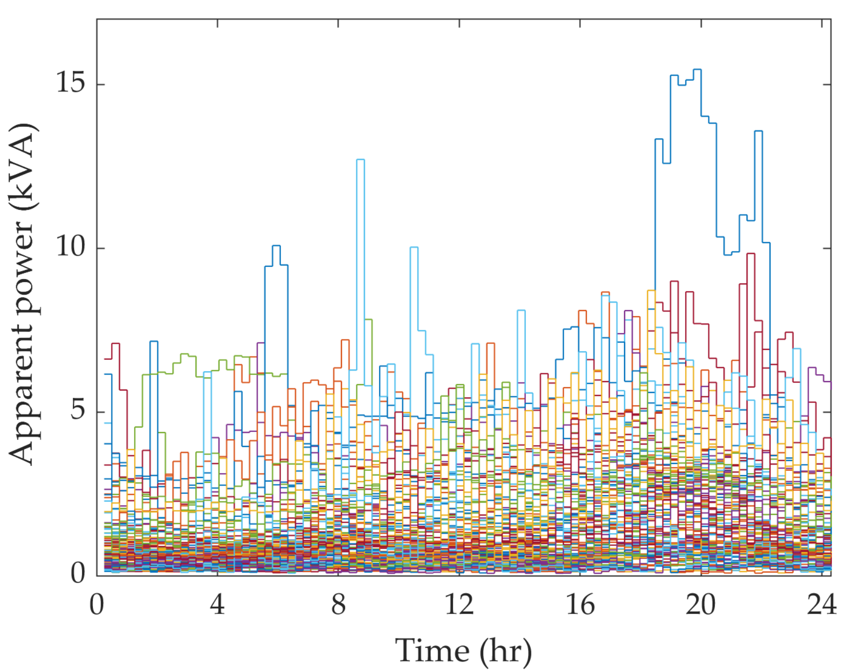
Base load profile of hot days in Regina of 98 houses

- The figure below represents the base load profile of 98 houses on June 23rd (Thursday) and June 29th (Wednesday) 2022.
- The highest temperature on June 23rd and June 29th was 31℃ and 30℃, respectively.



(a) June 23rd (Thursday)



(b) June 29th (Wednesday)

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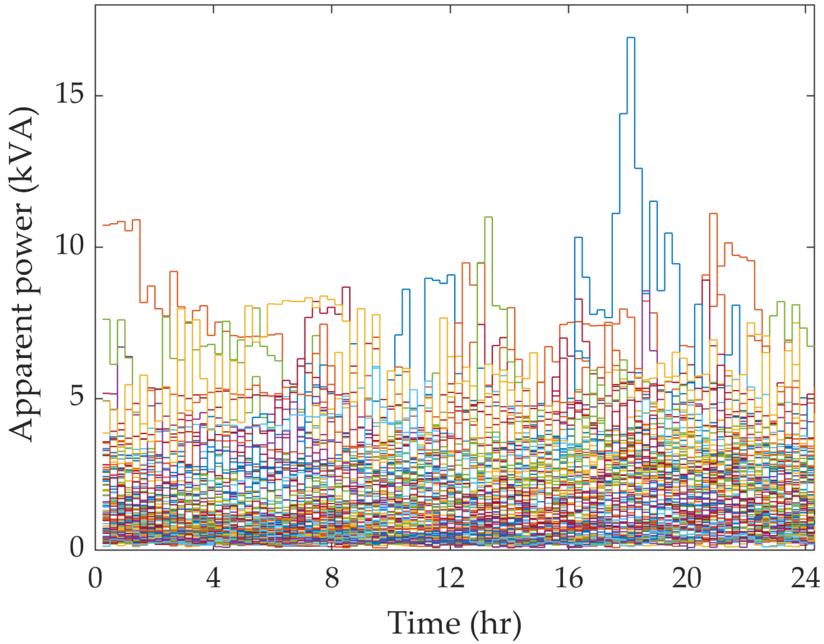
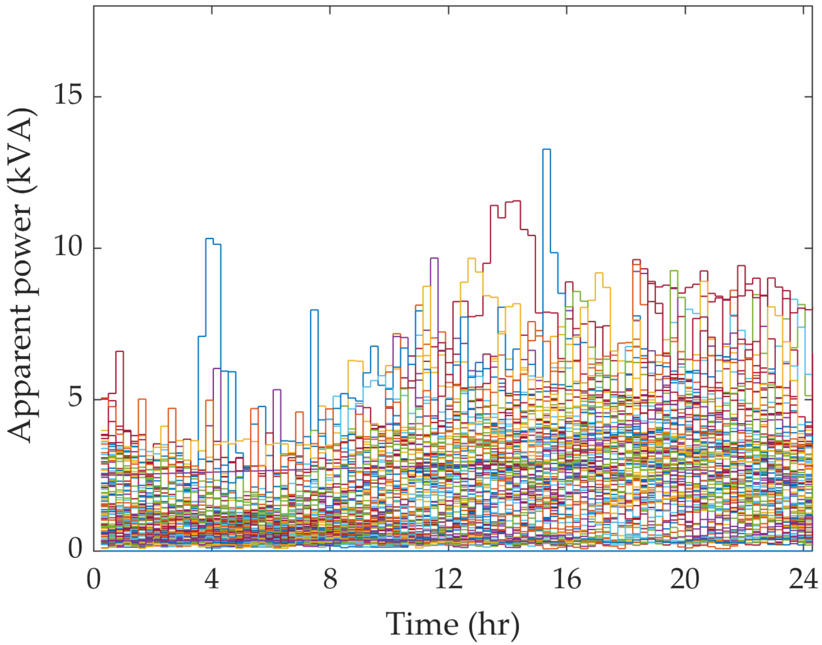
Base load profile of hot days in Regina of 99 houses

- The figure below represents the base load profile of 98 houses on July 16th (Saturday) and July 17th (Sunday) 2022.
- The highest temperature on July 16th and July 17th was 34℃.



(a) July 16th (Saturday)



(b) July 17th (Sunday)

How to select the day with the highest peak base load

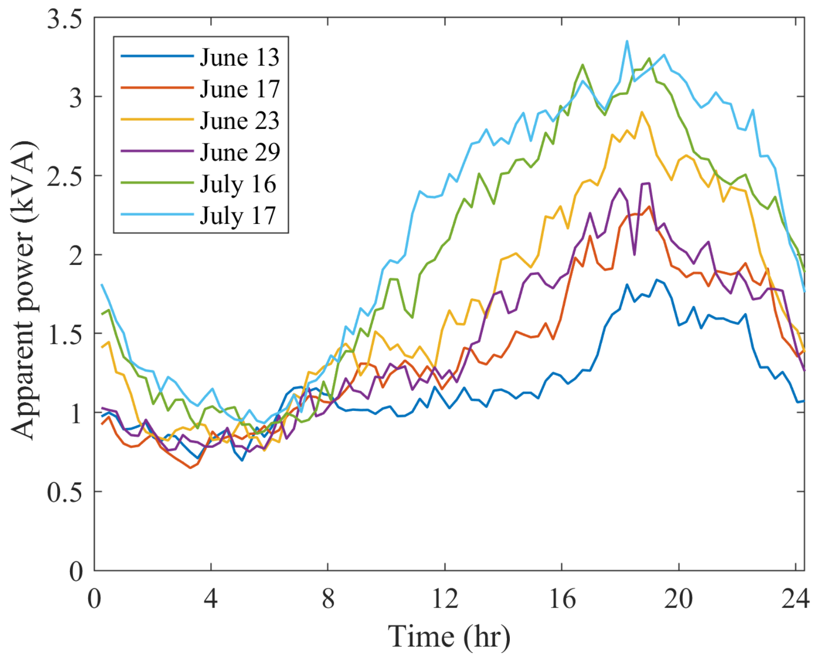
- The main objective of this study is to evaluate the impact of EV penetration on the distribution networks by checking the transformer loading and voltages values at customers’ houses during **on-peak** demand.
- We used two methods to determine which day has the highest peak load.
  1. Check the highest daily energy consumption.
  2. Check the highest peak demand of the daily load profile.

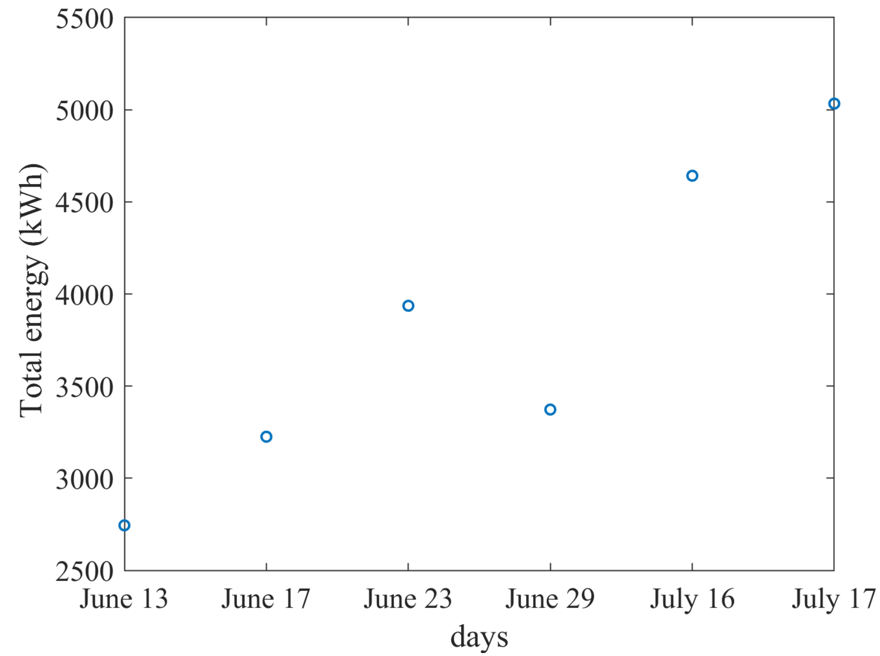
Method 1: Check the highest daily energy consumption

- In this method, we calculate the aggregated daily energy consumption for all houses.
- In this case, we only considered the hot days in Regina.
- The day with the worst energy consumption is selected as the worst case.

Aggregated base load profile of hot days in Regina of 98 houses

- The figures below represent the average aggregated load profile of 98 houses on hot days in Regina and the total energy during these days.
- June 13 (Monday), June 17 (Friday), June 23 (Thursday), June 29 (Wednesday), July 16 (Saturday), and July 17 (Sunday).





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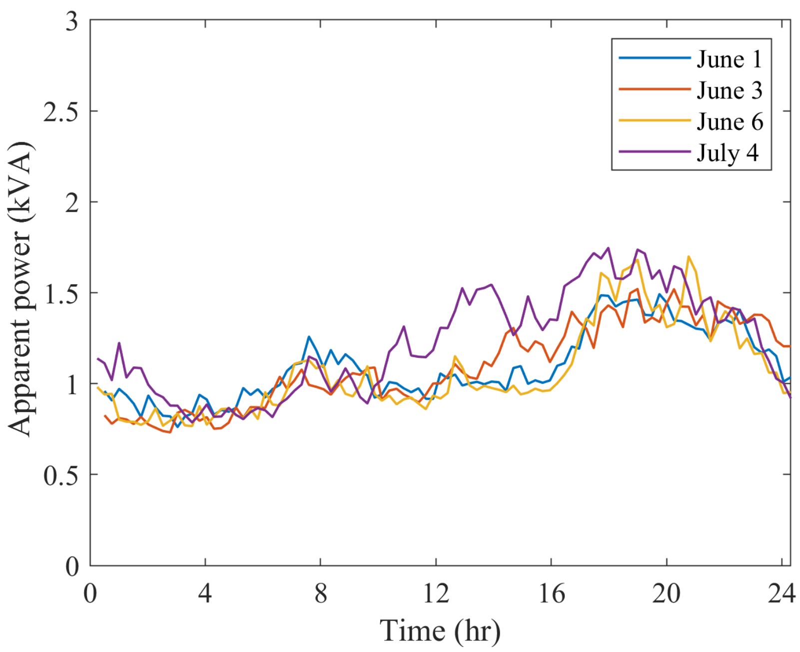
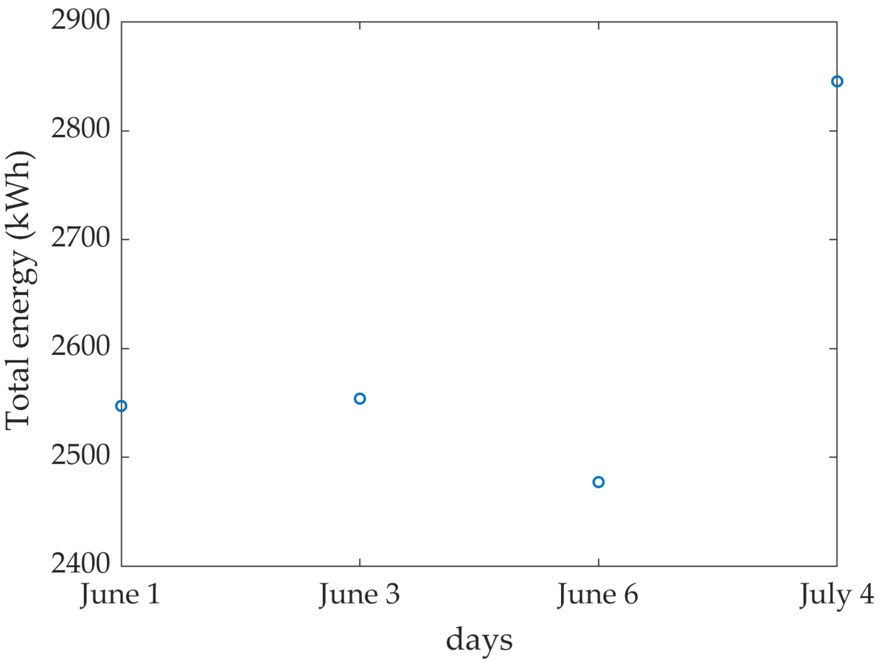
Aggregated base load profile of 98 houses on randomly selected 4 days

- To compare the load profile in the hot day and in regular days, the figures below represent the aggregated load profile of 98 houses on randomly selected 4 days in Regina and the total energy during these days.





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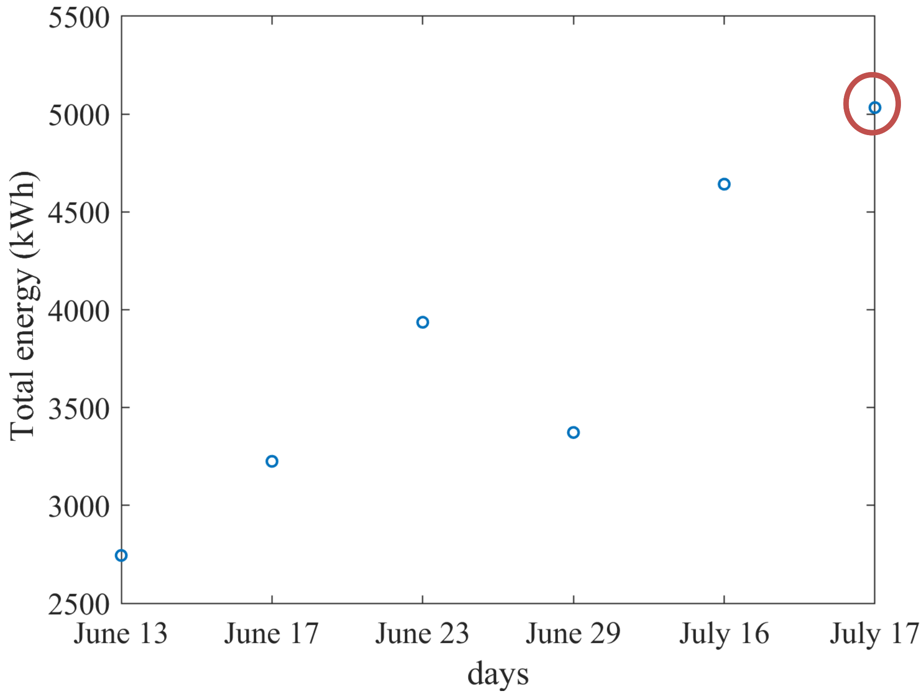
The day with highest energy

- The figure below shows the total daily energy of the hot days in Regina.
- It can be seen that the highest energy demand occurs on July 17th.
- The total energy is 5000 kWh.



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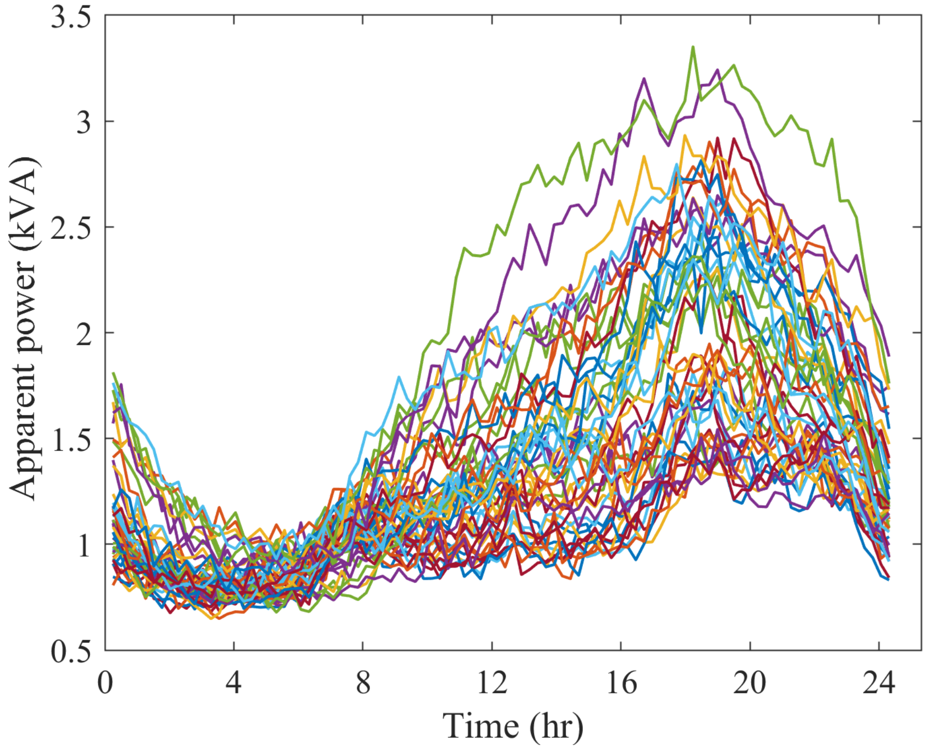
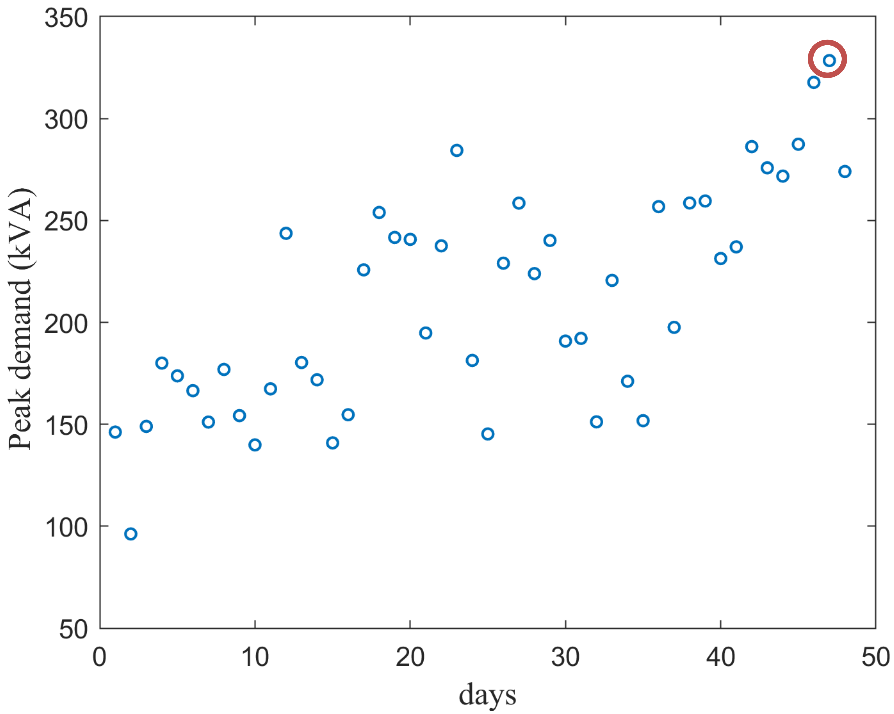
Method 2: Check the highest peak demand of the daily load profile.

- In the figure below, each curve shows the average aggregated base load profiles of 98 houses for one day.
- There are 48 curves representing the base load profile of 48 days from June 1st to July 18th.



Method 2: Check the highest peak demand of the daily load profile.

- The figure below shows peak demand of the 48 load profiles shown in the previous slide.
- It can be seen that July 17th (Sunday) has the highest peak demand (328.4 kVA).



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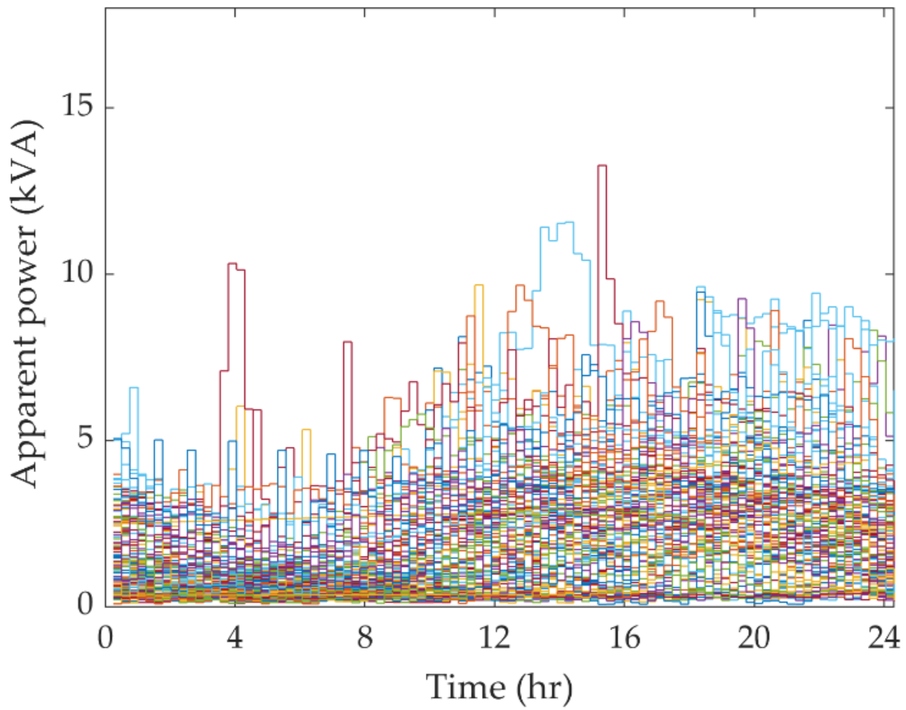
Base load for on-peak demand

- Both Method 1 and Method 2 show that the on-peak demand occurs on July 17th (Sunday).
- The figure below represents the individual base load profile of 98 houses on July 17th, 2022.

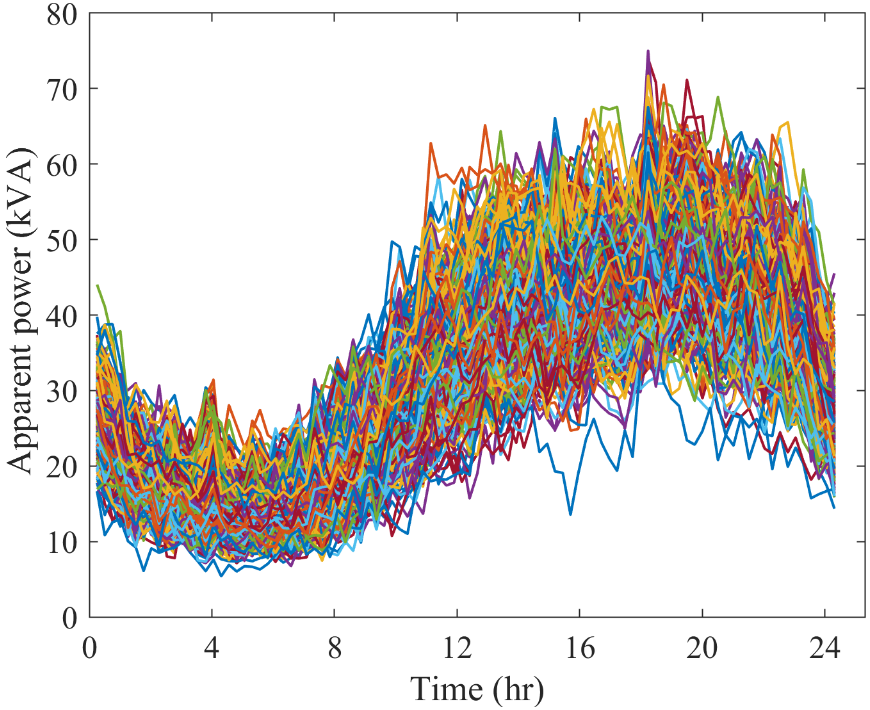


Base load profile selection

- The main objective of this study is to evaluate the impact of EV penetration on the distribution networks by checking the transformer loading and voltages values at customers' houses during **on-peak** demand.
- On-peak demand means the base load (without considering EVs) is the most reasonable on-peak household load profiles for the distribution system.

Base load profile selection 15-house distribution system

- To obtain the reasonable worst case for the 15-house distribution system, we randomly selected 15 house base load 500 times from the peak day on July 17th (Sunday).
- Figure below shows the aggregated load profile of 15 houses. There are 500 curves.



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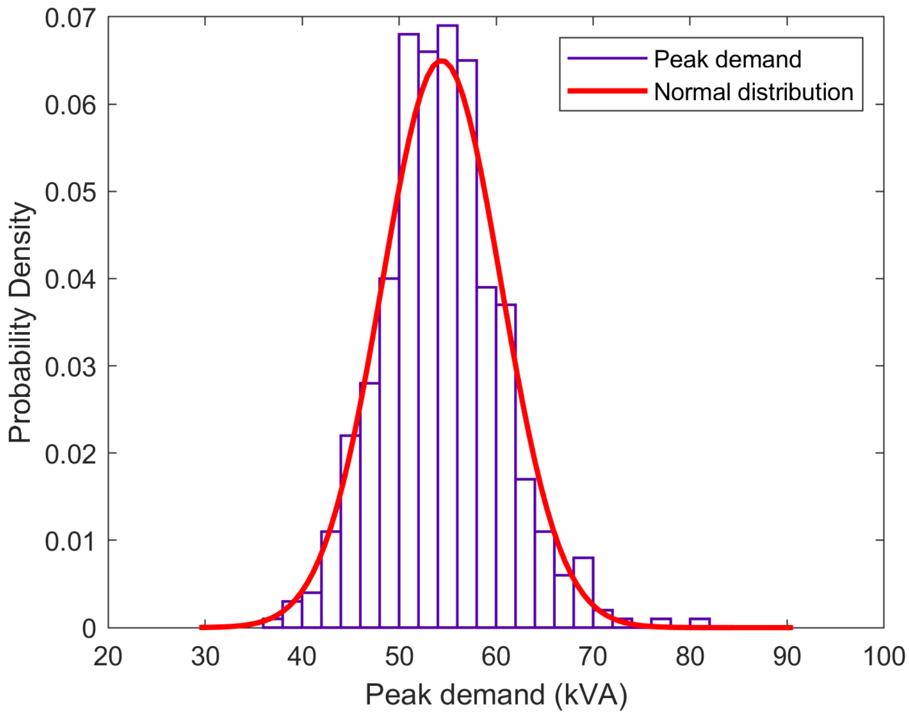
Histogram of the aggregated peak demand of 15-house distribution system

- The figure below shows the histogram of the aggregated peak demand of randomly selected 15 houses 500 times.
- The distribution of the peak demand is normal distribution where the mean distribution (μ) is 54 kVA, and the standard deviation (σ) is 6 kVA



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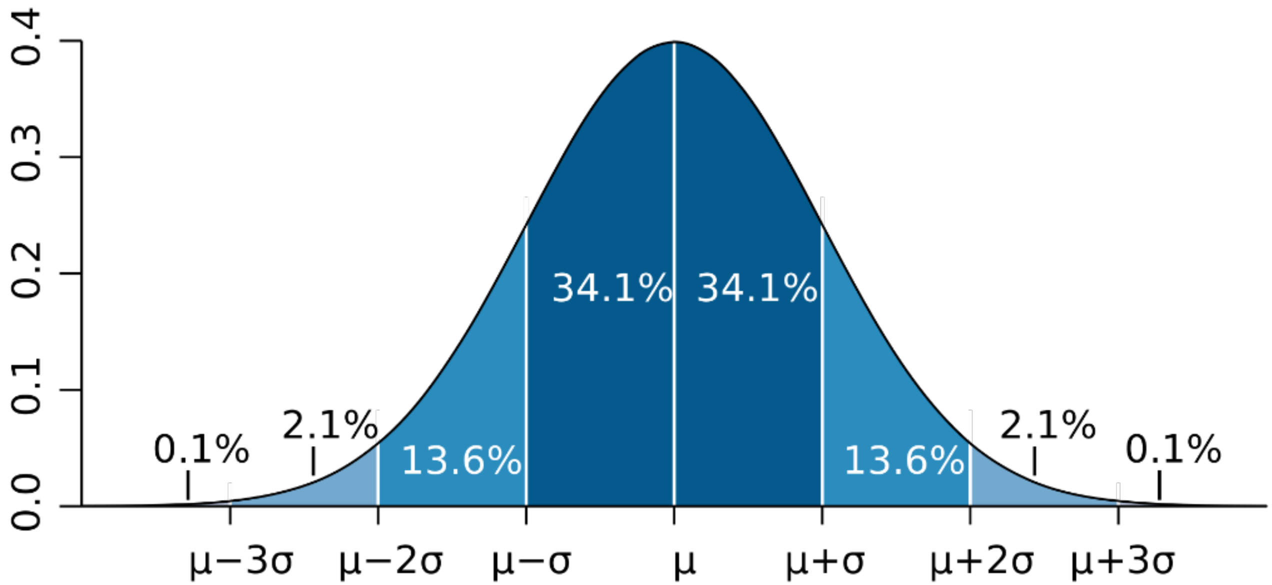
Histogram of the aggregated peak demand

- For the normal distribution function, 68% of values are within one standard deviation (σ) away from the mean (μ). In addition, about 95% of the values lie within two standard deviations; and about 99.7% are within three standard deviations as shown in figure below.



Ref: Wikipedia

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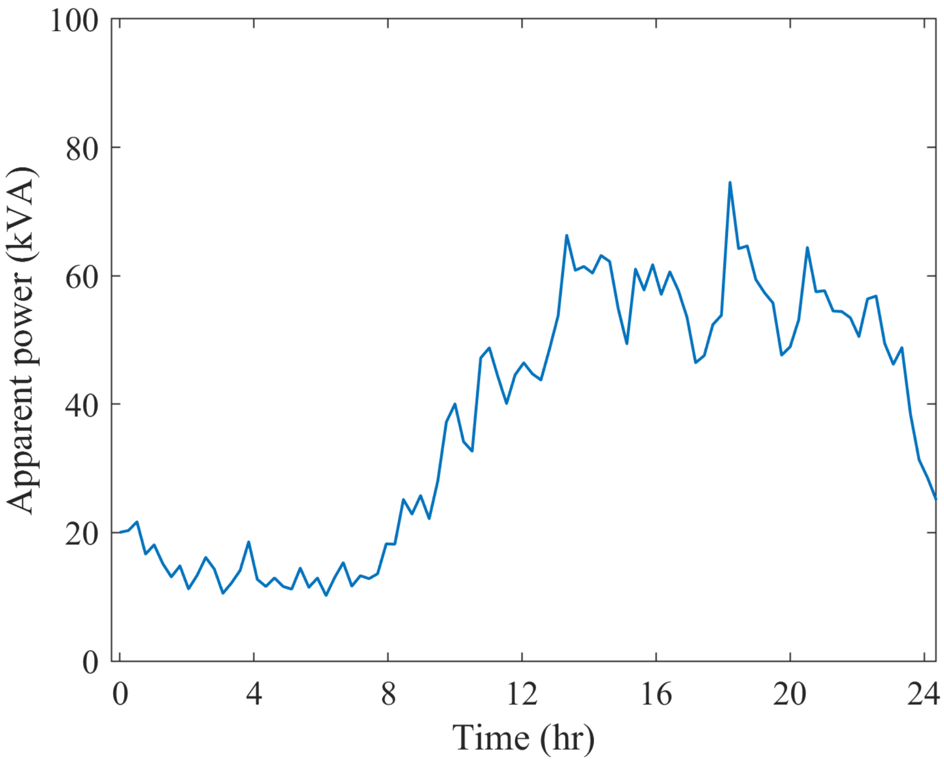
Base load profile with a reasonable on-peak demand of 15-house distribution system

- In this study, we need to choose 15 household load profiles with a reasonable on-peak demand.
- We selected the peak demand 72 kVA that is $\mu+3\sigma$, as the reasonable on-peak demand.
- The probability for peak demand is greater or equal to 72 kVA is 0.1%. In other words, the peak demand of the load profile will be lower than the selected value in 99.9% of the time.
- If the power distribution system can handle this peak demand, the system will be reliable for 99.9% of the time.

Base load profile with a reasonable on-peak demand of 15-house distribution system

- The following figure shows the aggregated load profile of 15 houses with the peak demand of 72 kVA (μ+3σ).



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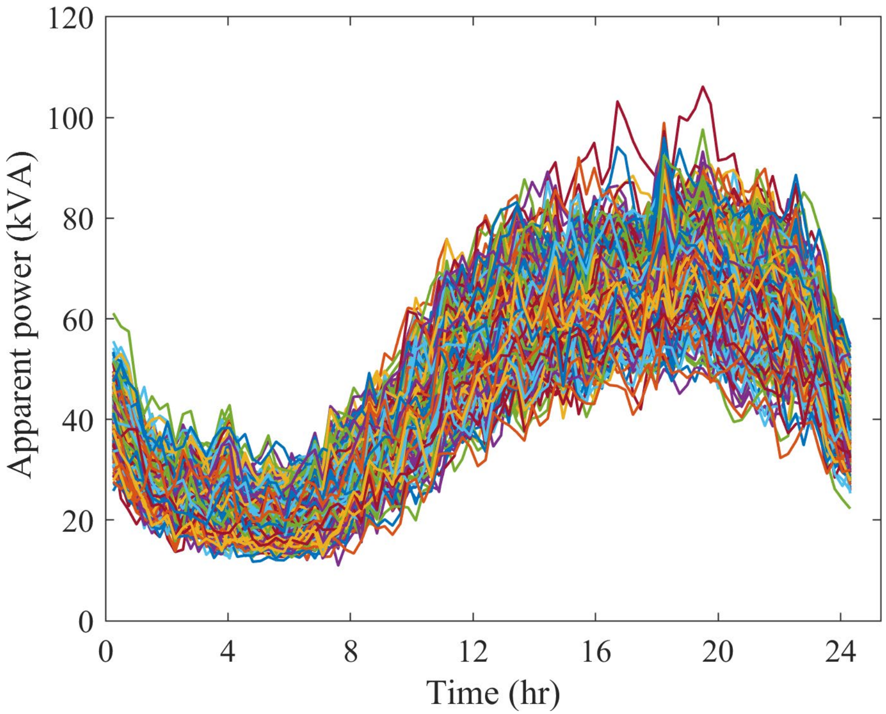
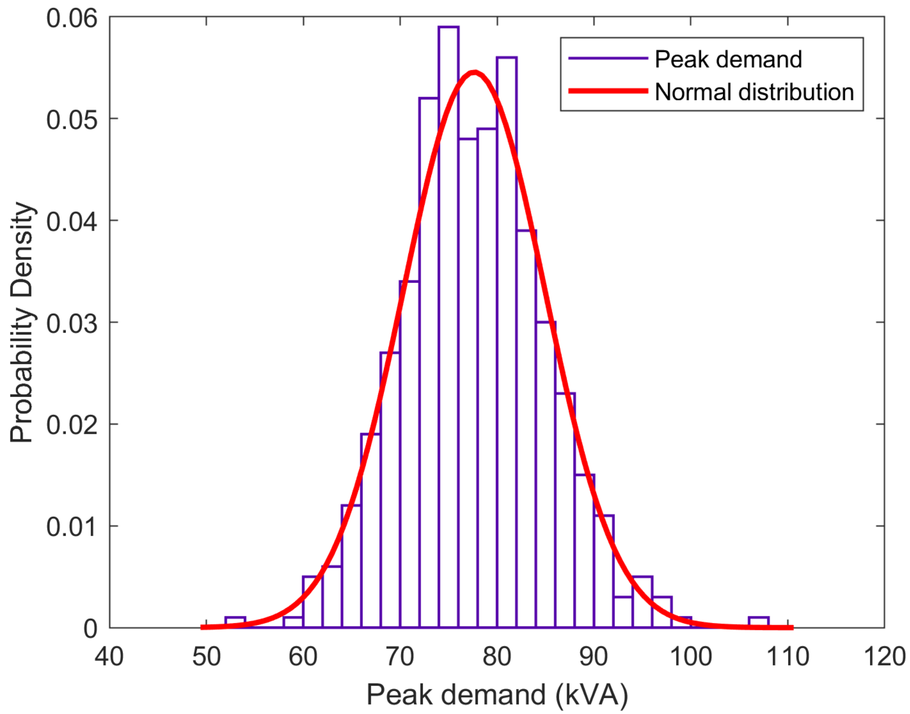
Base load profile selection 22-house distribution system

- To obtain the reasonable worst case for the 22-house distribution system, we randomly selected 22 house base load 500 times from the peak day on July 17th (Sunday).
- Figure below shows the aggregated load profile of 22 houses. There are 500 curves.



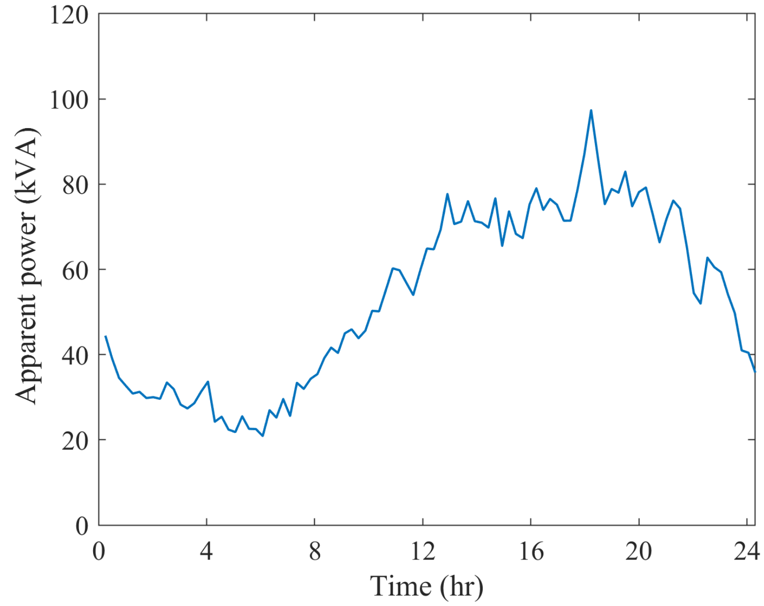
Histogram of the aggregated peak demand of 22-house distribution system

- The figure below shows the histogram of the aggregated peak demand of randomly selected 22 houses 500 times.
- The distribution of the peak demand is normal distribution where the mean distribution (μ) is 77 kVA, and the standard deviation (σ) is 7 kVA



Base load profile with a reasonable on-peak demand of 22-house distribution system

- In this study, we need to choose 22 household load profiles with a reasonable on-peak demand.
- The following figure shows the aggregated load profile of 22 houses with the peak demand of 98 kVA that is $\mu+3\sigma$. The probability for peak demand is greater or equal to 98 kVA is 0.1%.

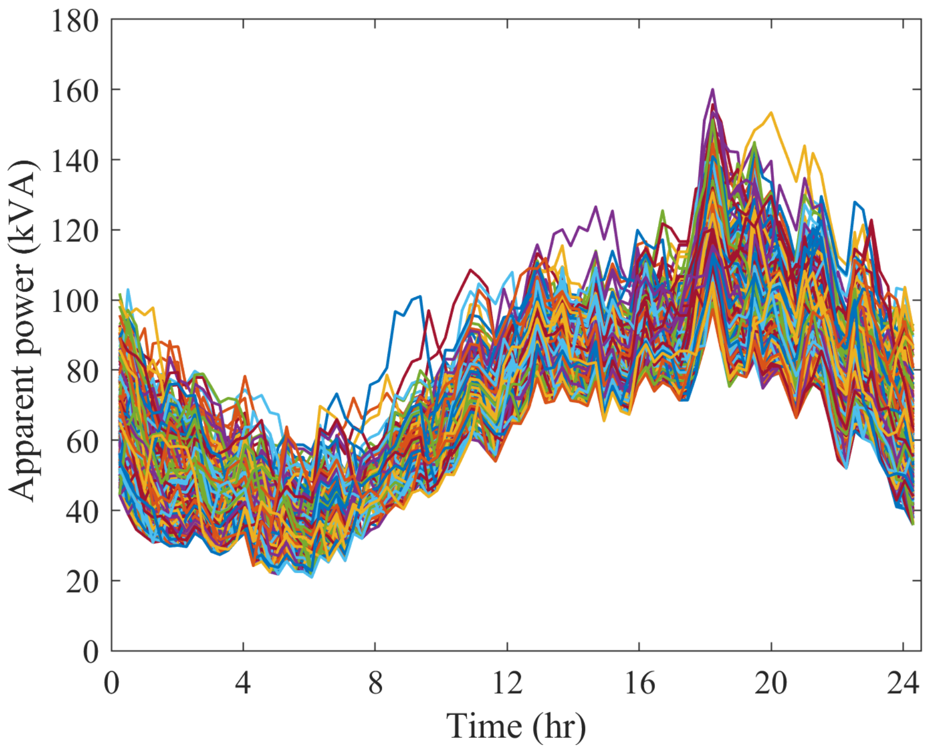


EV charging profile selection

- We want to find a reasonable on-peak demand scenario with base load plus EV charging.
- We have described how to obtain the reasonable worst case in terms of base load for the both distribution systems.
- The following steps describe the process to select EV charging load.
  - Step 1: Run EV model with 1000 EVs to get 1000 EV charging profiles.
  - Step 2: Randomly pair the 1000 EV charging profiles with the selected houses' base load profiles
  - Step 3: Aggregate load profiles (with EV charging) randomly for 500 times.
  - Step 4: Determine the distribution of the peak demand of the 500 aggregated load profiles.
  - Step 5: Find the most reasonable aggregated profile ($\mu+3\sigma$).

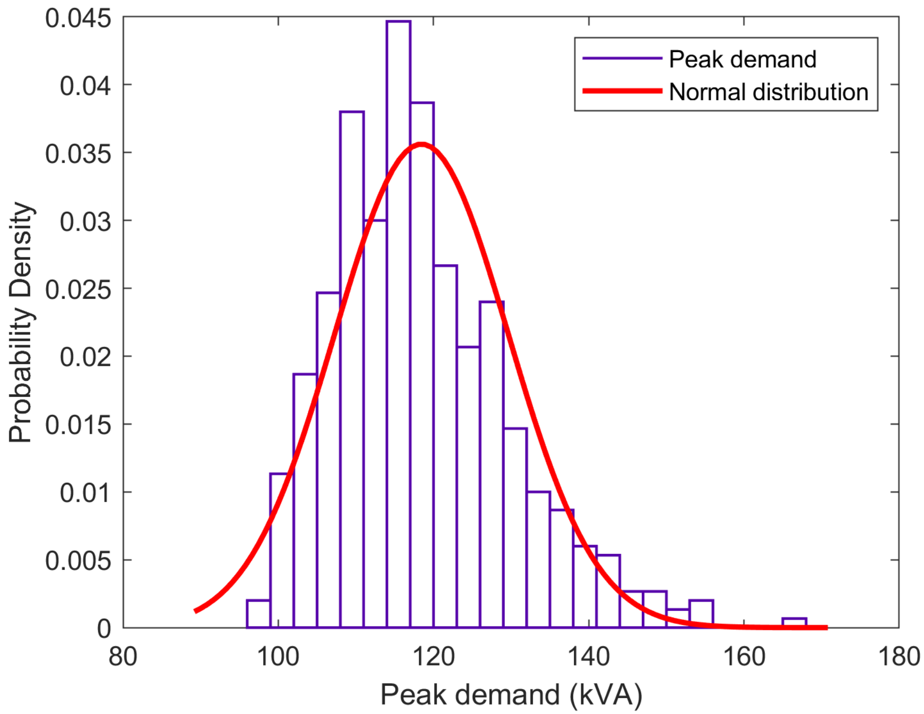
Example: Aggregation of 22 load profiles

- Figure below shows the aggregated load profile of 22 load profiles with EV charging (from Step 3). There are 500 curves.
- Each house has one EV.



Histogram of the aggregated 22 load profiles

- The figure below shows the histogram of the peak demand of the 500 load profiles (with EV charging).
- The distribution of the peak demand is normal distribution where the mean distribution (μ) is 118 kVA, and the standard deviation (σ) is 11 kVA



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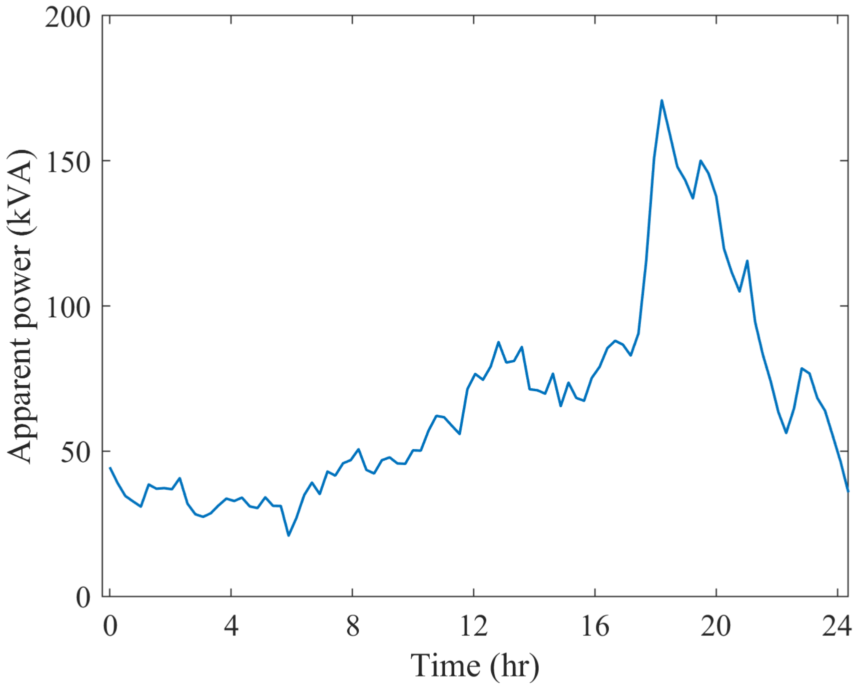
Load profile with a reasonable on-peak demand

- We select the peak demand of 151 kVA (μ+3σ) as the reasonable worst case.
- Among the 500 load profiles, the lowest peak demand that is greater than 151 kVA was 170.8 kVA. Therefore, the load profile with 170.8 kVA (shown below) was selected.



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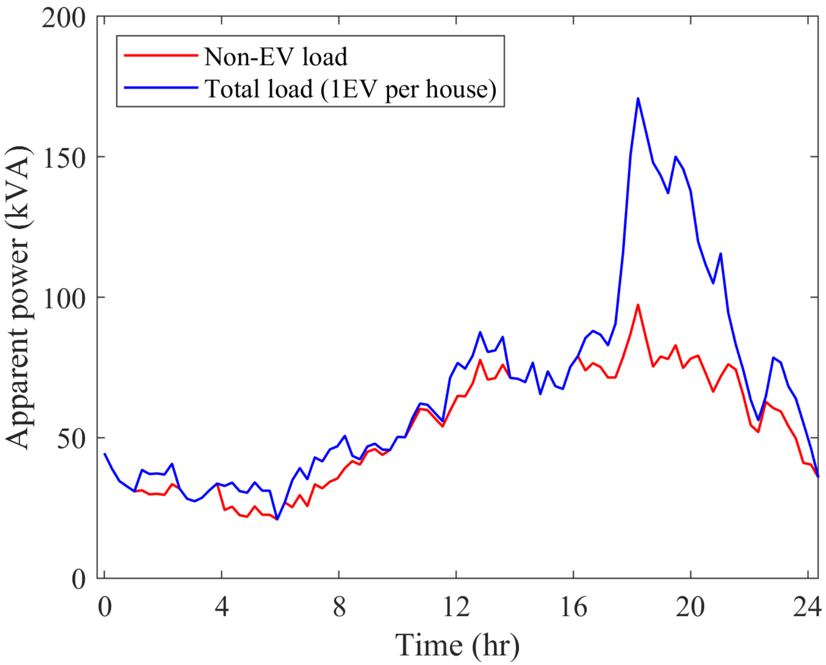
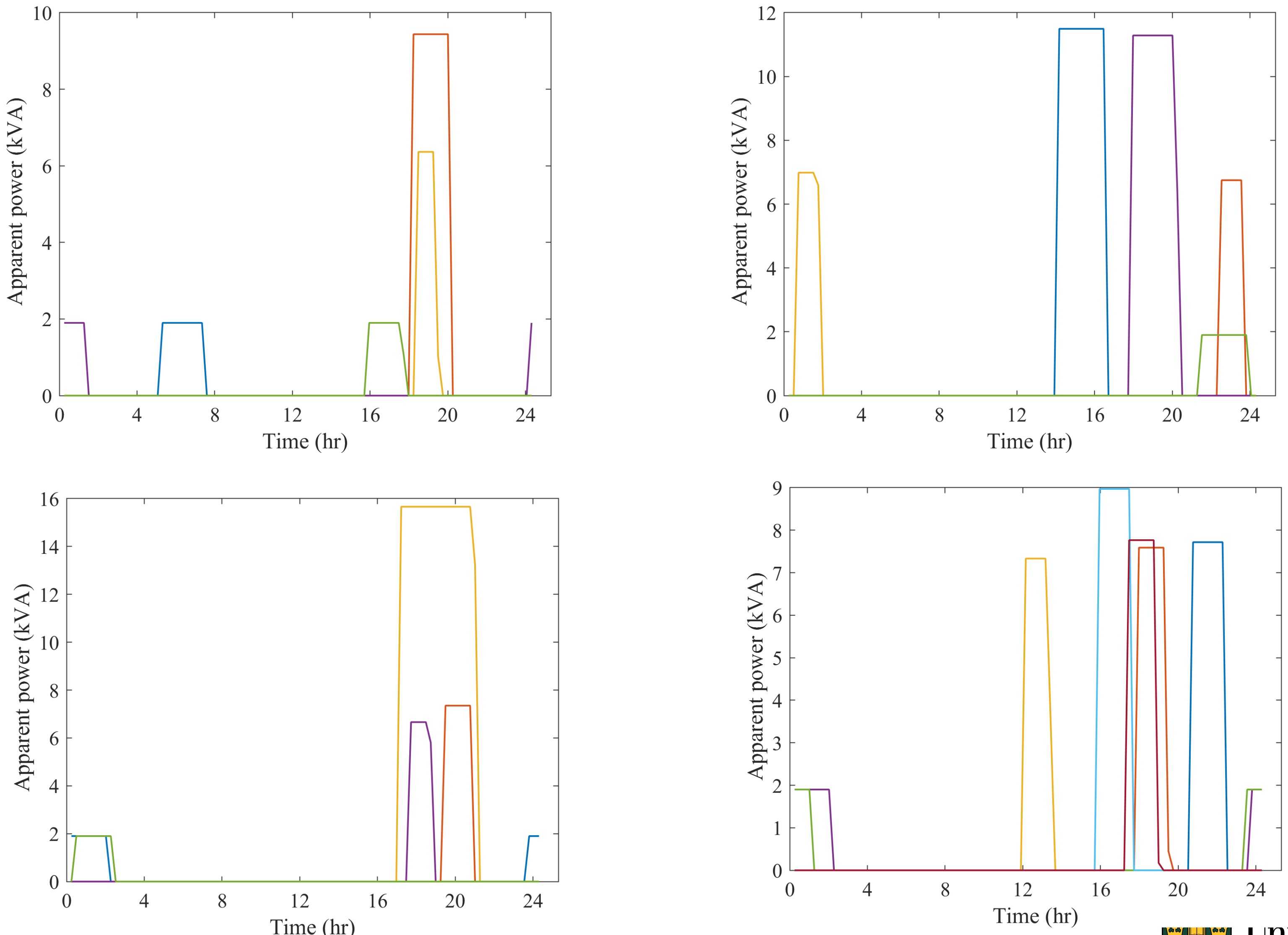
Load profile with a reasonable on-peak demand

- In this study, we need to choose 22 household load profiles with 1 EV per house under a reasonable on-peak demand.
- We select the load profile with a peak demand more than $\mu+3\sigma$.
- The following figure shows the aggregated load profile of 22 houses and 22 EVs with the peak demand of 170.8 kVA.



The selected 22 individual EV charging profiles

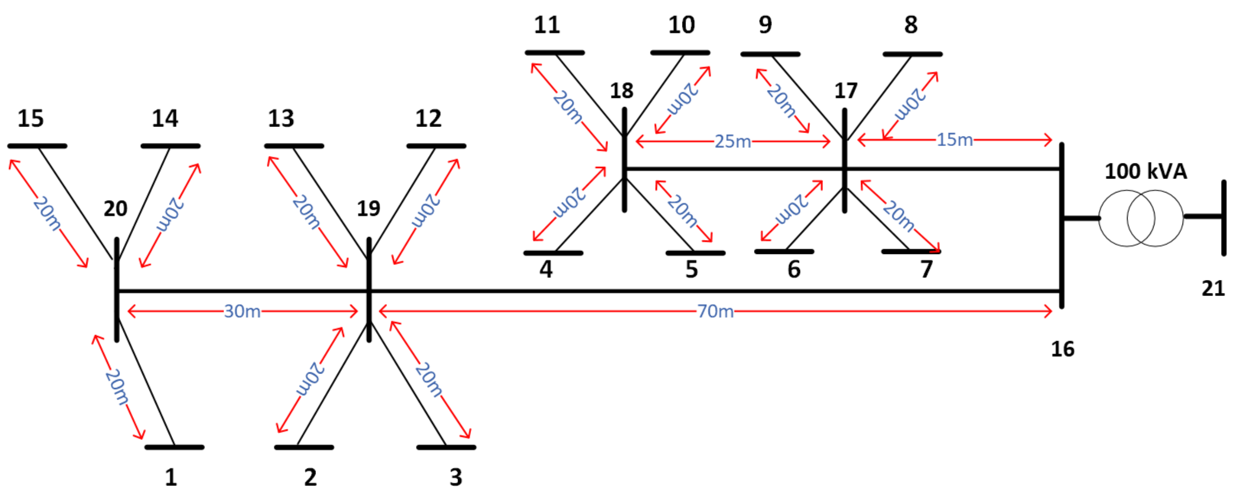


Evaluation of 15-house distribution system

- To test the impact of integrating EVs on the distribution network, we conducted 4 scenarios as follows:
  - Scenario #1: under **on-peak** demand with 15 EVs
  - Scenario #2: under **on-peak** demand with 30 EVs
  - Scenario #3: under **on-peak** demand with 15 Electric Trucks
  - Scenario #4: under **on-peak** demand with 15 Electric Trucks and 15 EVs.
- We assume the Electric Trucks consumes double amount of energy comparing with the EVs. In addition, all Electric Trucks charge at level-2.

15-house distribution system model

- The figure below shows a single line diagram of a 15-house distribution system.
- The transformer rating is 100 kVA.
- Buses from 1 to 15 represent load buses.
- Cables between the transformer and pedestals are 500 MCM AL.
- While the cables between pedestals and houses are 1/0 AL.
- The transformer impedance value is R=0.004211 Ω, X=0.009474 Ω.



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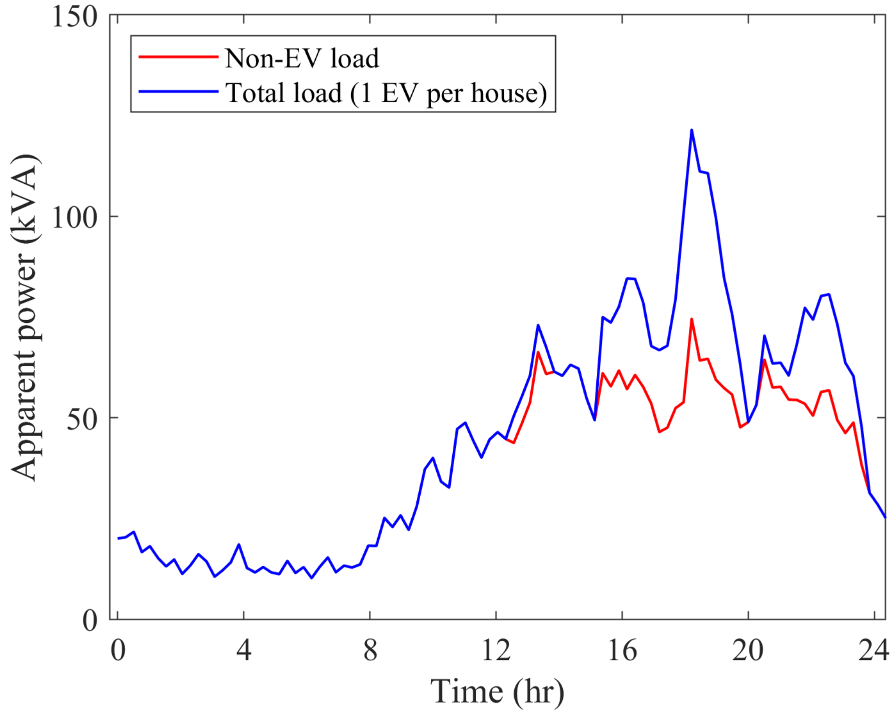
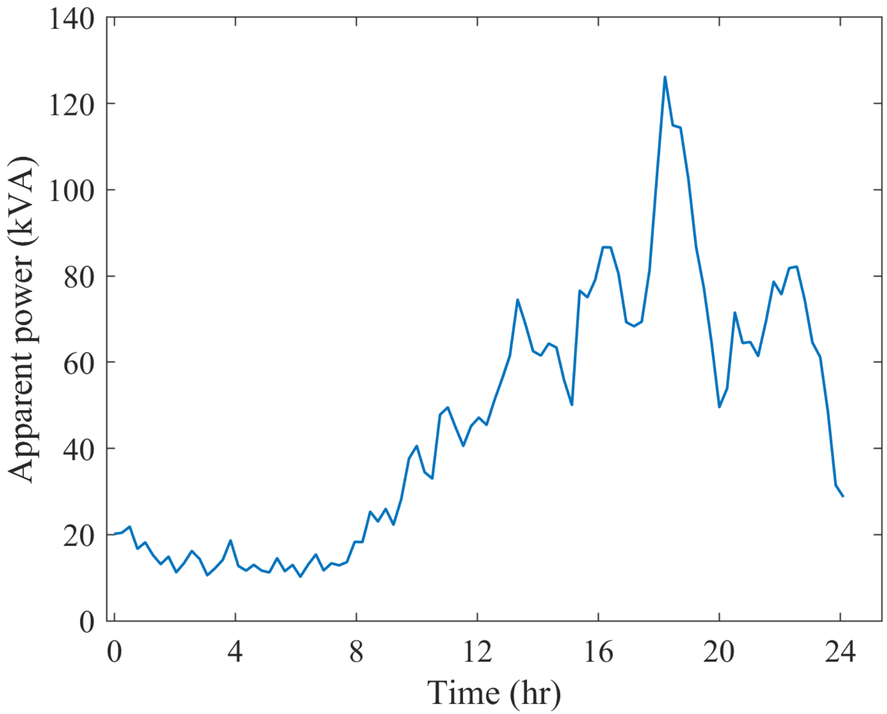
Scenario #1: Base load with 15 EVs

- In this scenario, we assumed each household has 1 EV.
- The figure below shows the non-EV load profile, and the total households load with 15 EVs.



Scenario #1: Transformer loading results

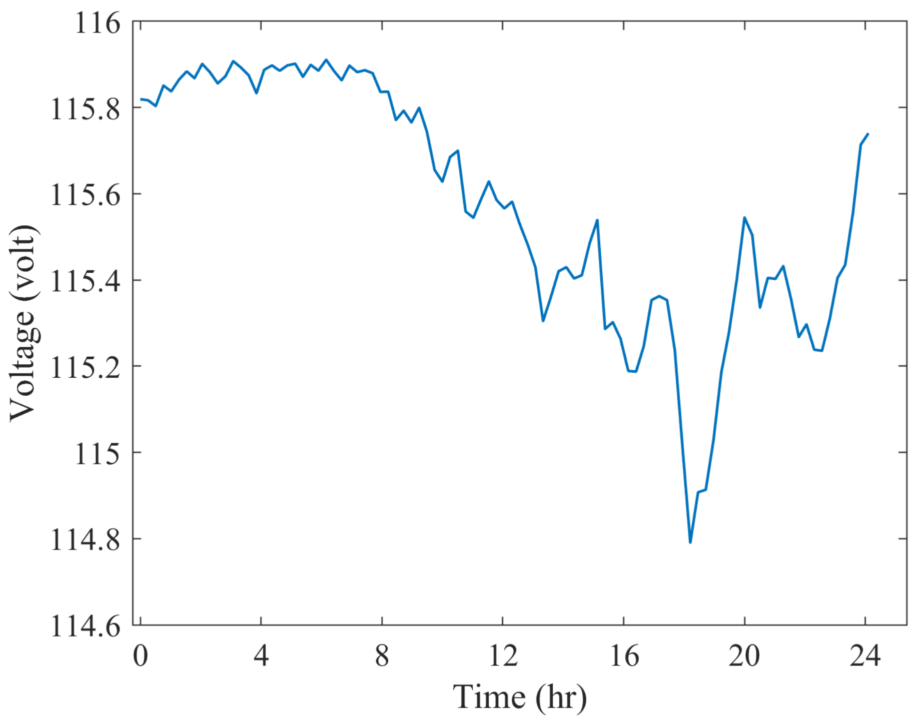
- The figure below shows the aggregated load profile of 15-house and 15 EVs.
- The maximum aggregated load is 121.5 kVA, which is 121.5% of the transformer rating.



On-peak demand with 15 EVs.

Scenario #1: Voltage values

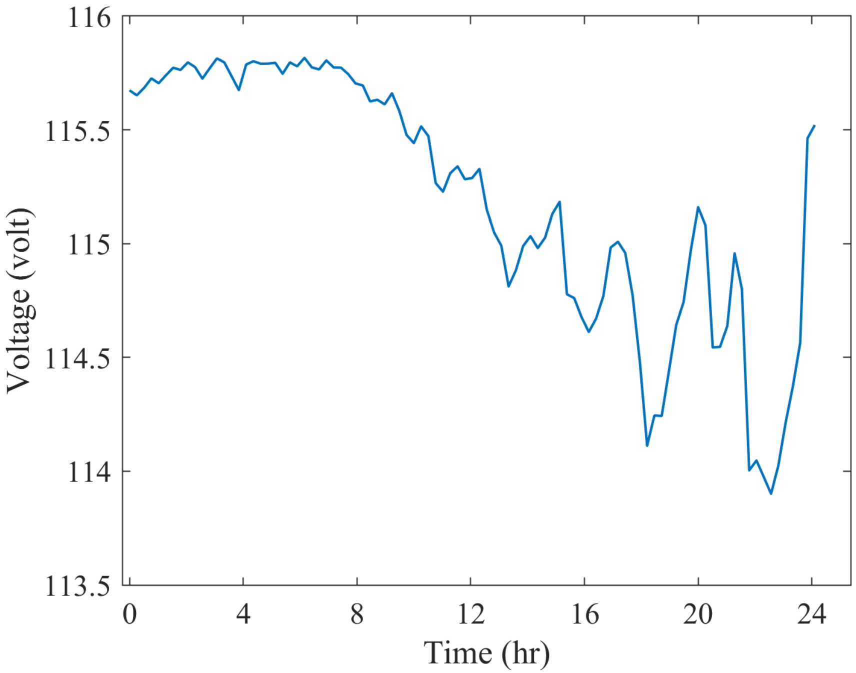
- The figure below shows the voltages at the secondary side of the transformer.



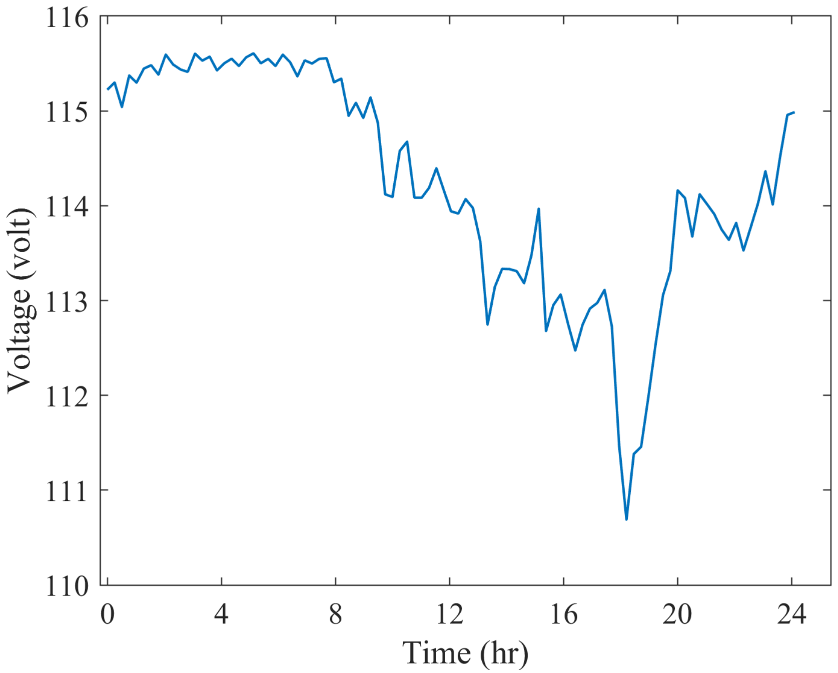
Voltage at the secondary of the transformer

Scenario #1: Voltage values

- The figures below show the voltages at bus 9 which is located right after the transformer and bus 1 which is located at the end of the line.



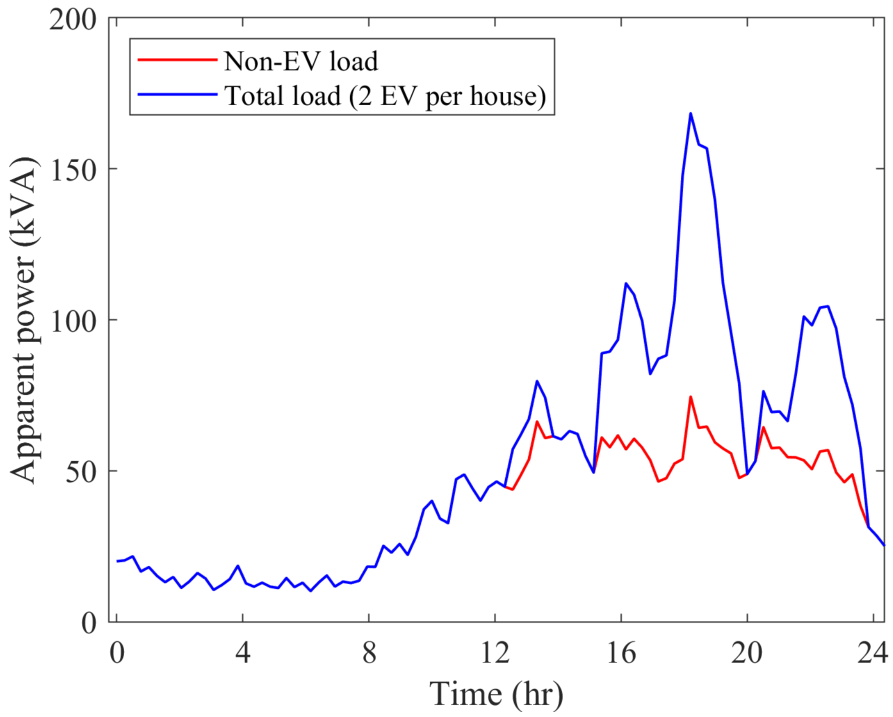
(a) Voltage at bus number 9



(b) Voltage at bus number 1

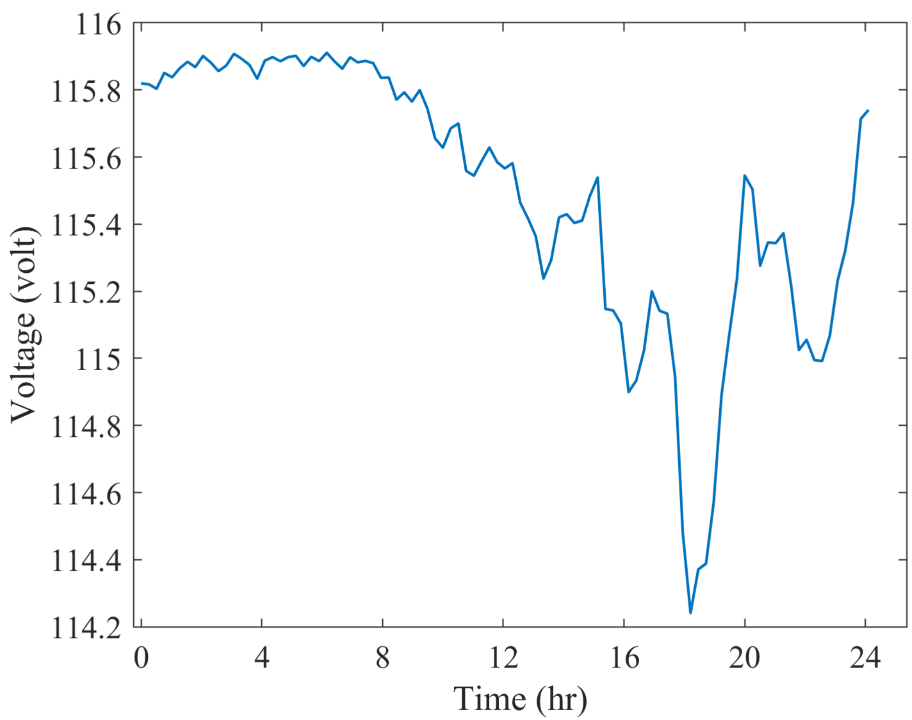
Scenario #2: Base load with 30 EVs

- In this scenario, we assumed each household has 2 EVs.
- The figure below shows the non-EV load profile, and the total households load with 30 EVs.
- We used the EV charging profiles from Scenario #1, but with 30 EVs.



Scenario #2: Voltage values

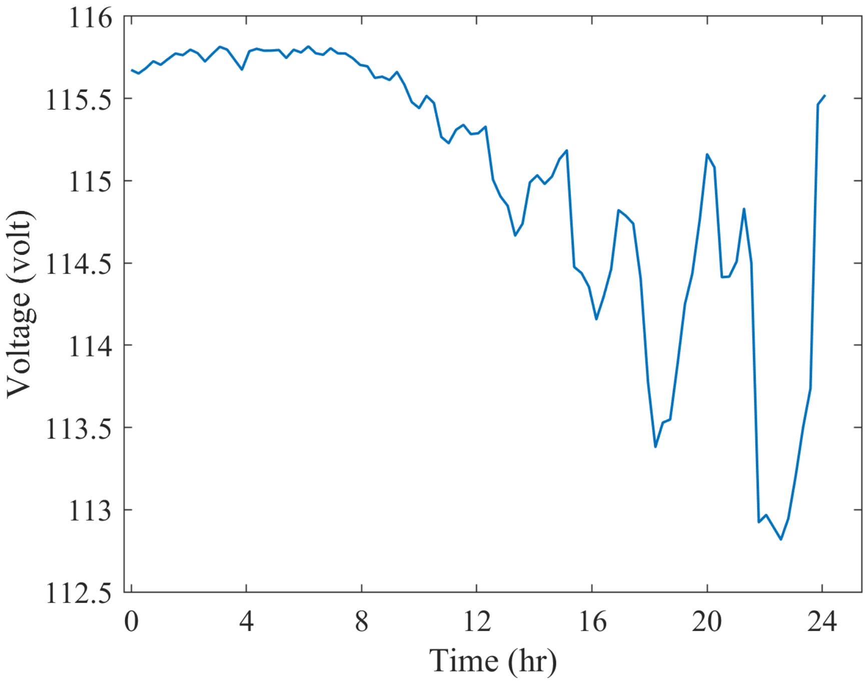
- The figures below show the voltages at the secondary side of the transformer.



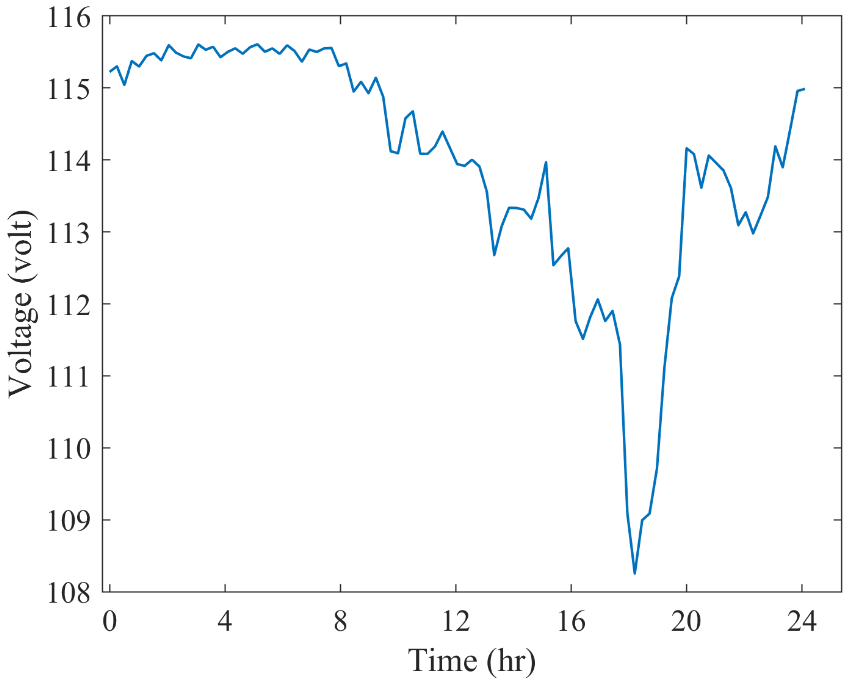
Voltage at the secondary of the transformer

Scenario #2: Voltage values

- The figures below show the voltages at bus 9 which is located right after the transformer and bus 1 which is located at the end of the line.



(a) Voltage at bus number 9



(b) Voltage at bus number 1

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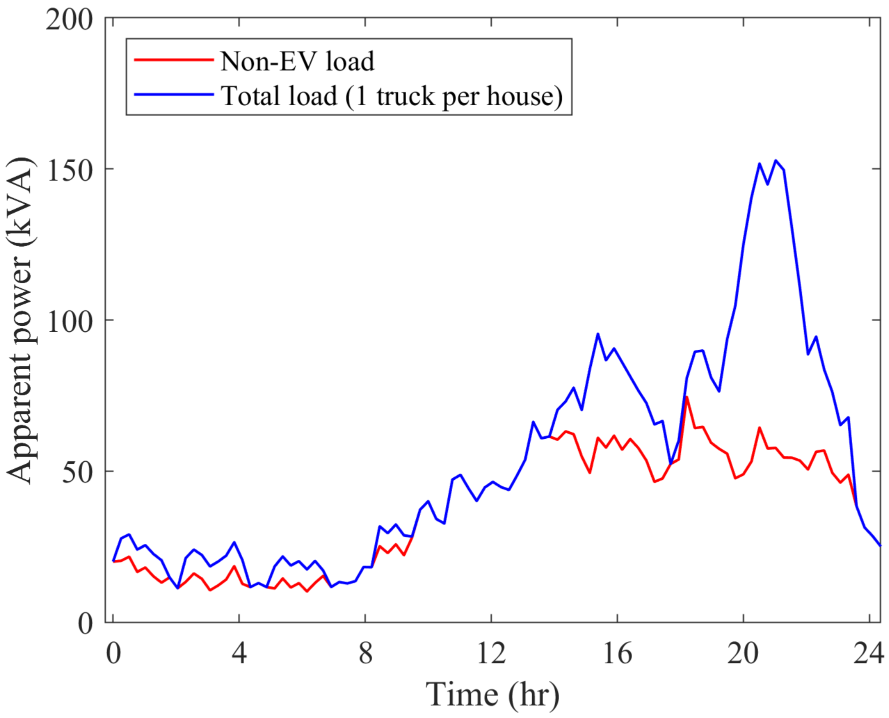
Scenario #3: Base load with 15 Electric Trucks

- In this scenario, we assumed each household has 1 Electric Truck.
- The figure below shows the non-EV load profile, and the total households load with 15 Electric Truck.



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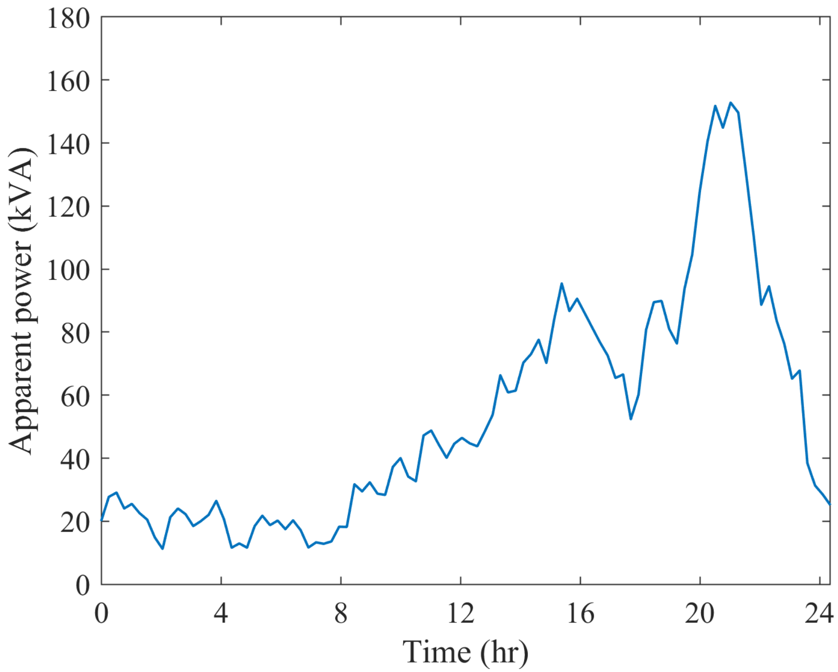
Scenario #3: Transformer loading results

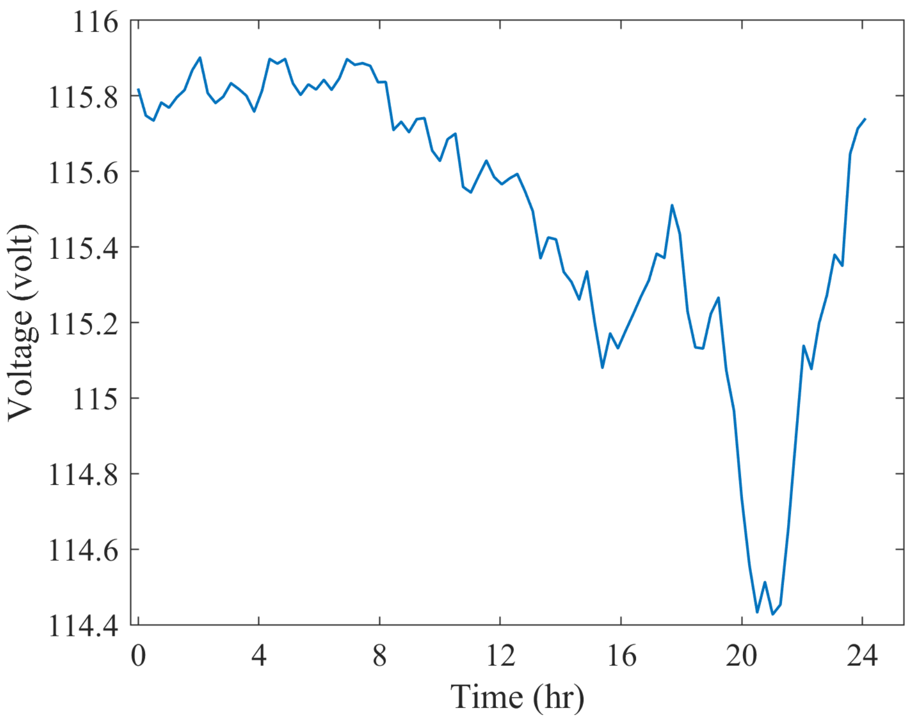
- The figure below shows the aggregated load profile of 15-house and 15 Electric Truck.
- The maximum aggregated load is 152.8 kVA, which is 152.8 % of the transformer rating.



On-peak demand with 30 EVs.

Scenario #3: Voltage values

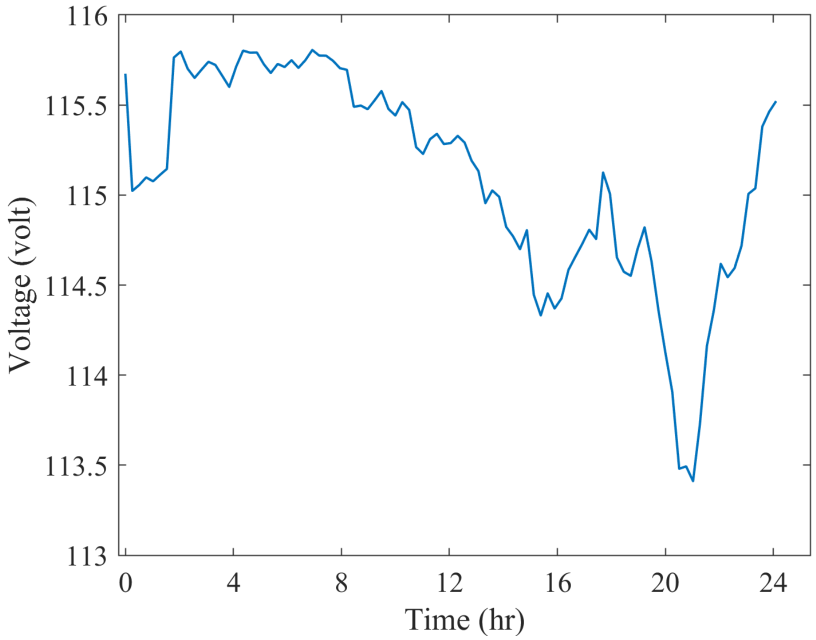
- The figures below show the voltages at the secondary side of the transformer.



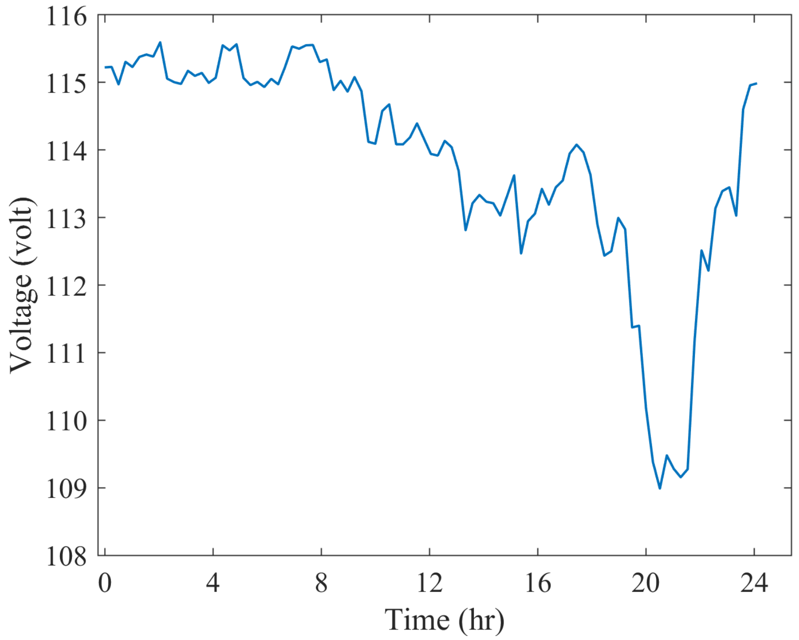
Voltage at the secondary of the transformer

Scenario #3: Voltage values

- The figures below show the voltages at bus 9 which is located right after the transformer and bus 1 which is located at the end of the line.



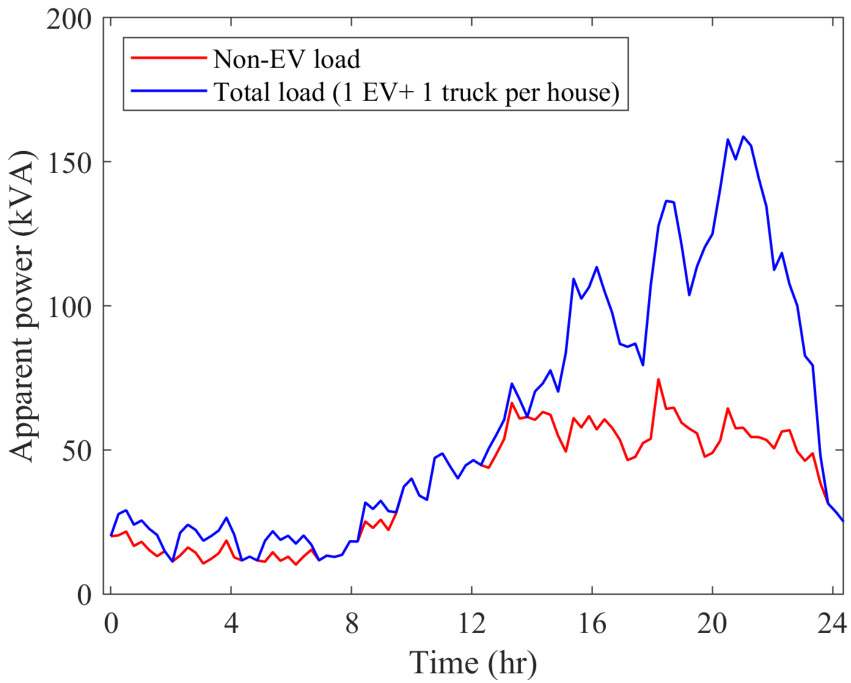
(a) Voltage at bus number 9



(b) Voltage at bus number 1

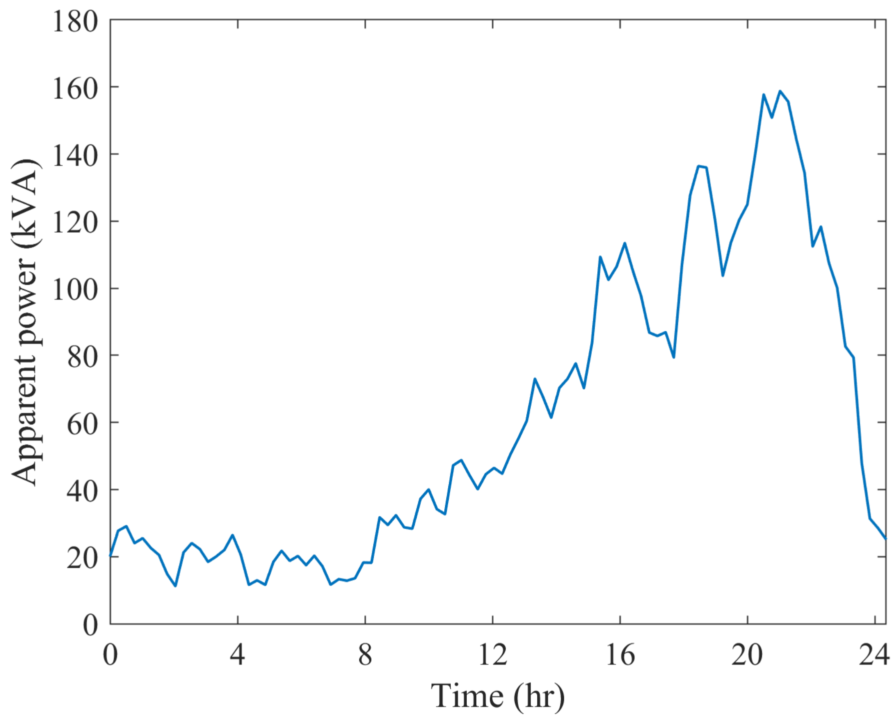
Scenario #4: Base load with 15 EVs and 15 Electric Trucks

- In this scenario, we assumed that each house has 1 EV and 1 Electric Truck.
- The figure below shows the non-EV load profile, and the total households load with 15 Electric Truck.
- We selected 15 EV charging profiles from Scenario #1 and 15 Electric Truck charging profiles from Scenario #3.



Scenario #4: Transformer loading results

- The figure below shows the aggregated load profile of 15-house and 30 large and regular EVs.
- The maximum aggregated load is158.8 kVA, which is 158.8% of the transformer rating.



On-peak demand with 30 EVs.

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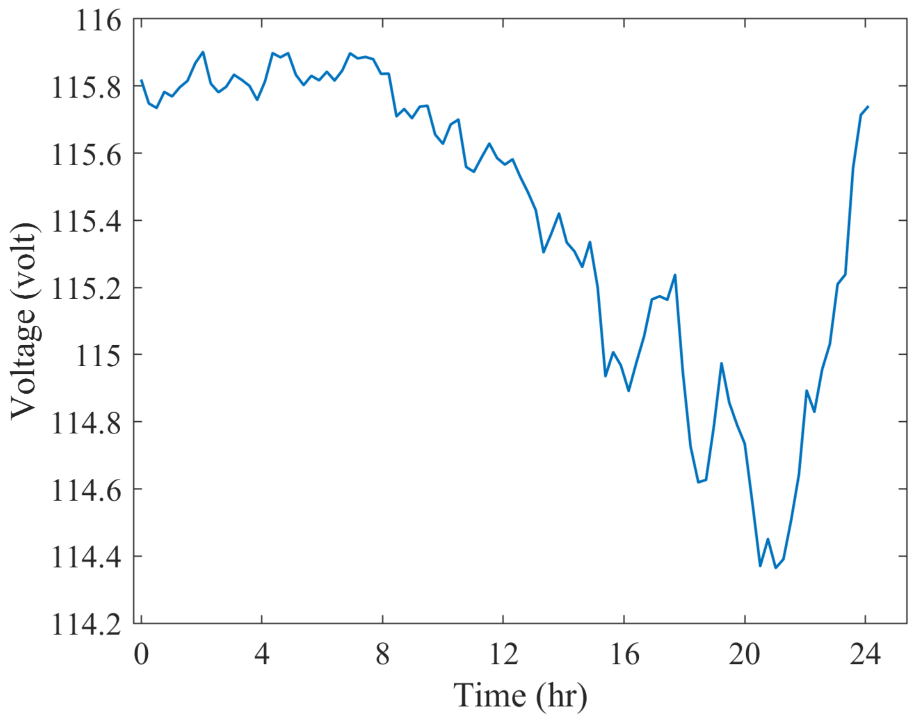
Scenario #4: Voltage values

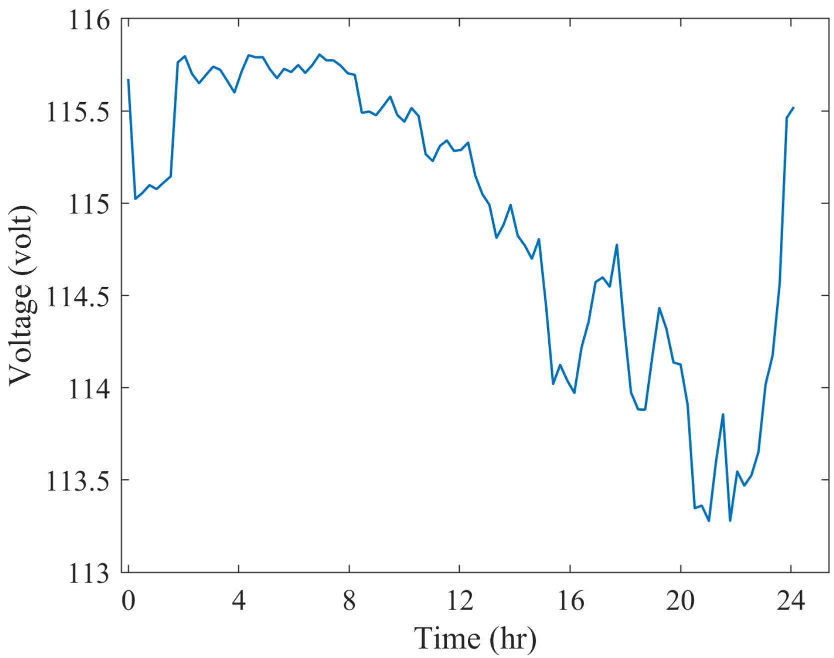
- The figures below show the voltages at the secondary side of the transformer.



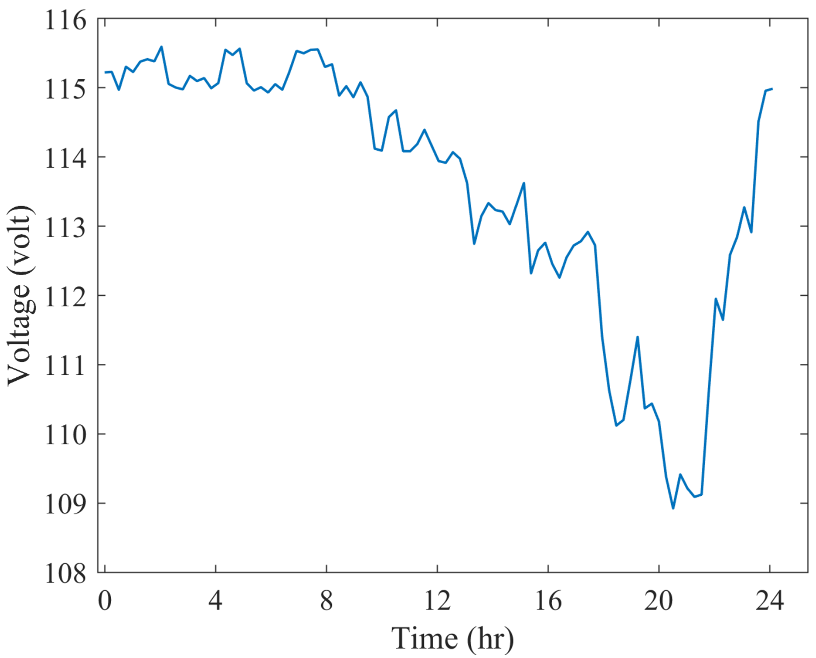
Voltage at the secondary of the transformer

Scenario #4: Voltage values

- The figures below show the voltages at bus 9 which is located right after the transformer and bus 1 which is located at the end of the line.

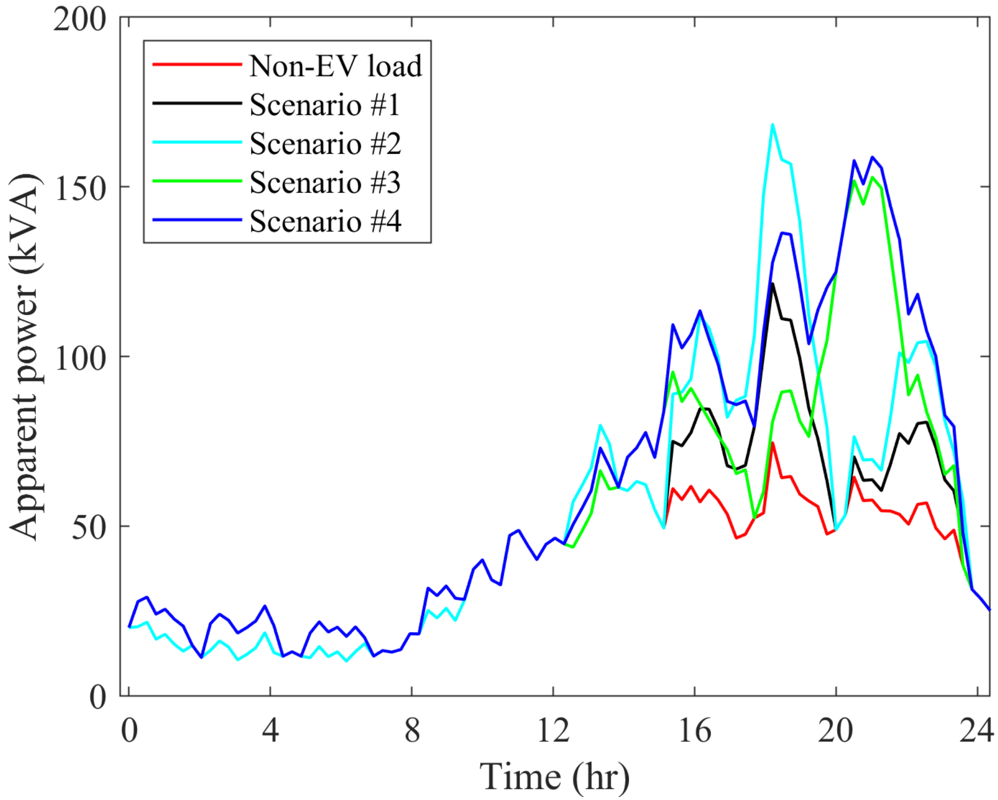


(a) Voltage at bus number 9



(b) Voltage at bus number 1

Comparison of the load profiles



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Summary

- The table below shows the transformer loading and voltage maximum values at each scenario. Note: the results are obtained from the two power distribution system samples, which do not represent the overall distribution system in Saskatchewan.

Scenarios	The highest transformer loading (kVA)	The lowest voltage (volt)		
		Bus 16 (Transformer secondary)	Bus 9	Bus 1
On peak load only	74.5	115.4	114.6	112.9
Scenario #1	121.5	114.8	113.9	110.7
Scenario #2	168.4	114.2	112.8	108.3
Scenario #3	152.8	114.4	113.4	109
Scenario #4	158.8	114.4	113.3	108.9

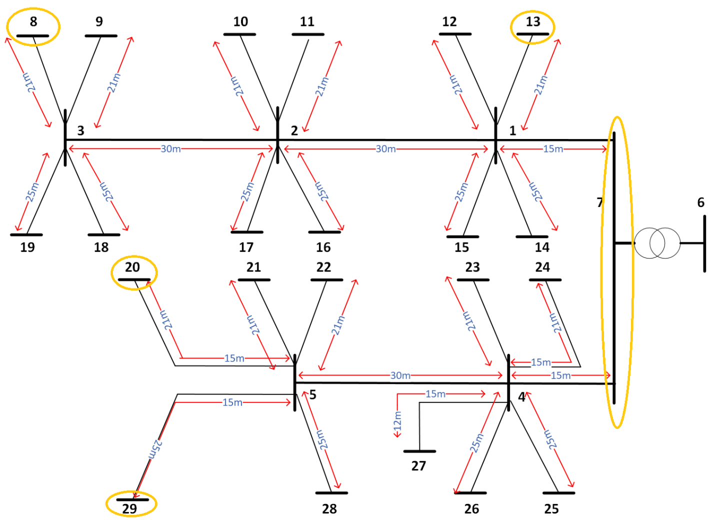
Red = voltage or transformer capacity violation, Orange= may or may not be a violation

Evaluation of 22-house distribution system

- To test the impact of integrating EVs on the distribution network, we conducted two scenarios as follows:
  - Scenario #5: under **on-peak** demand with 22 EVs
  - Scenario #6: under **on-peak** demand with 44 EVs

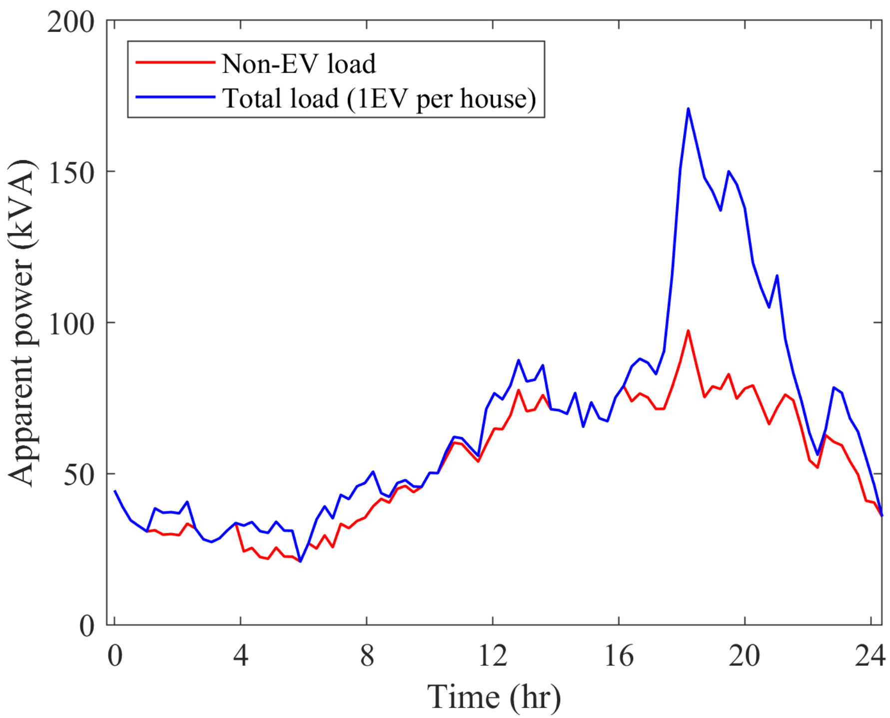
22-house distribution system model

- The figure below shows a single line diagram of a 22-house distribution system.
- The transformer rating is 100 kVA.
- Buses from 8 to 29 represent load buses.
- Cables between the transformer and pedestals are 500 MCM AL.
- While the cables between pedestals and houses are 1/0 AL.
- The transformer impedance value is R=0.004211 Ω, X=0.009474 Ω.



Scenario #5: Base load with 22 EVs

- In this scenario, we assumed each household has 1 EVs.
- The figure below shows the non-EV load profile, and the total households load with 22 EVs.



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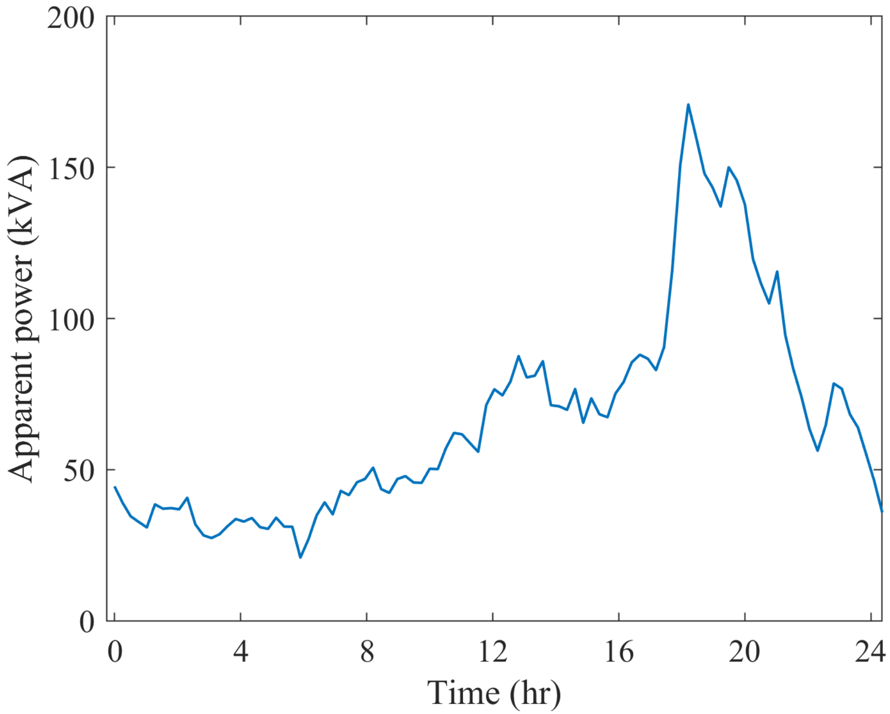
Scenario #5: Transformer loading

- The figure below shows the aggregated load profile of 22-house and 22 EVs.
- The maximum aggregated load is 170 kVA, which is 170% of the transformer rating.



Scenario #5: Voltage values

- The figures below show the voltages at the secondary side of the transformer.

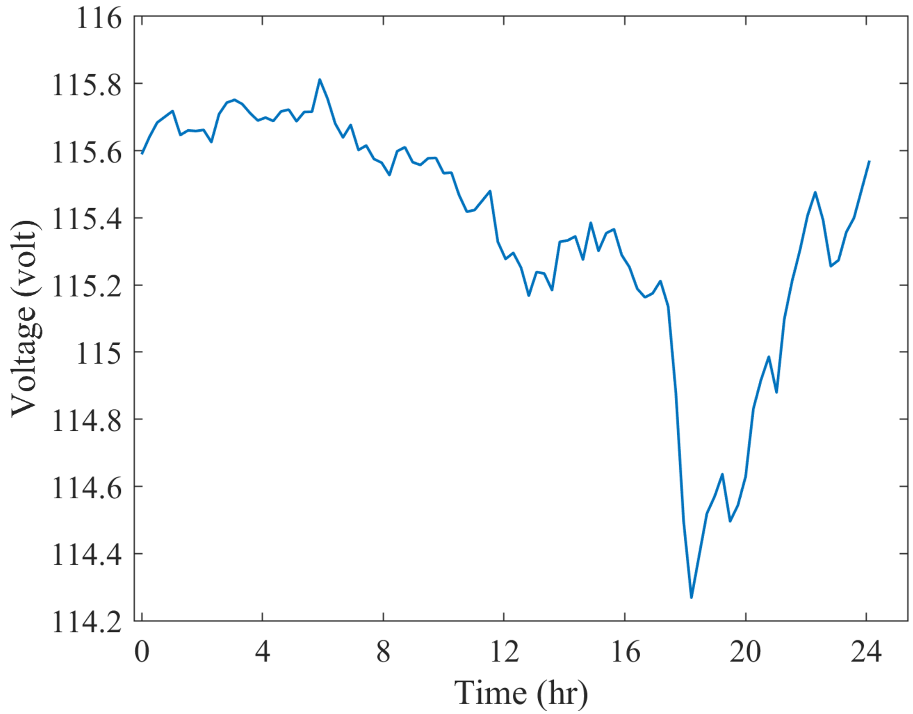
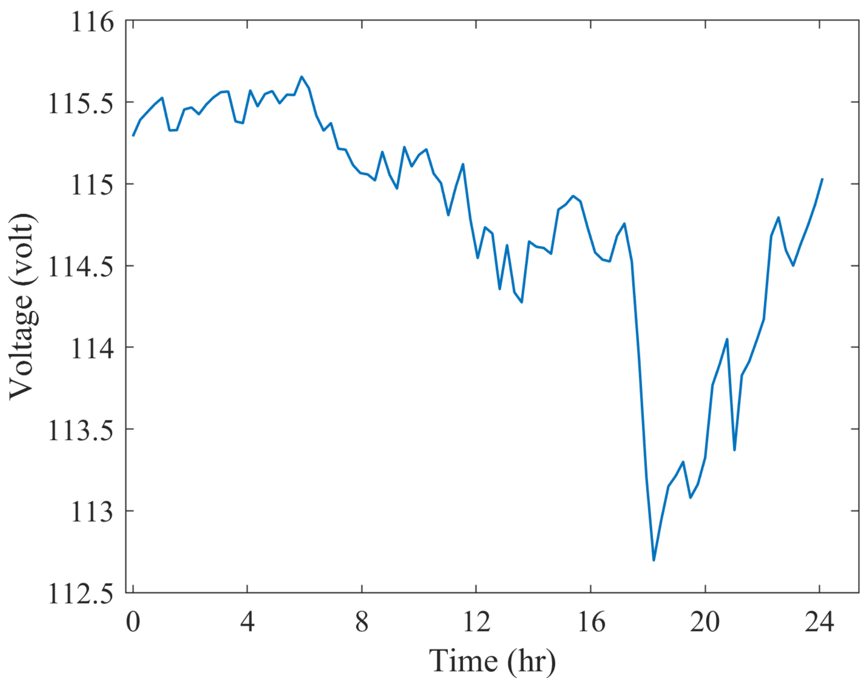


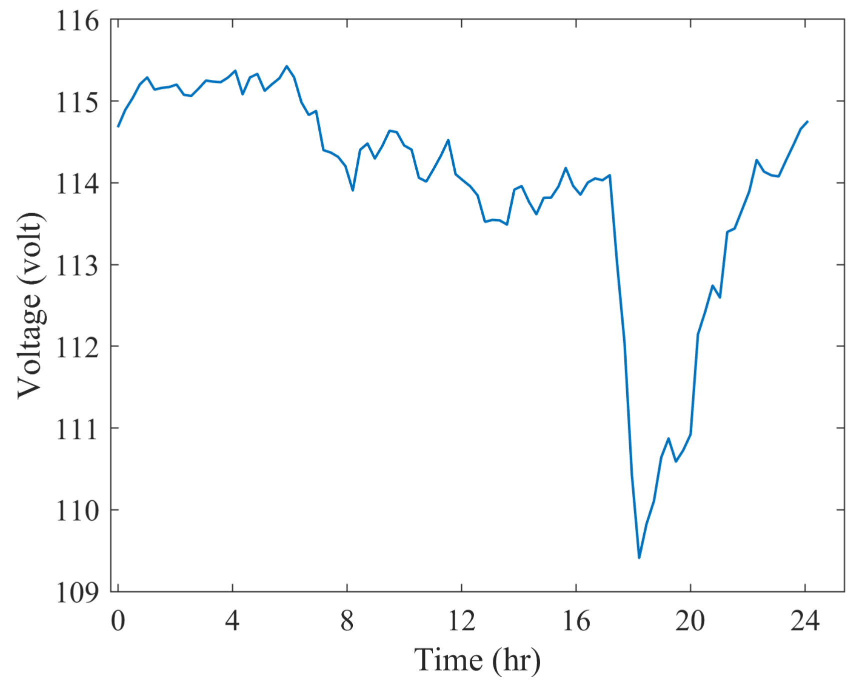
Fig. Voltage at the secondary of the transformer

Scenario #5: Voltage values

- The figures below show the voltages at bus 13 which is located right after the transformer, and bus 8 which is located at the end of the line 1.



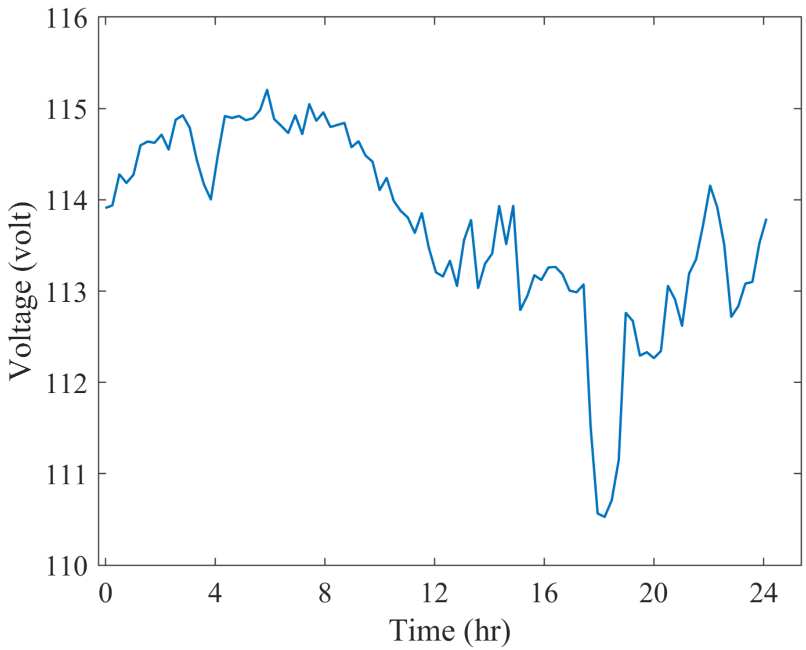
(a) Voltage at bus number 13



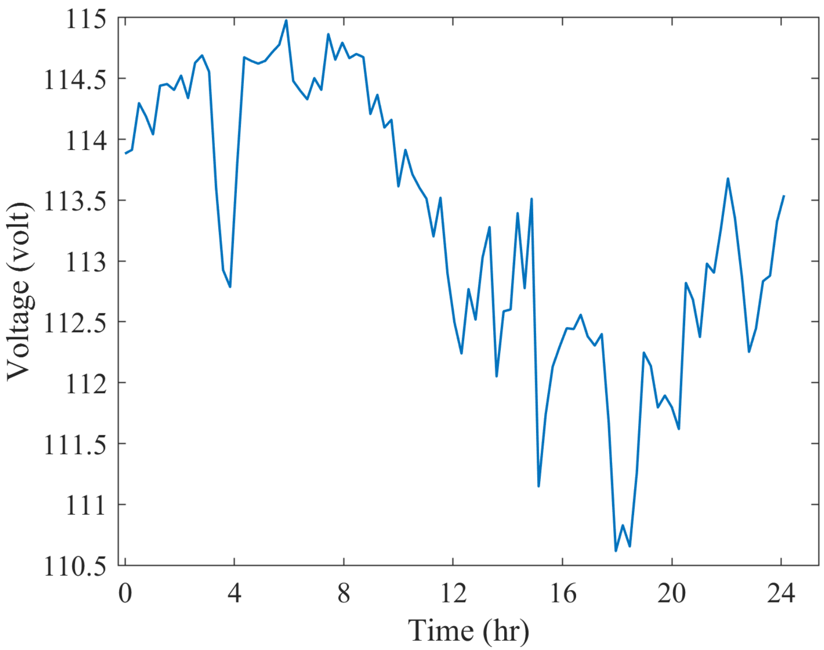
(b) Voltage at bus number 8

Scenario #5: Voltage values

- The figures below show the voltages at buses 20 and 29 which are located at the end of the line 2.



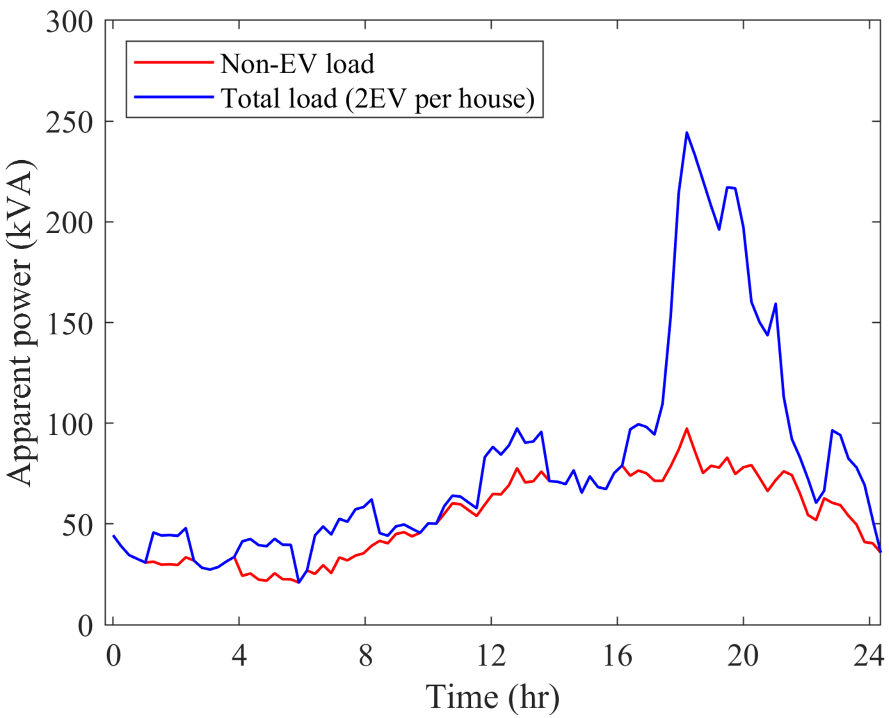
(a) Voltage at bus number 20



(b) Voltage at bus number 29

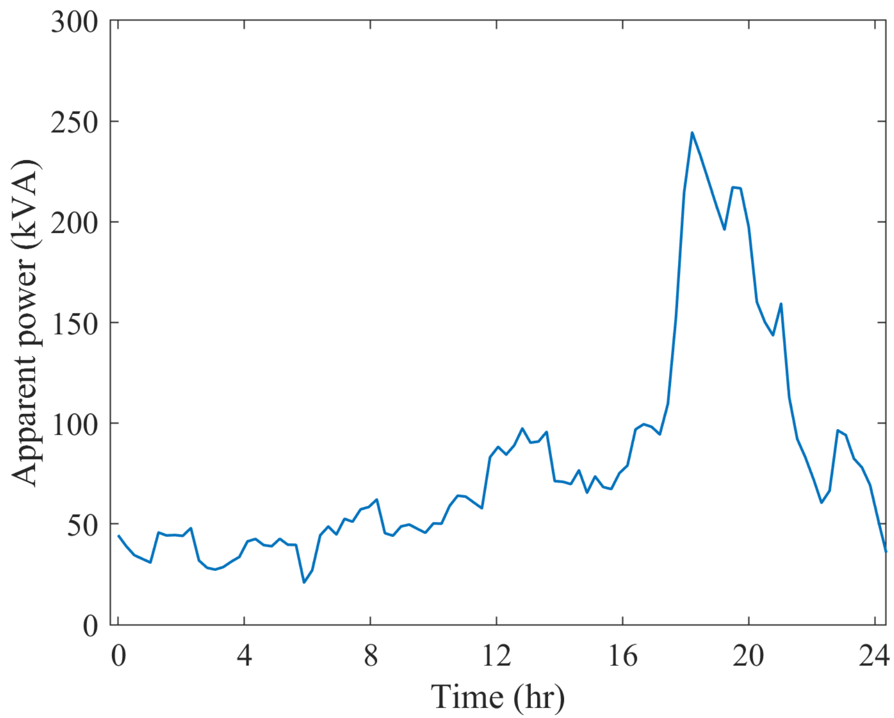
Scenario #6: Base load with 44 EVs

- In this scenario, we assumed each household has 2 EVs.
- The figure below shows the non-EV load profile, and the total households load with 44 EVs.
- We used the EV charging profiles from Scenario #5, but with 44 EVs.



Scenario #6: Transformer loading

- The figure below shows the aggregated load profile of 22-house and 44 EVs.
- The maximum aggregated load is 244 kVA, which is 244% of the transformer rating.



Scenario #6: Voltage values

- The figures below show the voltages at the secondary side of the transformer.

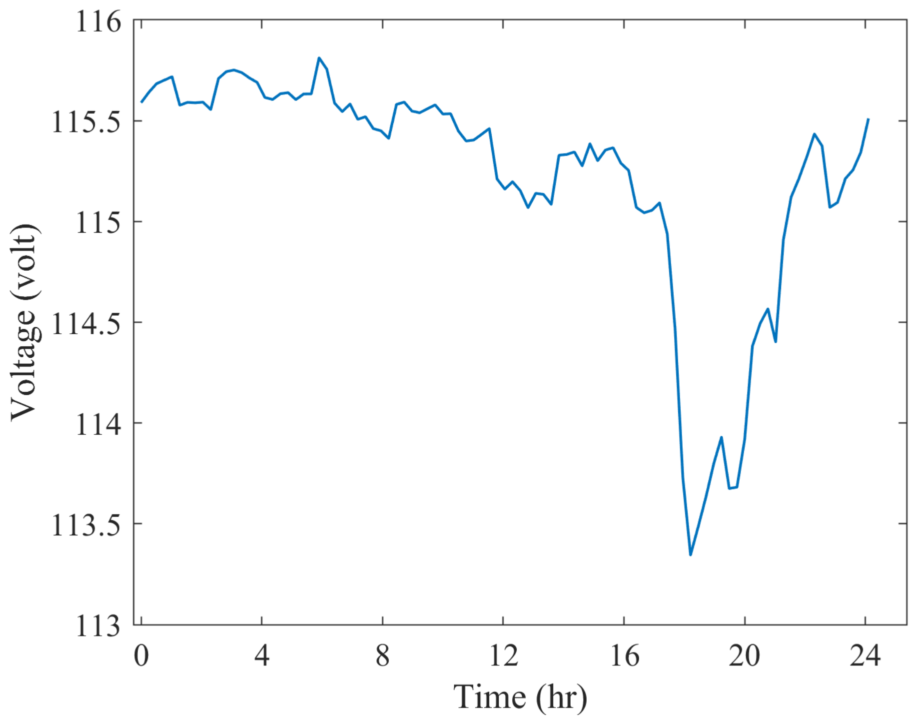
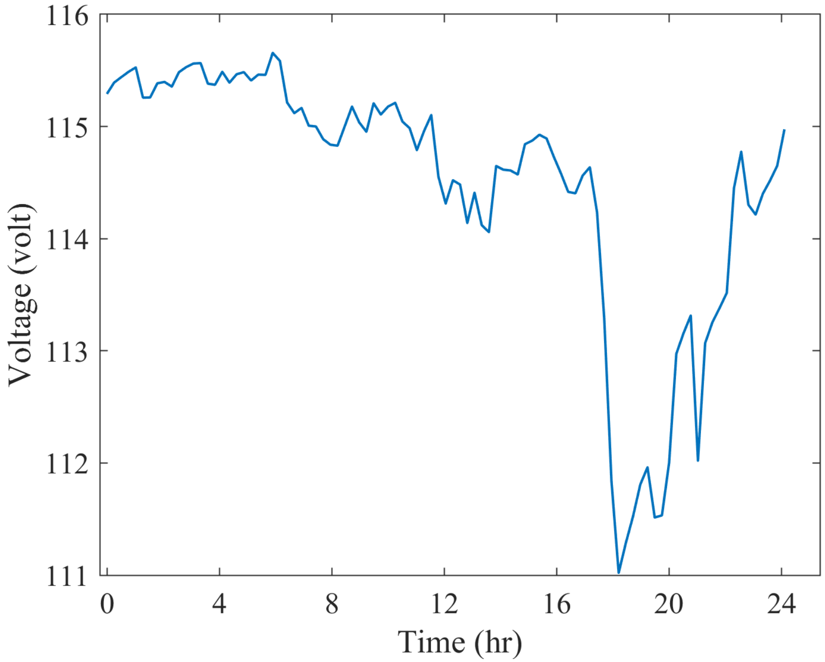


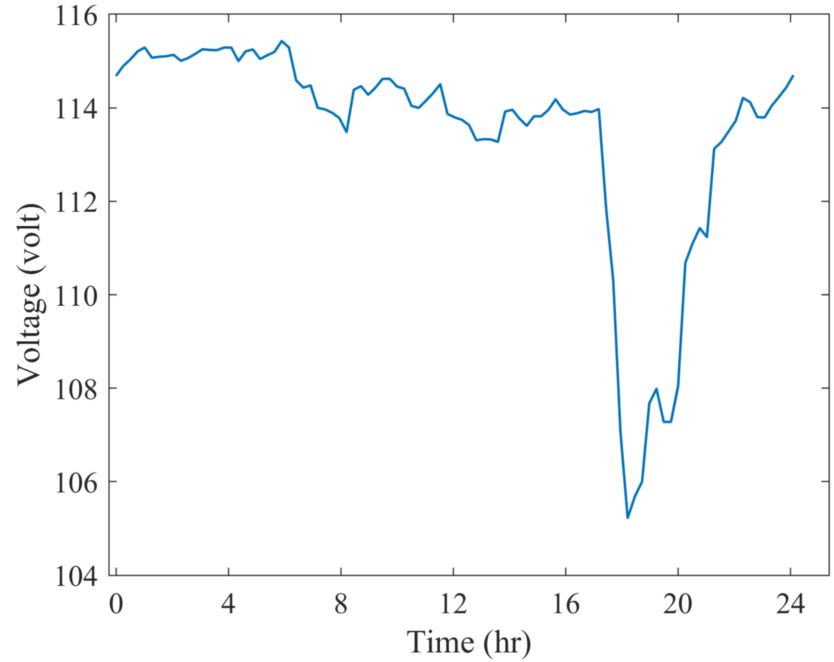
Fig. Voltage at the secondary of the transformer

Scenario #6: Voltage values

- The figures below show the voltages at bus 13 which is located right after the transformer and bus 8 which is located at the end of the line 1.



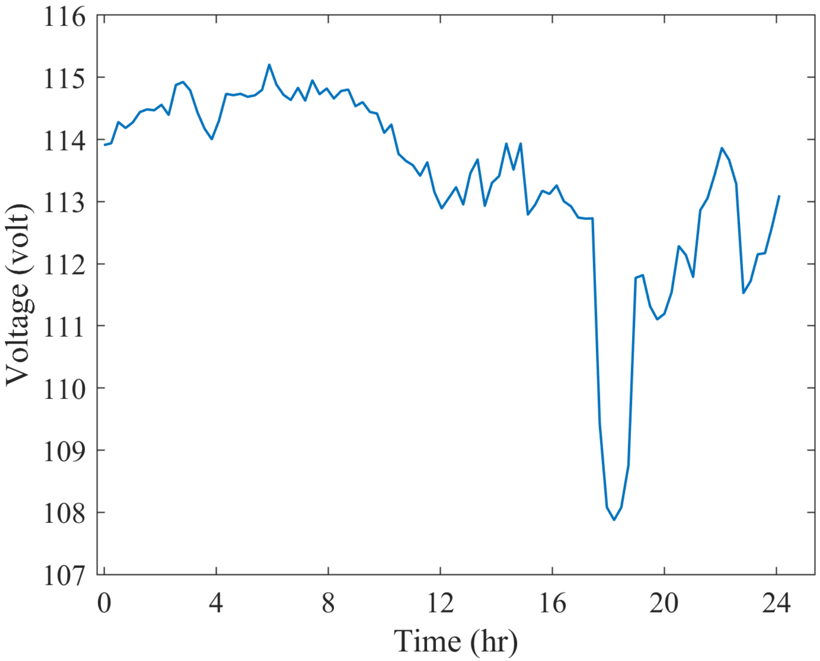
(a) Voltage at bus number 13



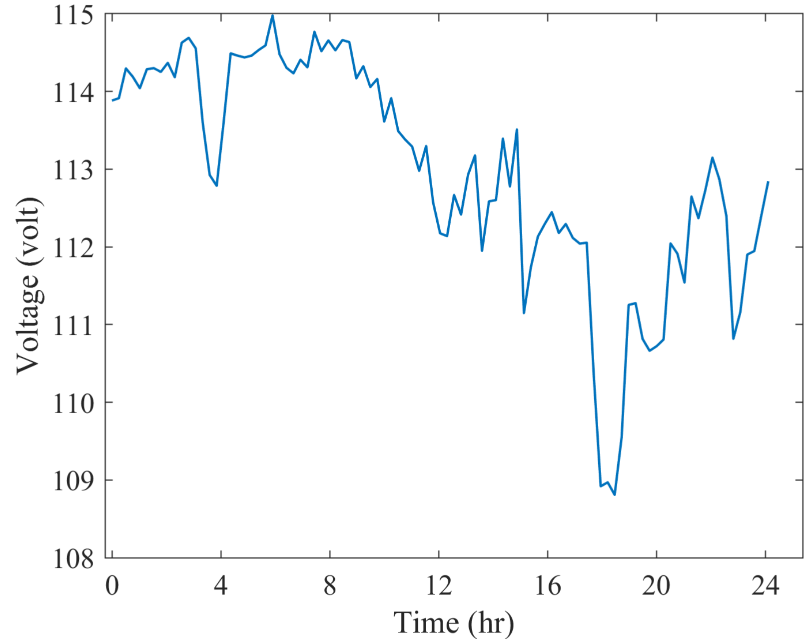
(b) Voltage at bus number 8

Scenario #6: Voltage values

- The figures below show the voltages at buses 20 and 29 which are located at the end of the line 2.



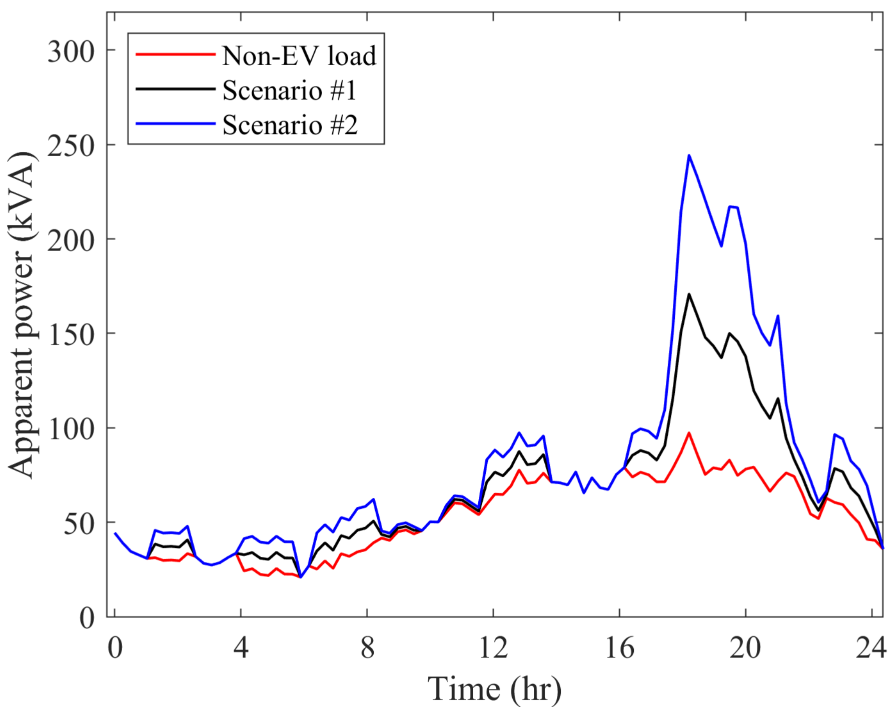
(a) Voltage at bus number 20



(b) Voltage at bus number 29

Comparison of the load profiles

- The red curve represents the non-EV load profile.
- The black curve represents the total household load with 1 EV per house.
- The blue curve represents the total household load with 2 EVs per house.



Summary

- The table below shows the transformer loading and voltage maximum values at each scenario. Note: the results are obtained from the two power distribution system samples, which do not represent the overall distribution system in Saskatchewan.

Scenarios	The highest transformer loading (kVA)	The lowest voltage (volt)				
		Bus 7 (Transformer secondary)	Bus 13	Bus 8	Bus 20	Bus 29
On peak load only	97.3	115	114.2	113.2	112.8	111.2
Scenario #5	170.8	114.3	112.7	109.4	110.6	110.6
Scenario #6	244.3	113.3	111	105.2	107.9	108.8

Red = voltage or transformer capacity violation, Orange= may or may not be a violation

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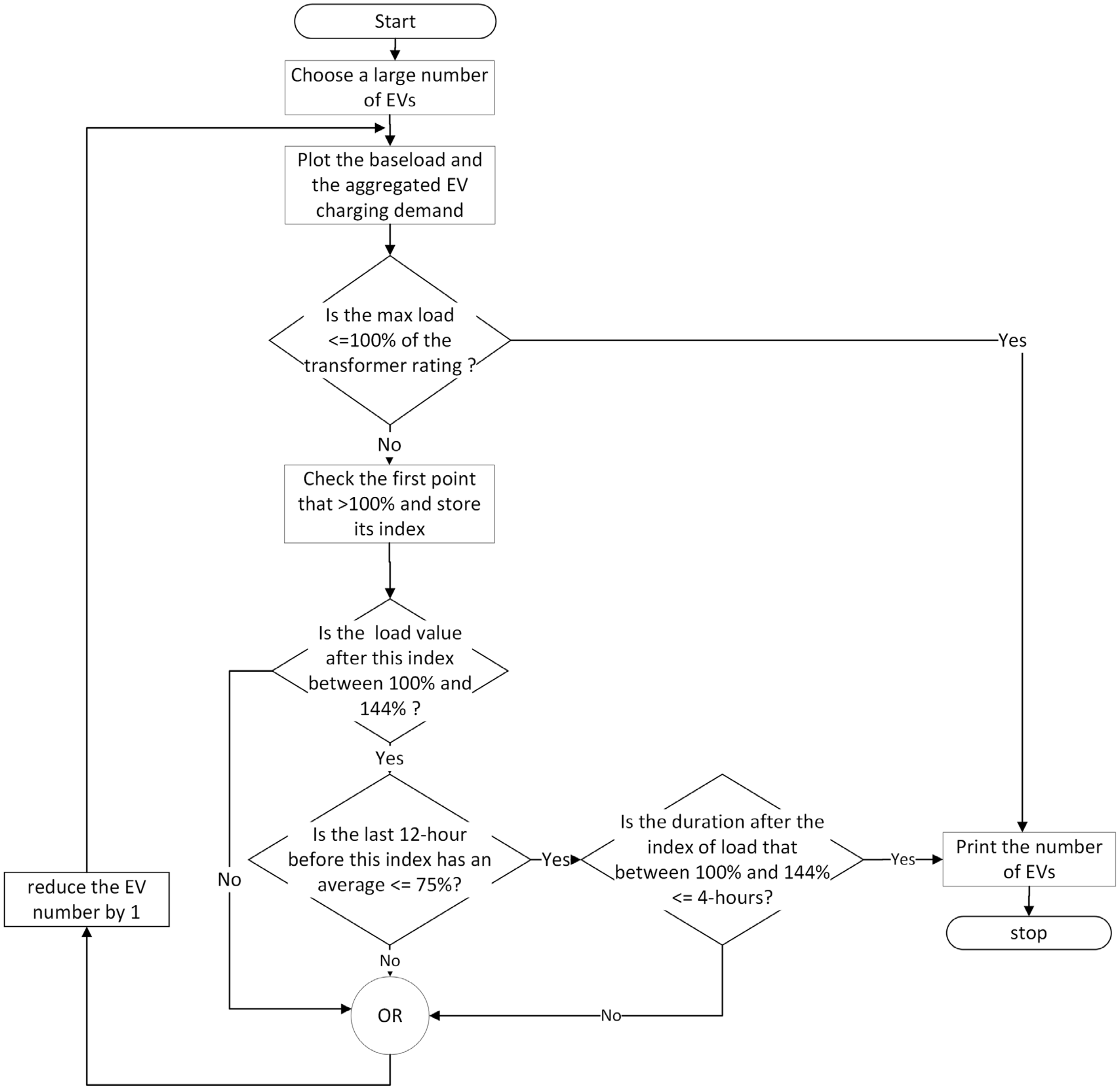
Identifying the critical number of EVs for the distribution network.

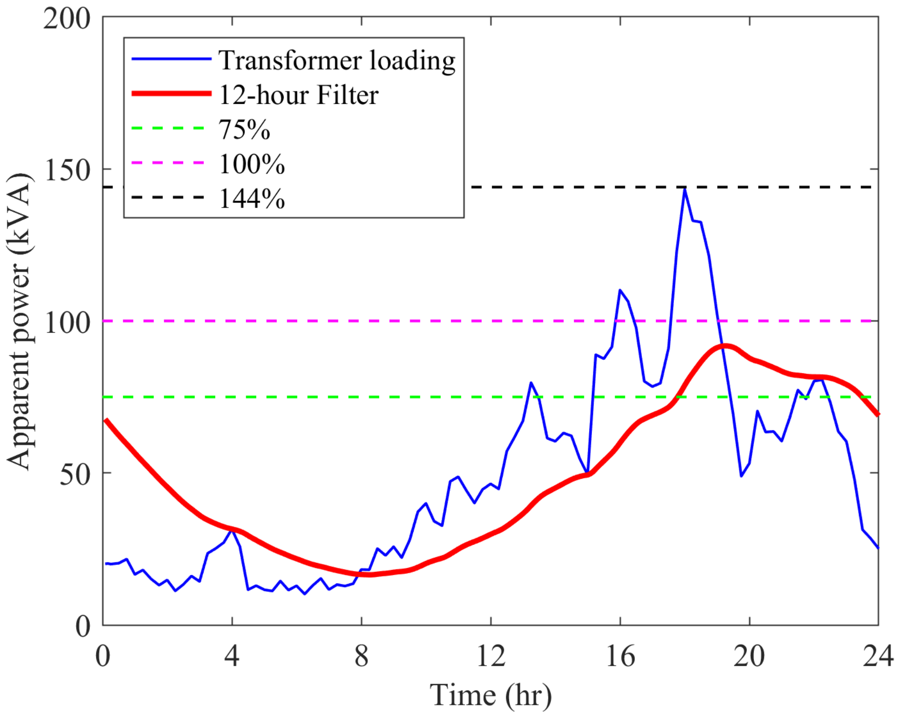
- In this part, we will check how many EVs can be added to the distribution system such that the transformer loading do not exceed the standard rating.

Flowchart to identifying the critical number of EVs



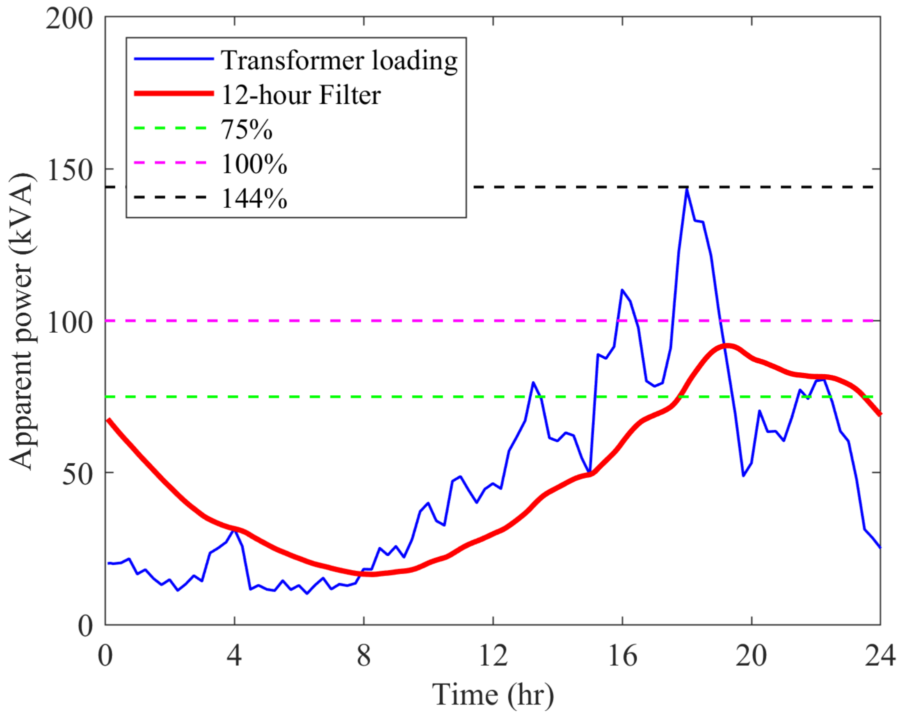
15-house distribution network under on-peak demand with EVs

- The maximum number of EVs is 22.
- The blue curve represents the transformer loading while the red curve represents the output of a 12-hour moving average filter.



15-house distribution network under on-peak demand with EVs

- The transformer loading from 16:00 to 19:00 is between 100% to 140%.
- In addition, the 12-hour average load before this period is less than 75%.
- As a result, the 15-house distribution system can be loaded to **22 EVs** before exceeding the transformer loading standard.

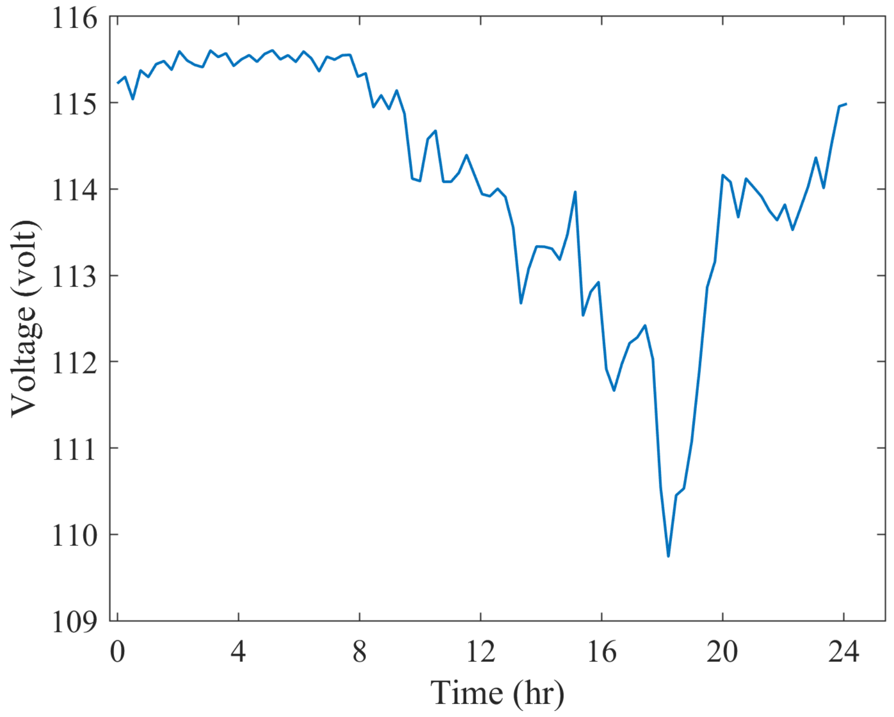


Scenario #7: 15-house distribution network with 22 EVs

- To evaluate the effect of integrating 22 EVs on the 15-house distribution system, we ran the load flow model to determine the voltage values at customers' houses.

Scenario #7: Voltage values

- The figure below shows the voltages at the secondary side of the transformer.



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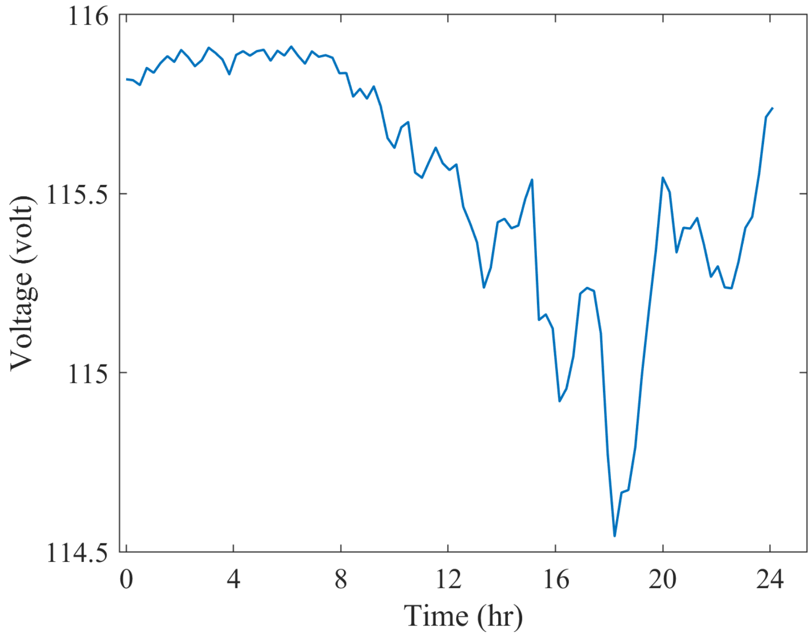
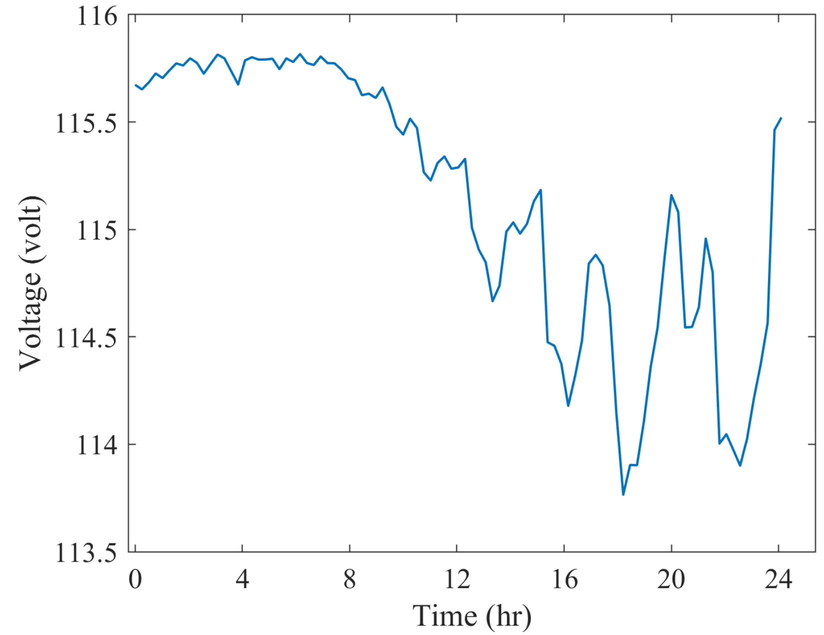
Scenario #7: Voltage values

- The figures below show the voltages at bus 9 which is located right after the transformer and bus 1 which is located at the end of the line.



(a) Voltage at bus number 9



(b) Voltage at bus number 1

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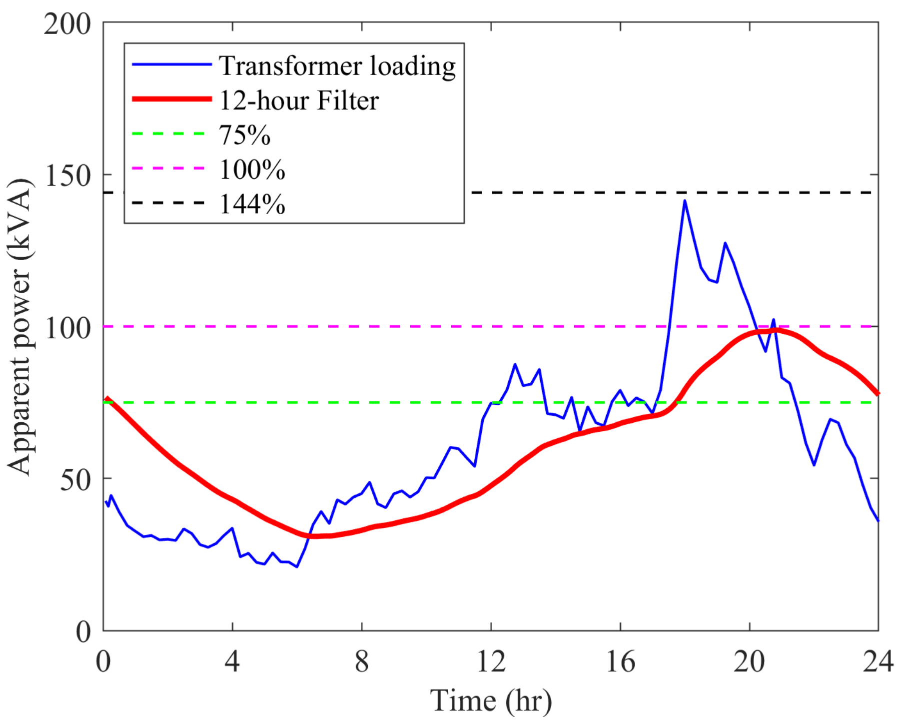
22-house distribution network under on-peak demand with EVs

- The maximum number of EVs that can be added to the 22-house distribution system is 11.
- The blue curve represents the transformer loading while the red curve represents the output of a 12-hour moving average filter.



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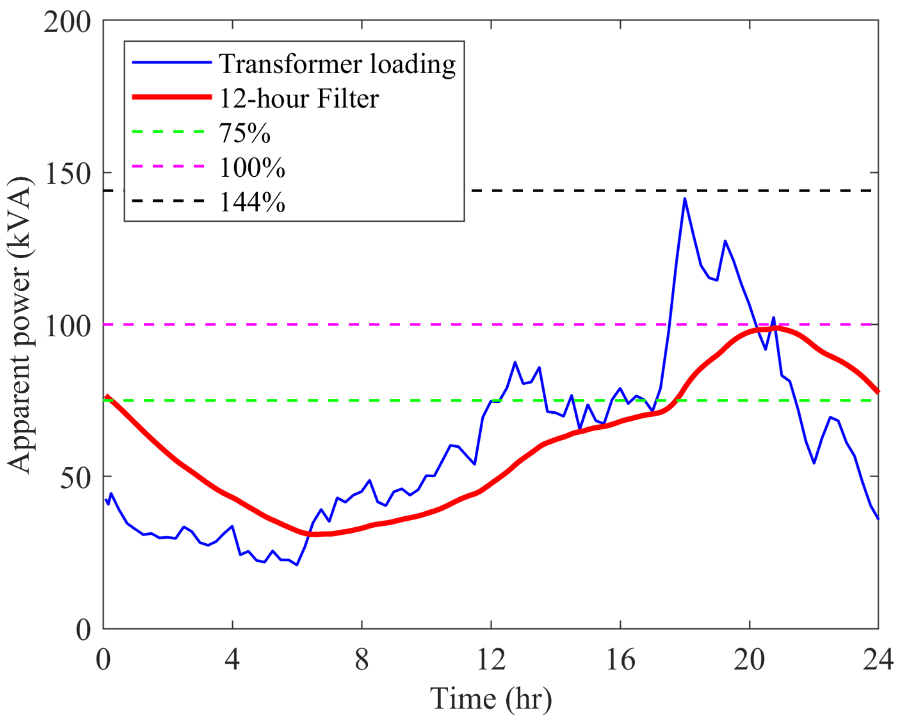
22-house distribution network under on-peak demand with EVs

- The transformer loading from 18:00 to 20:00 is between 100% to 140%.
- The 12-hour average load before this period is approximately 75%.
- As a result, the 22-house distribution system can be loaded to **11 EVs** before exceeding the transformer loading standard.



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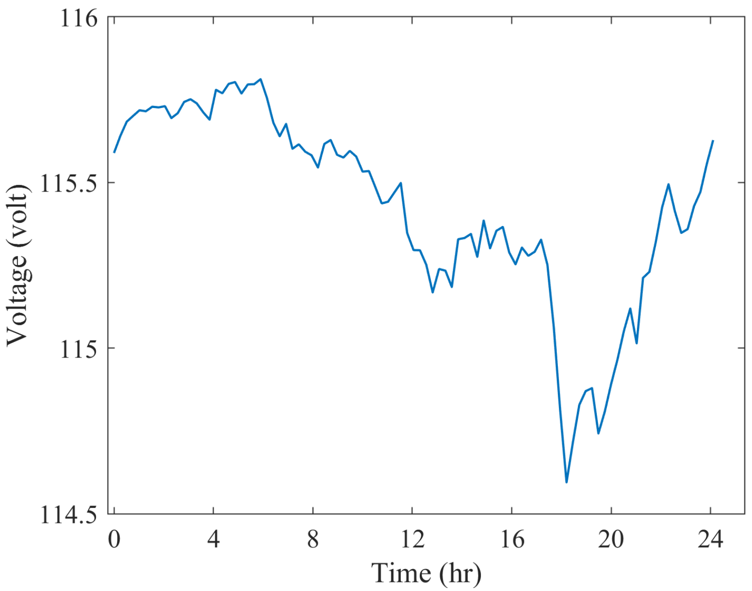
Scenario #8: 22-house distribution network with 11 EVs

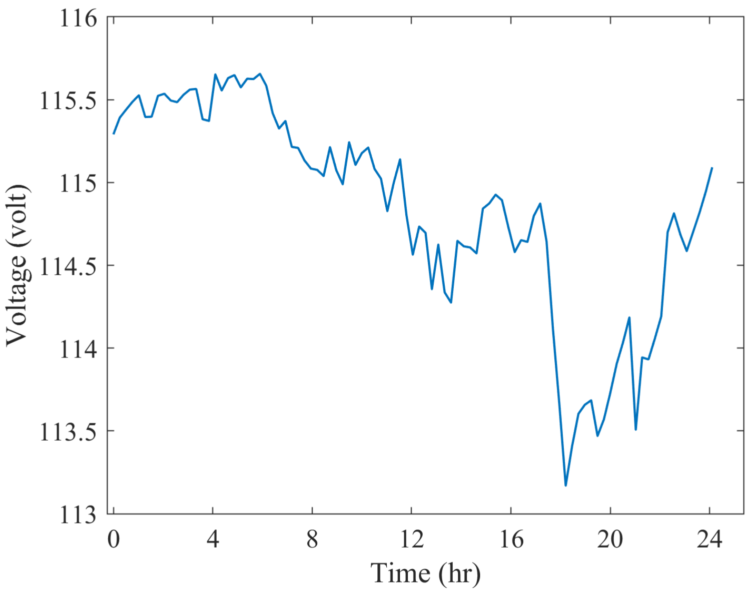
- To evaluate the effect of integrating 11 EVs on the 22-house distribution system, we ran the load flow model to determine the voltage values at customers' houses.

Scenario #8: Voltage values

- The figures below show the voltages at the secondary side of the transformer and bus 13 which is located right after the transformer.



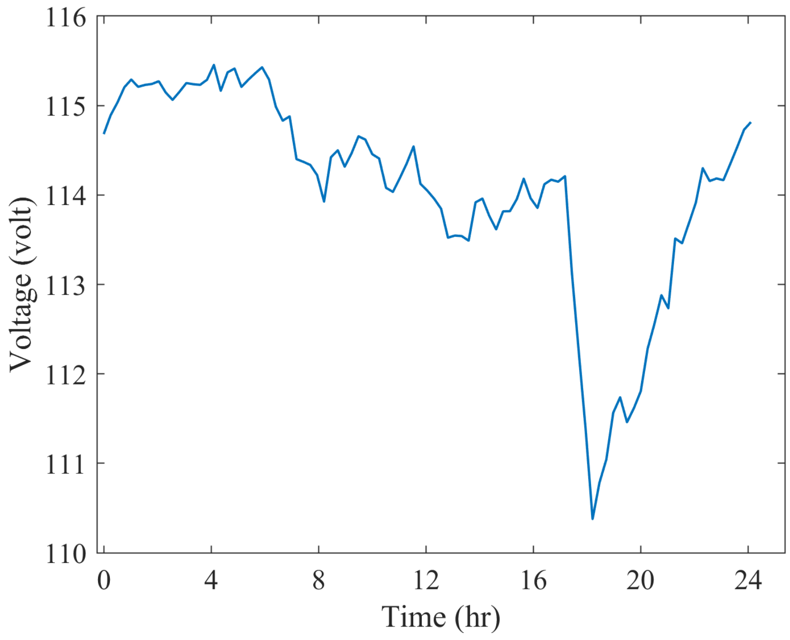
(a) Voltage at bus number 7



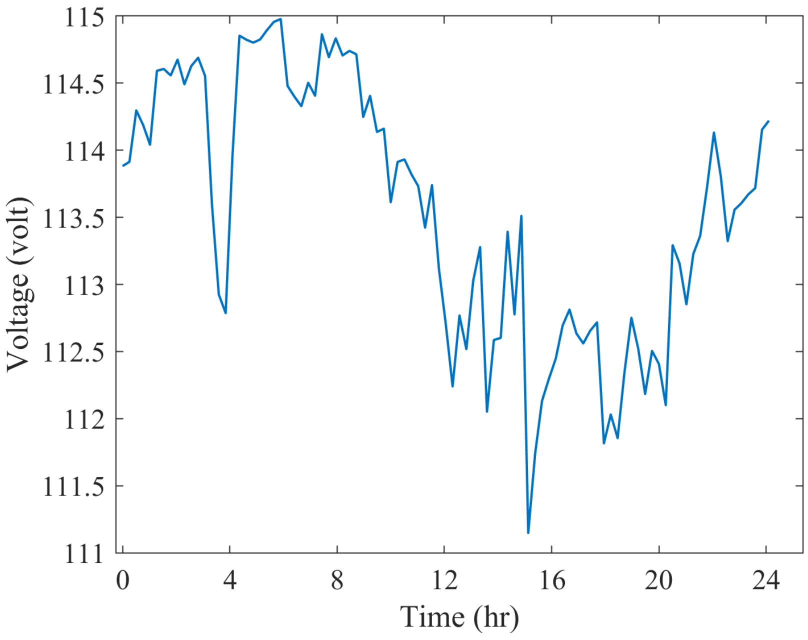
(b) Voltage at bus number 13

Scenario #8: Voltage values

- The figures below show the voltages at bus 8 which is located at the end of the line 1 and 29 which is located at the end of the line 2.



(a) Voltage at bus number 8



(b) Voltage at bus number 29

Summary of Objective 3

- We developed an AC load flow models to evaluate the impact of EV load growth on the current urban residential power distribution grid based on transformer loading and voltage drop at each bus.
- Two distribution system representations have been designed.
  - 15-house distribution system.
  - 22-house distribution system.
- Different scenarios are considered, by changing the types of EVs, and number of EVs.
- In each scenario, we checked the transformer loading and voltage drop at customers' houses.
- The critical number of EVs for each distribution system is identified.
- The results show that 22 EVs is the critical number of EVs for 15-house distribution system while 11 EVs only for 22-house distribution system.

Objective 3

- This section represents the development of optimal charging models to schedule/control EV charging.
- This model can be used to aggregate the controlled EV charging to shift load off from peak demand period.
- The proposed model can provide the utility or EV aggregator a day-ahead or hours-ahead plan for EV charging control.
- The argument of the optimal power flow model (the scheduled/controlled EV charging load profiles) can be used as a control policy for charging EVs.
- The models can schedule EV charging in order to reduce peak demand, improve energy efficiency, and delay infrastructure investment.

Outlines

- How to schedule EV charging.
- Home departure and arrival time modeling.
- Optimal charging model.
- Simulation results.

How to schedule EV charging

- Smart charging systems use advanced algorithms and data analytics to optimize the EV charging process, taking into account factors such as the availability of electricity, and the charging power level.
- In the proposed optimization model, the decision variables are the charging times and charging power
- Changing the parameters value is occurred iteratively using an optimization method.

How to schedule EV charging

- EVs can only be charged when they are plugged in at home.
- Therefore, it is necessary to consider the times when the owners leave and return home when solving the optimization model for charging the vehicles.

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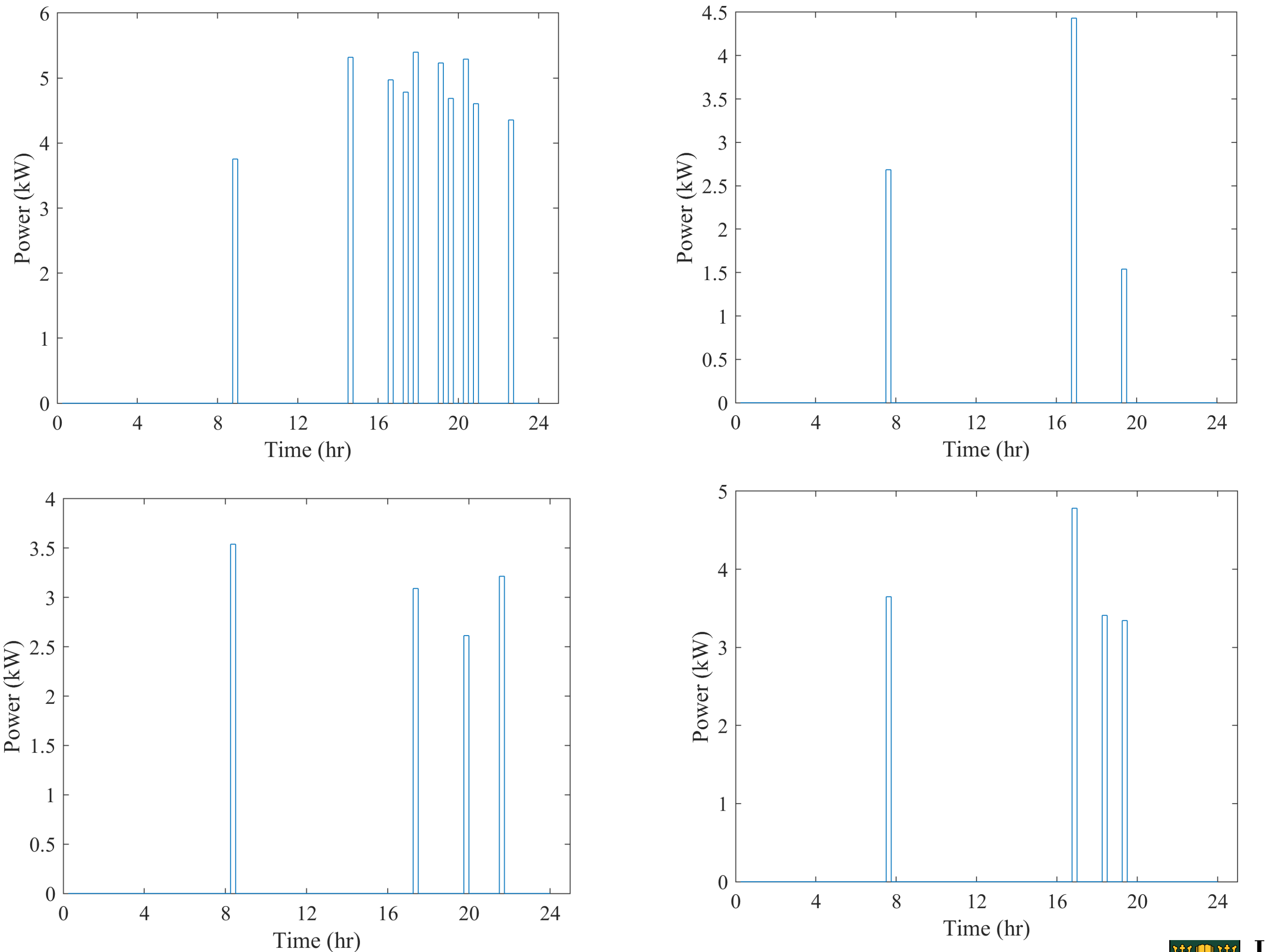
How to determine home departure and arrival time

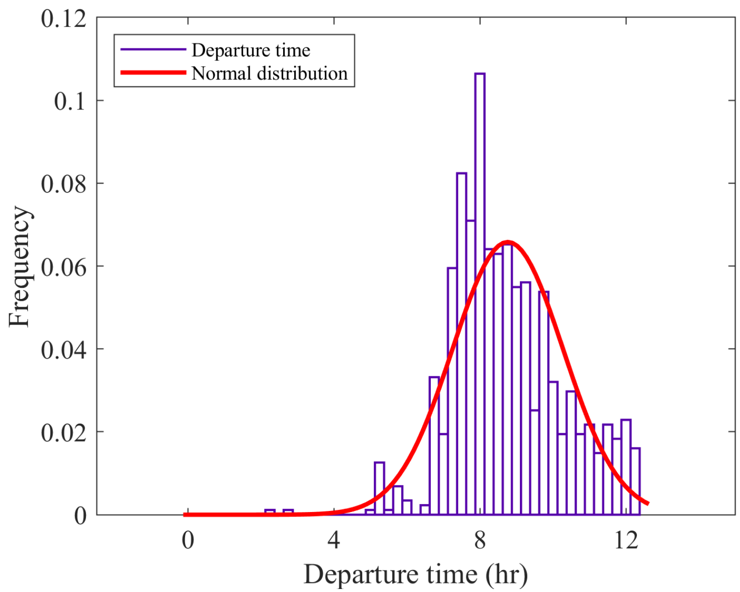
- From the actual trip data (the Excel sheet) we can determine the daily driving for each EV.
- We assumed that the start driving time is home departure time and the end of the last trip is home arrival time for each EV (Next slide shows some examples of daily EV driving during weekdays).
- Then, we can use the statistical analysis to find the distribution of home departure and arrival time.

Examples of daily EV driving during weekdays



Modeling of home departure time

- We used statistical analysis to find the distribution of home departure time.
- The figure below shows the histogram of the actual home departure (t_1) during September 2021.
- Due to similar daily routines as shown in the figure, t_1 tend to be normally distributed.



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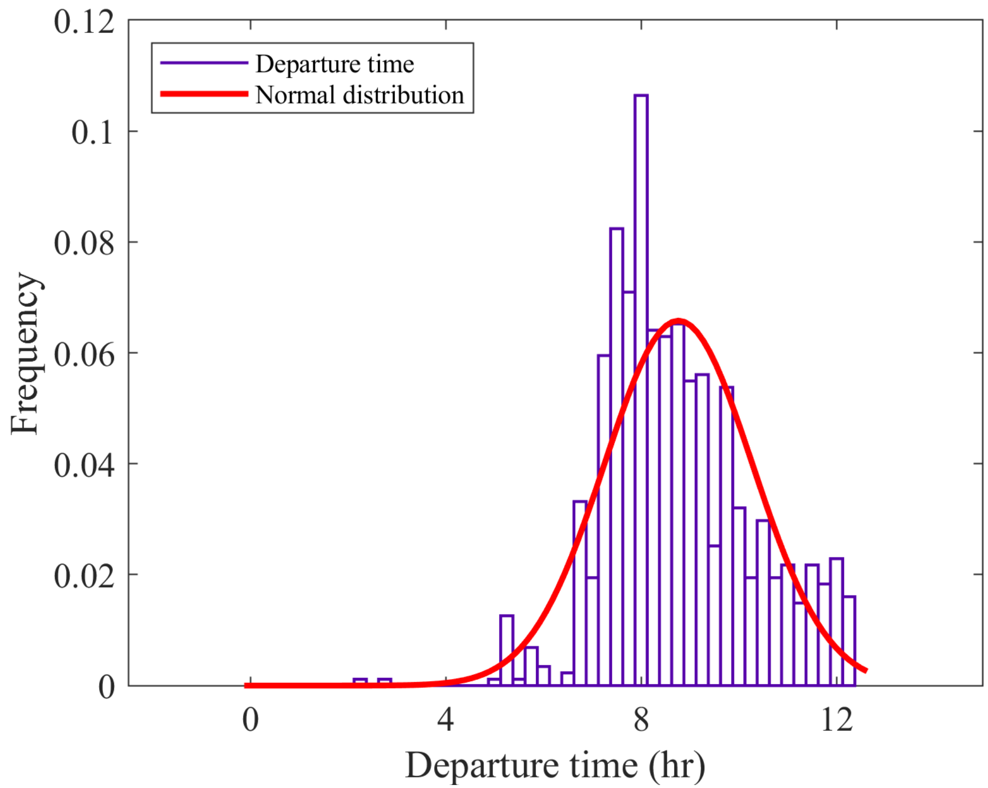
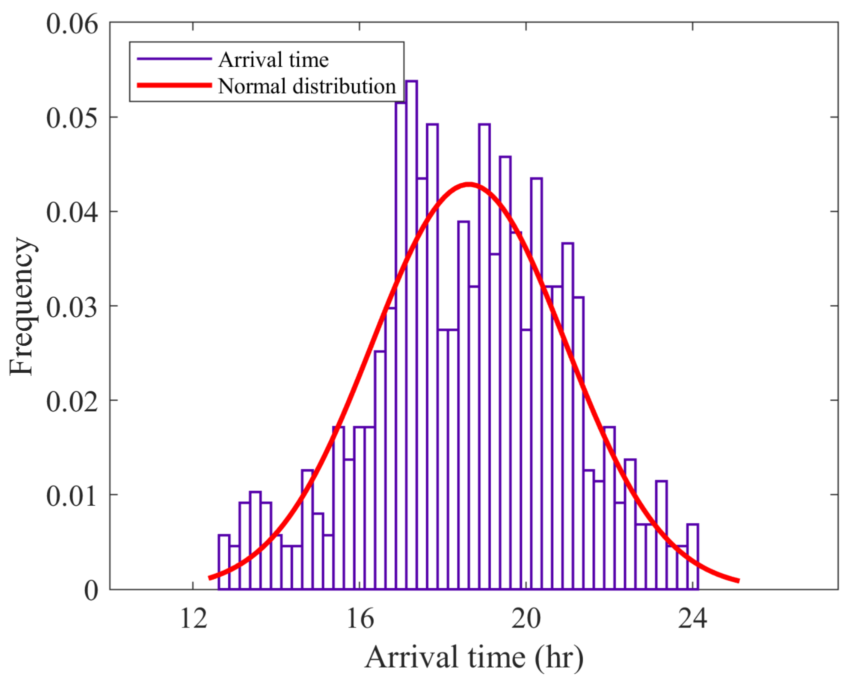
Modeling of home departure time

- The parameters are calculated as follows:
  - The average value is 8:45.
  - The standard deviation is 1.5 hrs.



Modeling of home arrival time

- We used statistical analysis to find the distribution of home arrival time.
- The figure below shows the histogram of the actual home departure (t_2) during September 2021.
- Due to similar daily routines as shown in the figure, t_2 tend to be normally distributed.



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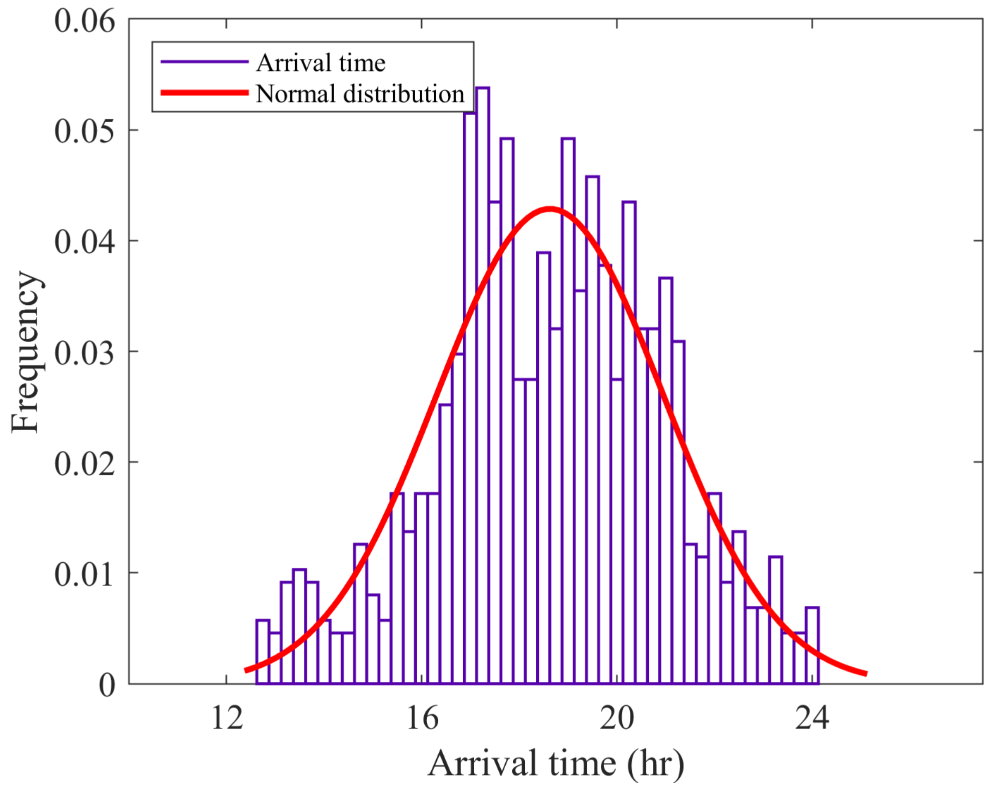
Modeling of home arrival time

- The parameters are calculated as follows:
  - The average value is 18:37.
  - The standard deviation is 2.3 hrs.



Optimal charging model

- The optimization model minimizes the peak demand of the load profile.
- Some constrains have to be considered:
  - The EV charging power should not exceed the maximum charging level for each EV.
  - Each EV can not charge between departure and arrival time.
  - The SOC for Each EV at the arrival time equals the initial SOC, which is calculated based on the daily consumption and battery capacity of each EV.
  - The accepted value of $SOC_{t1,i}$ before departure time is 95%, meaning that each electric vehicle (EV) must have a 95% charge before starting to drive.

Optimal charging model

- We formulated a linear program to solve the optimization model as follows:

$$minimize\ \sum_{i=1}^{M}(\max(P_t^{EV_i} + P_{base,t}))$$

subject to

$$0 \leq P_t^{EV_i} \leq P_{rated}^{EV_i} \quad \forall t \notin [t_1, t_2]$$

$$SOC_{0,i} = 95\% - \frac{E_i}{C_i}$$

$$SOC_{t_2,i} = SOC_{0,i}$$

$$SOC_{t1,i} = 95\%$$

$$SOC_{t,i} = SOC_{0,i} + \sum_{t=0}^{T} P_t^{EV_i}$$

$$10\% \leq SOC_{t,i} \leq 95\%$$

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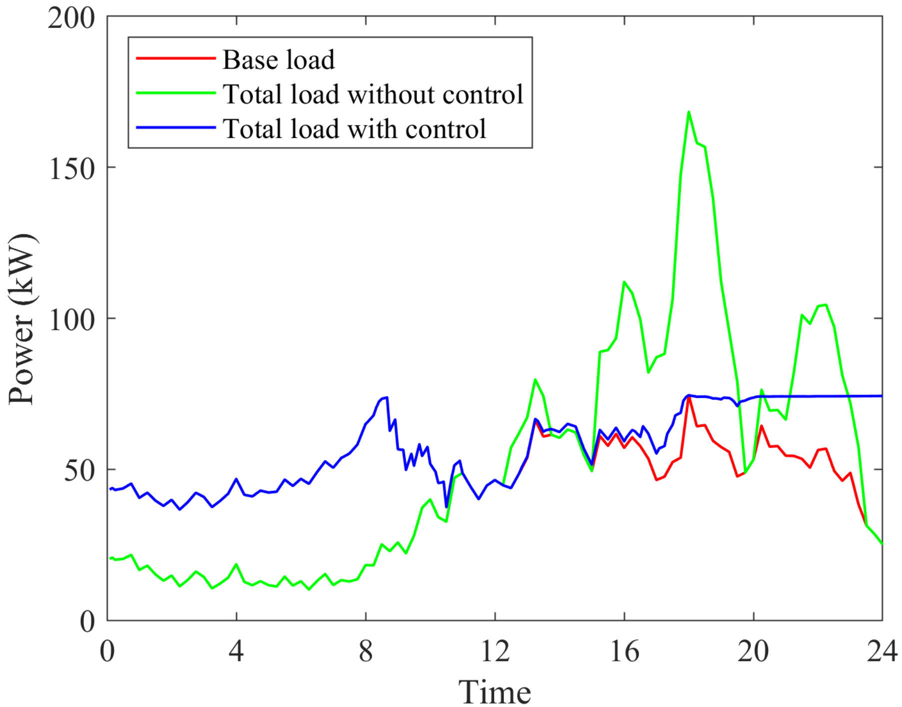
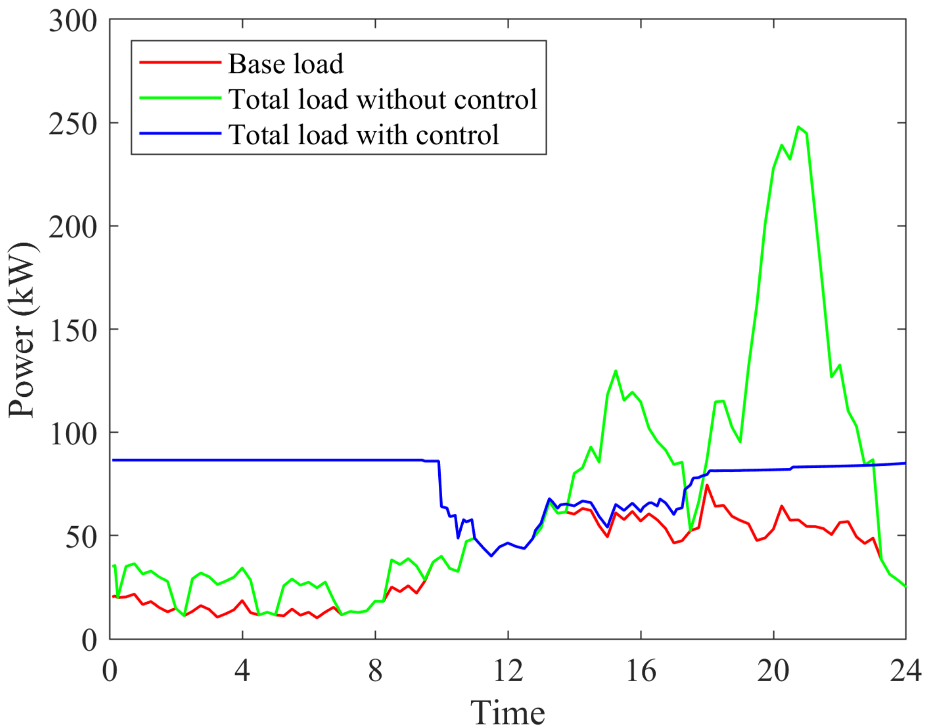
Scenario #9:15-house distribution with 30 EVs

- In this scenario, we assumed each household has 2 EVs.
- The figure below shows the base load profile (red curve), and the total households load with 30 EVs without control (green curve) and with control (blue curve).



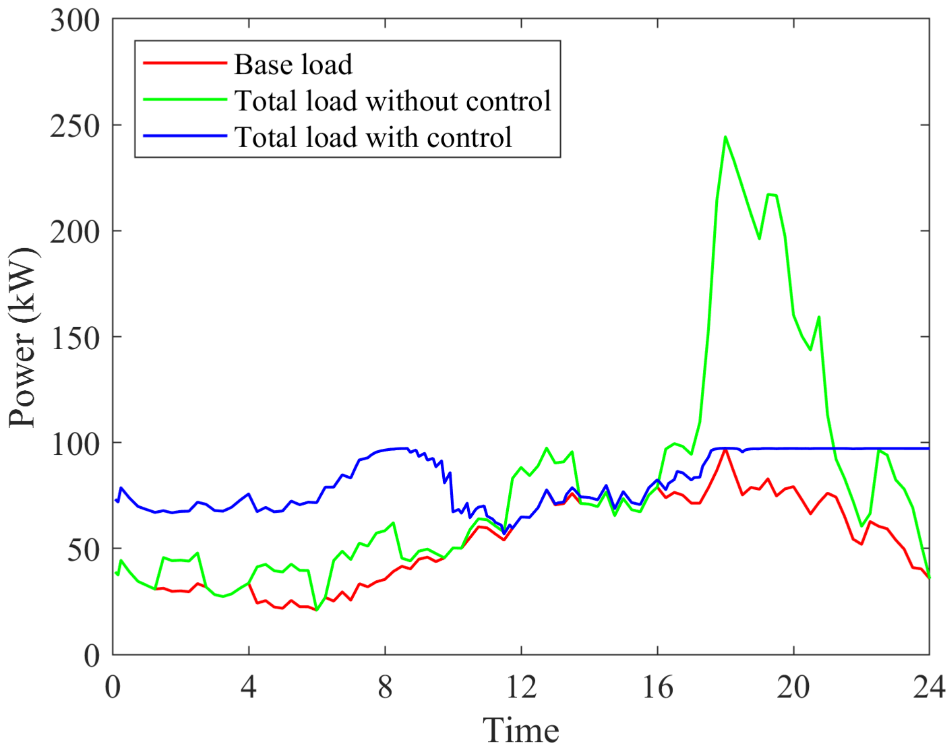
Scenario #10:15-house distribution with 30 electric trucks

- In this scenario, we assumed each household has 2 electric trucks.
- The figure below shows the base load profile (red curve), and the total households load with 30 electric trucks without control (green curve) and with control (blue curve).



Scenario #11: 22-house distribution with 44 EVs

- In this scenario, we assumed each household has 2 EVs.
- The figure below shows the base load profile (red curve), and the total households load with 44 EVs without control (green curve) and with control (blue curve).



Results summary

- The table below shows the aggregated peak demand with/without EV charging control at each scenario.
- The transformer rating is 100 kVA.

Scenarios	Base load peak demand (kW)	Total peak demand without EV control (kW)	Total peak demand with EV control (kW)
Scenario #9	74.5	168.3	74.5
Scenario #10	74.5	247.9	86.5
Scenario #11	97.3	244.3	97.3

Summary of Objective 3

- This section has developed an optimal EV charging model to enable the integration of EVs into the power system while minimizing peak demand.
- The optimization model is proposed to charge customers' EVs with minimizing the aggregated peak demand.
- Scenarios # 9, 10, and 11 present a detailed examination of the efficacy of the proposed optimal EV charging model.
- The results of the study indicate that the implementation of the proposed optimal EV charging model can effectively prevent excessive expenditure on upgrading the electric power system.