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RESEARCH REPORT

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UNIVERSITY
OF
CALIFORNIA

# Resiliency Impacts of Plug-in Electric Vehicles in a Smart Grid

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**16. Abstract**

This project assesses the impact of plug-in electric vehicles (PEVs) on the resiliency of the electricity distribution system by: (1) Assessing the use of PEVs as a resiliency resource during grid outages (Mobility Services+), (2) Assessing and simulating the impact of PEVs on the distribution infrastructure during normal operations, and (3) Determining the local environmental impact of clustering PEVs. A previously developed model of a smart grid consisting of two distribution circuits and a distribution substation was modified to enable the use of PEVs in vehicle-to-home (V2H) and vehicle-to-grid (V2G) configurations. Scenarios were simulated in which PEVs were used to serve critical loads in a home or community shelters, and a model was developed to assess the feasibility of using PEVs in grid restoration, which determined the inrush current of the substation transformer to determine the required power and energy for startup. The use of clustered PEVs and scattered PEVs in grid restoration was also considered. During normal operations, the stress on system components from high PEV demand resulted in accelerated aging and possible failure, thereby negatively impacting distribution infrastructure during normal grid operations. Smart charging is required to retain an acceptable level of resiliency. In contrast, during grid outages, this study demonstrated that PEVs can be used as an environmentally friendly resiliency resource to both serve critical loads and facilitate grid restoration with the qualification that implementation requires system upgrades including smart switches, upgraded inverters, energy management systems, and communication links.

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## Disclaimer

# Resiliency Impacts of Plug-in Electric Vehicles in a Smart Grid

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# Glossary

| Term/Acronym | Definition |
|---|---|
| APEP | Advanced Power and Energy Program |
| Blackstart | The process of starting-up or restarting an electrical asset without relying on the external electric power transmission network to recover from a total or partial shutdown. |
| CES | Community Energy Storage. This is a battery energy storage unit deployed close to the transformer and serving all the customers served by that particular transformer |
| CYME | A Power system analysis software with advanced simulation tools for transmission, distribution and industrial power systems simulation and analysis. |
| DER | Distributed Energy Resource. Resources (examples of which are generation, energy storage, and controllable loads) connected to the distribution system (66 kV and lower) and close to the loads they serve. |
| EMS | Energy Management System |
| EVSE | Electric Vehicle Supply Equipment |
| Feeder Microgrid | A group of interconnected loads and DERs in a utility feeder forming a power system cell, equipped with advanced information and communication technology, protection, and automated control technology with the ability to operate as a controllable entity and participate in system-level services |
| GMC | Generic Microgrid Controller. |
| Grid-Following | The case where inverters reference and follow the grid's voltage and frequency while operating. |
| Grid-Forming | The case when the grid is absent, the inverters cannot follow and reference the grid's voltage to operate and have the capability to operate without the grid and control the voltage and frequency of their output. |
| Hot Spot Temperature | Highest temperature of the oil in the oil-immersed transformers |

| | |
|---|---|
| Inrush Current | Alternating-current electric motors and transformers may draw several times their normal full-load current when first energized. This is referred to as inrush current. (It is an input surge current when a maximal instantaneous input current is drawn by an electrical device when first turned on or energized. ) |
| Inverter | A power electronic device or circuitry that transforms direct current (DC) to alternating current (AC) |
| ISGD | Irvine Smart Grid Demonstration. |
| ISO | Independent System Operator |
| Microgrid | A group of interconnected loads, power generation and other distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid and operate in both grid-connected or island-mode.’’ |
| Nanogrid | A small microgrid serving a single customer or facility |
| PEV | Plug-in Electric Vehicle |
| PV | Photovoltaic |
| PV Capture Mode | A battery operating mode wherein the battery charges when the PV output is more than the load demand and discharges when it is less, as long as the battery SOC remains within the acceptable predefined range. |
| Renewable Penetration | The percentage of electricity generated by renewable resources (such as solar PV and wind) relative to the total amount of electricity consumed. |
| RESU | Residential Energy Storage Unit. This system refers to a PV/battery combination on the same inverter deployed on the customer side of the meter |
| SCE | Southern California Edison. One of three Investor-Owned Utilities in the state of California |
| Simulink | A MATLAB-based block-diagram environment for modeling, simulating and analyzing multidomain systems and model-based design. It can model electrical power systems using specialized components and algorithms. |
| Smart grid | The thoughtful integration of intelligent technologies and innovative services into the electric grid that enable control, flexibility, stability, enhanced efficiency, , and an overall secure electrical supply in the presence of large scale diurnal variation and intermittencies associated with renewable solar and wind generation and zero-emission plug-in battery and fuel cell electric vehicles.. |
| SOC | State of Charge |
| UCI | University of California, Irvine |
| V2G | Vehicle to Grid. The process of a PEV discharging its battery and providing energy back to the grid |
| V2H | Vehicle to Home. The process of a PEV discharging its battery and providing energy back to the home |
| ZNE | Nero Net Energy |

# Executive Summary

# Executive Summary

Extreme weather events such as hurricanes, wildfires, and heatwaves have been recently occurring more frequently and with higher intensity mainly due to climate change. Seven of the largest wildfires in California occurred in the past three years, and in September 2020 an intense heatwave broke several temperature records in California including temperatures in Death Valley surpassing 134°F. These events negatively impacted the reliability and resiliency of the electric grid by stressing the system due to extremely high demand during heatwaves resulting in rolling outages, as well as necessitating preventive measures such as Public Safety Power Shutoffs (PSPS) wherein sections of the electric grid are purposefully de-energized in order to reduce the chance of wildfires being ignited by electric arcing between overhead distribution wires under high wind conditions. When the grid is de-energized locally or regionally, plug-in electric vehicles (PEVs) have the potential to provide electricity to critical loads and critical facilities.

While PEVs may tax the electrical grid under normal operations, PEVs can provide benefits during grid outages since they are essentially mobile energy storage resources. This concept. referred to as *Mobility Services+,* uses PEVs as a resiliency resource during grid outages to increase the reliability and resiliency of the grid by (1) serving critical loads through vehicle-to-home (V2H) or vehicle-to-grid (V2G) electricity transfer by discharging the batteries on the PEVs, and (2) assisting in restoring the grid after an outage by providing the necessary power and energy to restart a utility asset such as a transformer. During normal operations, however, the high electricity demand of PEVs can negatively impact the distribution network by stressing system components such as transformers. This can result in accelerated aging, increased chance of failure, and ultimately reduced reliability and resiliency of the electric grid.

This research project assessed the impact of PEVs on the resiliency of the electrical distribution system during grid outages as well as normal operation by:

1) Assessing the use of PEVs as a resiliency resource during grid outages (known as Mobility Services+)
2) Simulating and assessing the impact of PEVs on the distribution infrastructure during normal operations
3) Determining the local environmental impact of significant numbers of PEVs in the same system during both normal and emergency operations.

To conduct this research, a previously developed detailed model of the electricity distribution system in California was enhanced with PEV attributes. The final model included a smart distribution substation with two smart circuits, a high penetration of solar photovoltaic (PV) power generation, energy storage, PEVs, energy management systems, and a substation controller capable of controlling the operation of distributed energy resources (DERs) to achieve maximum efficiency and minimum emissions.

For grid outages, the use of PEVs through V2H and V2G to serve critical loads, as well as comparing the use of clustered PEVs (such as in a parking lot) and scattered PEVs, were evaluated in the context of facilitating grid restoration by providing the power and energy necessary to overcome the inrush current to restart a substation transformer. The system upgrades needed to implement the use of PEVs as a resiliency resource were identified such as upgrading to smart switches, equipping homes with home energy management systems, upgrading inverters to be capable of operating in the absence of the grid, and establishing communication between the central substation controller and energy management systems.

For normal grid operation, the model was used to simulate cases with high a PEV demand on the distribution system. In addition to uncontrolled charging, smart charging strategies including emission-based smart charging strategies were simulated to establish the electric load on individual transformers. A previously developed transformer model was employed to determine transformer stress metrics such as hot spot temperatures (HSTs), accelerate aging factors (AAFs), and equivalent aging factors (EAFs), as well as the probability of transformer failure.

The major findings of the project are:

- Under normal electric grid operation:
  - While PEVs with uncontrolled charging can stress the electrical infrastructure, accelerate the degradation of utility assets such as transformers, and overall degrade the resiliency of the grid, smart charging strategies can significantly mitigate the negative impact of increased PEV use on the grid infrastructure
  - A combination of DERs, energy efficiency measures and smart charging provides the best results in terms of reducing both infrastructure impacts and emissions
  - Smart charging enables an increase in renewable penetration in the distribution system
  - Flexible travel plans and additional charging stations can increase the effectiveness of charging strategies.
- Under grid outages:
  - With properly controlled charging, plugged-in PEVs can be an effective and environmentally friendly resiliency resource for V2G and V2H.
  - PEVs can serve critical loads with minimal system upgrades.
  - To increase resiliency for both service to critical loads and grid restoration through PEVs, system upgrades are required.
  - Clustered PEVs (e.g., in a parking lot) are more suitable to facilitate grid restoration compared to residential PEVs randomly scattered throughout the system.

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# Introduction

In recent years, frequency of extreme weather events has increased as well as their strength and severity [1][2]. The seven largest wildfires in California have occurred in the past three years, with the deadliest one being the Camp fire in November 2018 [3]. To reduce chances of wildfires, Public Safety Power Shutoffs or PSPS were implemented, a preventative measure that de-energizes the electric grid in high-risk areas in order to reduce the probability of wildfires caused by electrical faults. These extreme weather events and the resulting more frequent grid outages have highlighted the need for greater reliability and resiliency in the grid. In response to this need, as well as the increasing electrification of the transportation sector, both the structure and operation of the electric grid are evolving.

Transportation electrification, increased rate of plug-in electric vehicle (PEV) adoption, and especially clustering of PEVs in specific neighborhoods give rise to questions and concerns on the possibility for negative impacts of PEVs on the electric grid infrastructure and its resiliency. While the impact of PEVs on electricity generation and transmission has been studied extensively, their impact on the electricity distribution system has not been addressed in detail which can place additional pressures on what is already an aging power grid infrastructure and negatively impact the resiliency of the grid. For example, during normal operations, a large population of PEVs can stress system components such as transformers resulting in accelerated aging or even failure and thus reduce resiliency of the system. In contrast, PEVs can also increase system resiliency. When connected to the grid, PEVs are an energy resource that can provide electricity through vehicle to grid (V2G) or vehicle to home (V2H) for critical services (such as community shelters) during grid outages and facilitate grid restoration by providing electricity to support the blackstart of utility assets. Since these services are in addition to the mobility services that PEVs can provide during normal grid operation, they are referred to as Mobility Services+.

This research project assessed the impact of PEVs on the resiliency of the distribution system during grid outages as well as normal operations by:

1) Assessing the use of PEVs as a resiliency resource during grid outages (Mobility Services+). This was accomplished by evaluating the use pf PEVs during grid outages for serving critical load and utility assets.

2) Simulating the impact of PEVs on the distribution infrastructure during normal operation. Multiple scenarios were developed and simulated, and impact of smart charging on mitigating the negative impacts was assessed.

3) Determining the local environmental impact of significant numbers of PEVs in the same system during both normal and emergency operations.

The project leveraged results and capabilities (including modeling, and control strategies) from previous projects led by University of California Irvine (UCI) Advanced Power and Energy Program (APEP). These projects include the Generic Microgrid Controller (GMC) [4] project under a major U.S. Department of Energy program, Station Automation and Optimization of Distribution Circuit [5] project funded by the California Energy Commission as well as a smart charging protocol and algorithm [6] previously developed by APEP.

The project provides a better understanding of the interaction between the electric and transportation sectors, will help to increase the rate of transportation electrification, and develop roadmaps for a successful electrification of the transportation sector that will meet the resiliency needs of the community by providing grid services in addition to mobility. Ultimately, the project will help meet State energy and environmental goals while increasing/maintaining the reliability and resiliency of the electric grid. Electric service reliability and community resiliency must be maintained for PEVs to have a significant future mobility role.

To accomplish the objectives of the project, a distribution system in southern California was utilized that includes two 12kV distribution circuits and a distribution substation, and was a part of the Irvine Smart Grid Demonstration (ISGD) project [7]. The ISGD project included thirty homes equipped with solar photovoltaic (PV), smart appliances, smart meters, community energy storage, and plug-in electric vehicles. The homes were distributed in the following four blocks (on separate streets), each with an individual transformer supplying electricity to the homes:

1) ZNE (Zero Net Energy) block. In this block, homes were outfitted with energy efficiency upgrades,[1] devices capable of demand response,[2] a Residential Energy Storage Unit (RESU), a solar array, and a plug-in electric vehicle.

2) RESU (Residential Energy Storage Unit) block. The homes in this block were identical to ZNE block except that they did not have energy efficiency upgrades.

3) CES (Community Energy Storage) block. This block was identical to the RESU block, but instead of each home having its own RESU, a community energy storage device served the entire block.

4) Control block. These homes served as the control group with no upgrades, solar panels or energy storage devices. A schematic of the homes is shown in **Error! Reference source not found.**.

During the ISGD project, almost two years of data were collected including detailed home electricity consumption. Nearly all the individual household electric loads and major appliances were sub-metered and recorded, along with charge/discharge data associated with energy storage in various operation modes, PV data, weather data, transformer data, and PEV data. In a project funded by the California Energy Commission [5][8], these data were used to develop and validate models of the two circuits and develop control strategies (e.g., device or local controls) for individual distributed energy resources (DERs) that can generate and store electricity (often from renewable energy sources) as well as a controller based on GMC specifications [4,9] and simulated at the substation. The GMC-based controller was designed to coordinate and optimize the operations of all the DERs in the system under study, effectively transforming the system into a feeder microgrid.

The model was developed in CYME and MATLAB Simulink and validated with the data collected from the ISGD project. The model is shown in **Error! Reference source not found.**.

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[1] Examples include upgraded insulation, efficient lighting, electrified appliances (instead of gas), replaced HVAC, and refrigerator.

[2] These are smart appliance that can respond to a utility request such as a smart refrigerator that could put off automatically defrosting itself (an energy intensive event) during grid peaks.

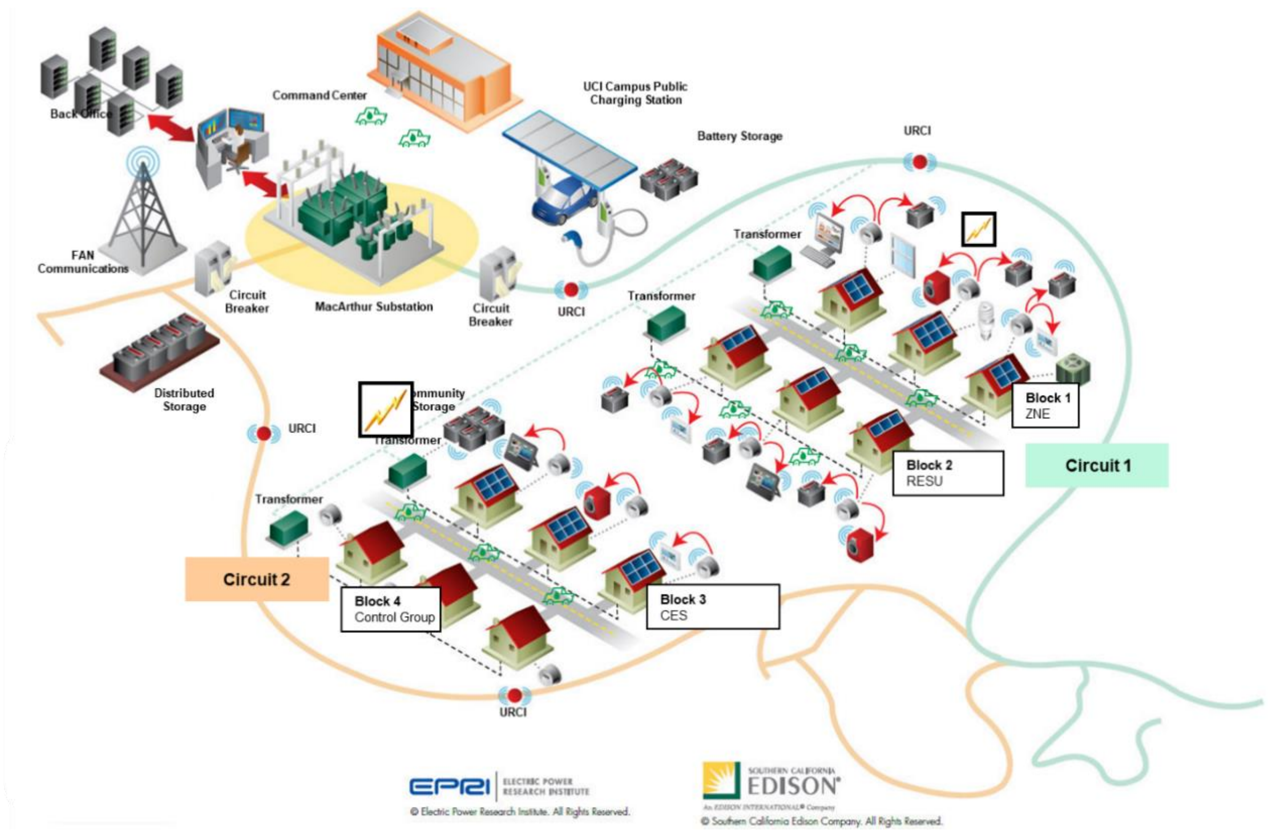

Figure 1. ISGD Project (Courtesy of SCE and EPRI)

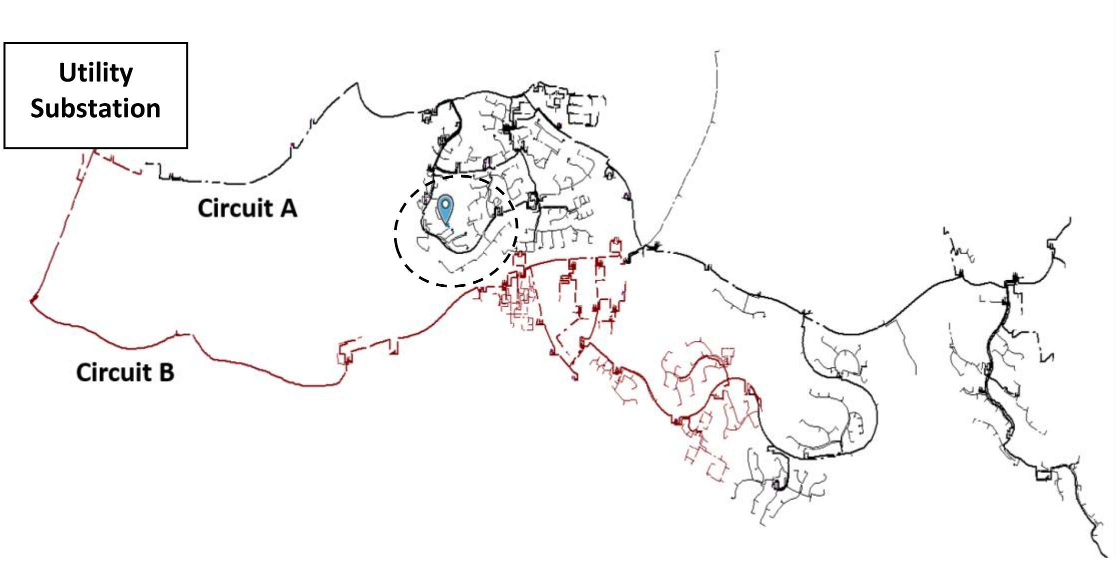

Figure 2. System Model

In Section 1, the feasibility and efficacy of PEVs as a resiliency resource during a grid outage are addressed. Scenarios are simulated which include providing electricity to the home by a single PEV during an outage (V2H), providing service to a critical facility by several PEVs at a parking lot (V2G), and using clustered PEVs as well as scattered residential PEVs in support of grid restoration by restarting a substation transformer. The key findings of this section are:

- PEVs can be used to serve critical loads at homes complementing RESUs. The implementation requires an electric vehicle charger (also referred to as “electric vehicle supply equipment” or “EVSE”) that allow for electricity to flow in both directions, and an inverter[3] that is capable of operating in the absence of the grid.
- Clustered PEVs at a parking lot can provide electricity to nearby critical facilities. In addition to the upgrades mentioned above, the implementation also requires upgrading a few switches to smart switches for automation.
- Clustered PEVs are suitable for providing required power and energy to restart a substation transformer. The implementation requires an EVSE that allows for electricity to flow in both directions, an inverter that is capable of operating in the absence of the grid, upgrading switches on the route from parking lot to the substation to smart switches, and a controller capable of coordinating the process.
- Although residential PEVs are also capable of supporting service restoration by restarting the substation transformer, the implementation requires upgrading the entire distribution system and sophisticated controls and fast communication.

Providing electricity to critical facilities and to the transformer substation during an emergency, assessed in Section 1, requires a significant number of PEVs. These PEVs can negatively impact the distribution system during non-emergency normal operations. In Section 2, the impact of large number of PEVs connected to a distribution system is assessed during normal operations. To this end, the electricity load on each transformer in the system is determined and used to assess transformer impact metrics including the hot spot temperature (HST), and the accelerated aging factor (AAF). These metrics are an indicator of both the accelerated transformer aging due to the increased load of the PEVs and probability of transformer failure. Different cases were simulated which covered different DERs, multiple electricity demand profiles, and different smart charging strategies. The key findings of Section 2 are:

- Implementing smart charging strategies reduce and, in some cases, eliminate the negative impact of PEVs on local grid infrastructure and resiliency.
- With smart charging, the use of solar PV on the system can be increased which increases the resiliency of the system during outages and increases the opportunities for meeting State environmental goals during normal operation.

In Section 3, the environmental impacts of using PEVs as resiliency resource are compared to that of backup generators, and the impact of PEVs on GHG emissions (tailpipe emission + emissions associated with the charging from the grid) are assessed. The key findings of Section 3 are:

- Compared to backup generators, PEVs are a cleaner option to provide resiliency services during a grid outage.
- Although PEV charging increases emissions from the grid, the reduction in tailpipe emissions more than compensate for that increase and thus overall emissions (tailpipe emission+ grid emission) decrease with PEVs.
- Emission-based smart charging strategies and use of DERs for charging PEVs significantly reduce emissions.

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[3] A power electronic device or circuitry that changes direct current (DC) to alternating current (AC)

# 1. Plug-in Electric Vehicles as a Resiliency Resource

The use of alternative transportation options including plug-in electric vehicles (PEVs) are expected to continue to increase in order to meet state energy and environmental goals. During grid outages or other power interruptions, PEVs batteries can be discharged to provide electricity to address immediate critical loads on the system. Alternatively, a group of PEVs can be used to energize a larger critical load or help blackstart a utility asset such as a transformer which will result in quick and efficient grid restoration. In this section, the feasibility and efficacy of using PEVs as a resiliency resource for providing these *Mobility Services+* are assessed and analyzed. To this end, the models and control strategies previously mentioned were modified to provide for discharging the batteries in the PEVs when necessary during power grid outages. Two alternative situations were simulated: (1) Utilizing PEV batteries to provide power directly to the load during an outage, and (2) Restarting individual transformers on the grid after an outage helping with quick service restoration.

## 1.1 Serving Loads Using PEVs

In these simulations, the PEVs batteries were discharged to serve (1) existing household loads through vehicle to home (V2H) where the residence forms a nanogrid during grid outages and the PEV provides the necessary energy to ensure that nanogrid loads are served without interruption, and (2) certain community critical loads, such as designated shelters, where several PEVs parked in the same lot (or connected to the same transformer) are used to supply power.

### 1.1.1 Vehicle to Home (V2H)

V2H is a simple concept in which the vehicle supplies power back to the home by discharging the vehicle’s battery. This requires communication between the PEV and the grid or the home energy management system (HEMS). Assuming that homes are equipped with the proper electronic devices for this application, these smart homes would be able to isolate themselves from the grid when the grid is experiencing an outage or other power shutoff emergencies such as PSPS and will be able operate independent of the grid until power is restored.

In addition to the required communication and energy management system, the home also needs to be equipped with a bi-directional EVSE which can grid form and grid follow or with a separate inverter with those capabilities. The charger can be coupled with the solar PV and RESU system or can be in series with the separate inverter for the PV and RESU. The home nanogrid model is shown in Figure 3 which includes solar PV, battery energy storage, EVSE, and fixed and dynamic home loads[4].

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[4] Fixed loads do not vary during the simulations while dynamic loads change with time during simulation.

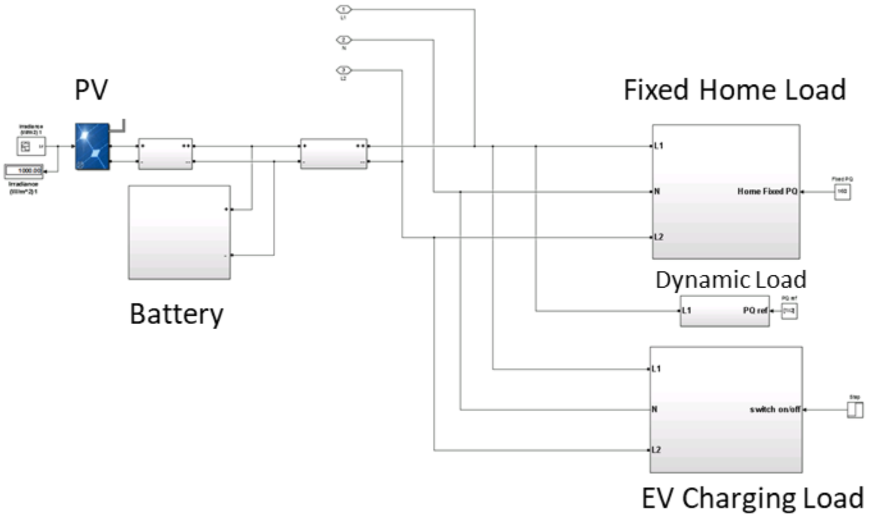


**Figure 3. Home Nanogrid Model [5]**

V2H simulations were conducted utilizing the ISGD data of the home load profiles. The following two sets of simulations were conducted: (1) using load profiles of the ZNE homes which have been upgraded with energy efficiency measures including smart appliances and house insulation, and (2) using load profiles of the control block, which had received no upgrades. In both sets of simulations, each home was equipped with a 7kW solar PV panel and a 4kW/10kWh residential energy storage unit (RESU) running in PV capture mode. The PV array and the battery were connected to a single inverter. The inputs to the RESU component, shown in Figure 4, included the home electricity load, PV array output, and mode of operation. The outputs included inverter power output and a measurement port containing the load power demand, the PV array output power, the battery output power, the inverter output power, and the battery state of charge (SOC).

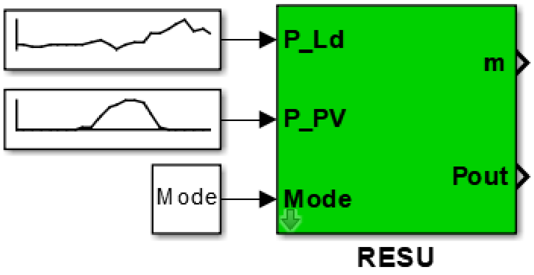


**Figure 4. RESU Component [5]**

Two operation modes were modeled: PV capture and Time-based load shifting. PV capture mode was used for V2H simulations. When operating in PV capture mode, the battery output follows its power set-point, which is the difference between the PV output and the load demand, as long as the battery SOC remains within the acceptable predefined range. The battery charges when the PV output is more than the load demand and discharges when it is less. If the battery reaches its maximum SOC and the load demand is met, the surplus PV power is fed back to the grid. Similarly, if it reaches its minimum SOC and the load demand is not met, the grid has to provide the required power. However, in the current scenarios under study, only the PV capture mode was considered since the home nanogrid is operating in islanded mode due to a grid outage or emergency power shutoff and thus electricity import from/export to the grid are not possible.

In Figure 5, net load profiles for several ZNE homes are shown. This figure indicates that PV and battery energy storage alone are not sufficient to serve the demand of the home nanogrid for an entire day although some nanogrids have excess PV generation that will be curtailed at times. One solution is to increase the size of energy storage which will result in the oversized battery storage for normal grid-connected operations making this solution less economic. Another solution studied here is the use of the PEV battery. To simulate this case, a PEV is added to each home which is equal to 50 percent market penetration since in California, each household has two vehicles. PEV and charger specifications are shown in Table 1.

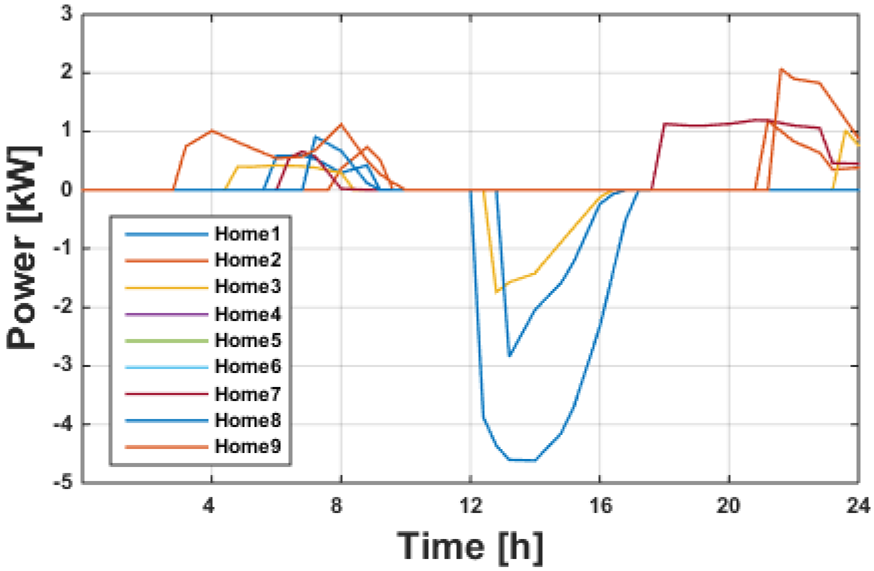


**Figure 5. ZNE Home Net Load Profiles**

The simulations with the PEVs showed that ZNE homes were able to reach 100 percent zero net energy and thus successfully operated in islanded mode without any interruptions in serving loads. Figure 6 shows the state of charge (SOC) of each of the PEVs in different ZNE homes and Figure 7 shows the power profile of the PEV for each home. Both Figure 6 and Figure 7 also show that PEVs in particular homes were able to charge during the day with the excess PV generated electricity, which would have otherwise been exported back to the grid if the system was grid-connected or curtailed. These are PVs in homes that had excess PV generation shown in Figure 5.

**Table 1. Electric Vehicle Specifications**

| | |
|---|---|
| Electric Vehicle Battery Capacity | 100kWh |
| Initial State of Charge | 50% |
| EVSE type | Level 2 charger / 6.6kW charge power |

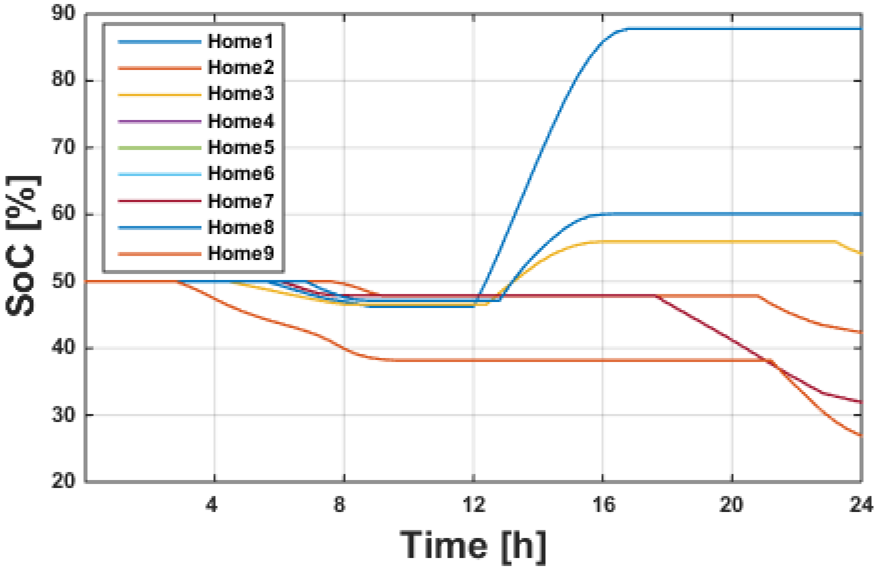


**Figure 6. PEV State of Charge, ZNE Homes**

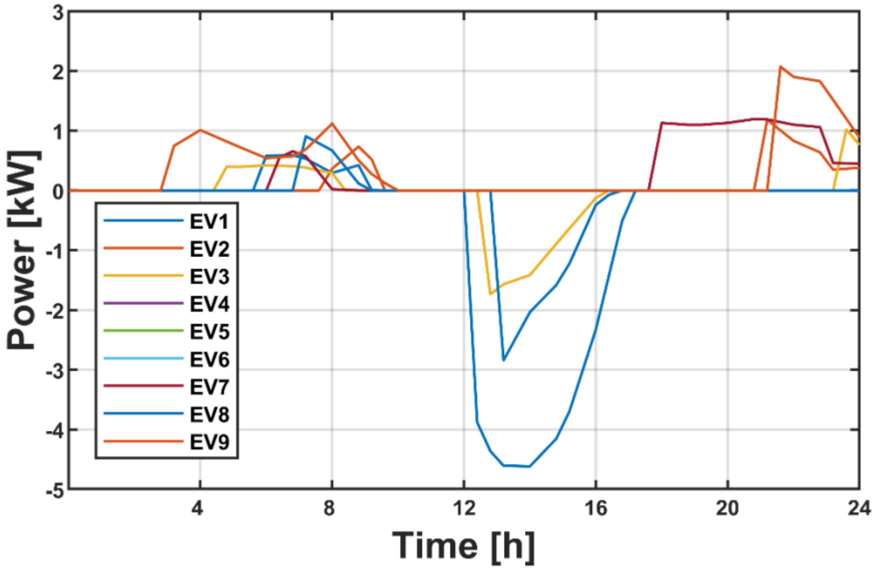


**Figure 7. PEV Power Profile, ZNE Homes**

Without energy efficiency measures, insulation upgrades, and smart appliances, the load demand of the homes in the control block is substantially greater compared to that of ZNE home load demands. This results in different netload profiles as shown in Figure 8 with more instances where generation is not sufficient to meet the demand and greater generation/load imbalance in general. With the addition of PEVs for V2H, the simulations were repeated. Unlike ZNE homes with V2H, half of the homes were not able to self-sustain for an entire day as shown in Figure 9. To be able to operate in islanded modes, these nanogrid homes will need to add additional energy storage or implement energy efficiency to reduce their demand or be able to shed non-critical loads.

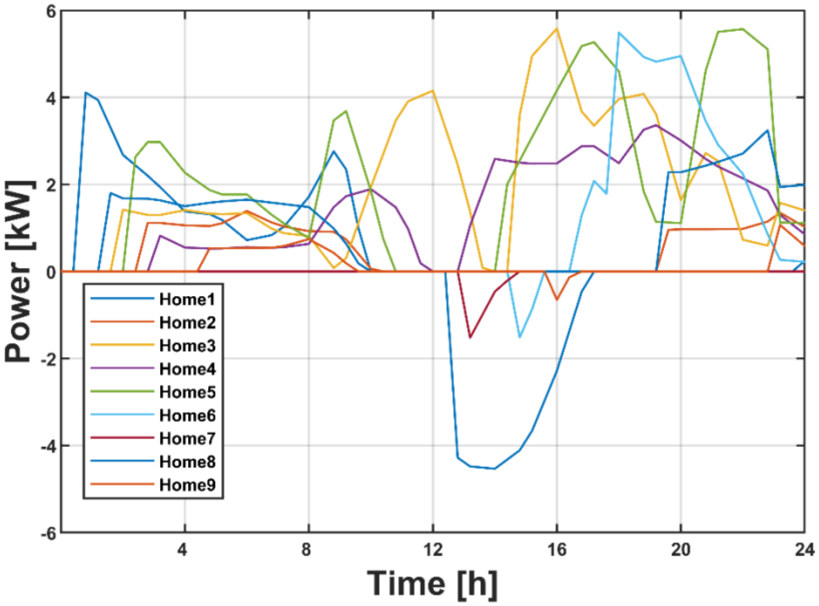


Figure 8. Netload of Control Block Homes

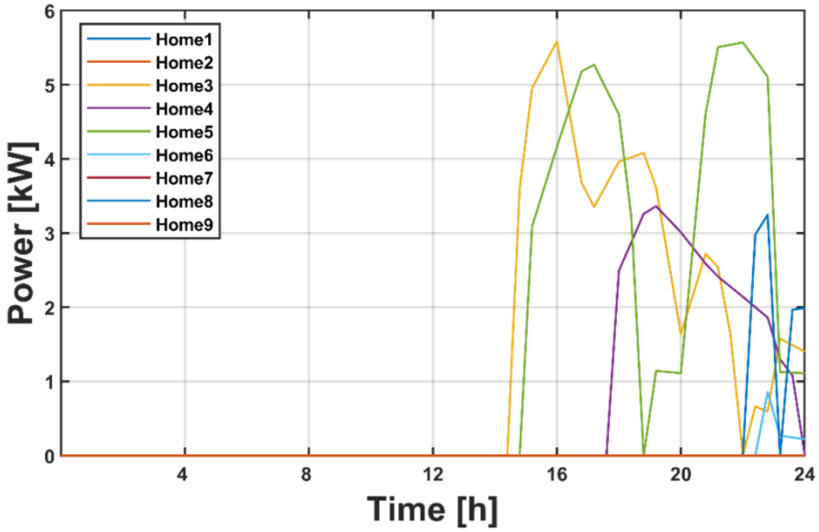


Figure 9. Netload of Control Block Homes with V2H

### 1.1.2 PEV Lots

The term Vehicle to Grid (V2G) means using PEV batteries as a power source to provide different grid services. In this section, the use of V2G is explored as a resource to enhance grid reliability and resiliency by serving critical loads such as shelters and schools during a grid outage.

To this end, a detailed model of the system, shown in Figure 2, is used. This model includes a distribution substation and two circuits with a high penetration of solar PV, energy storage and control equipment which were simulated in MATLAB Simulink [5][8]. The models were validated with extensive field data previously collected on both substation circuits during a demonstration project [7].The models were developed and utilized to optimize distributed energy resources integration and operation on each feeder and simulate each circuit as a microgrid capable of operation in an islanded mode. Since a single PEV is not sufficient to serve critical loads, this section focuses on using a cluster of PEVs in a commercial area, for example, the parking structure of a commercial building, a shopping center, or school. The energy stored in a cluster of PEVs connected to the same transformer can then be aggregated to serve the critical load. Parking lots in the system under study were identified and are shown in yellow in Figure 10.

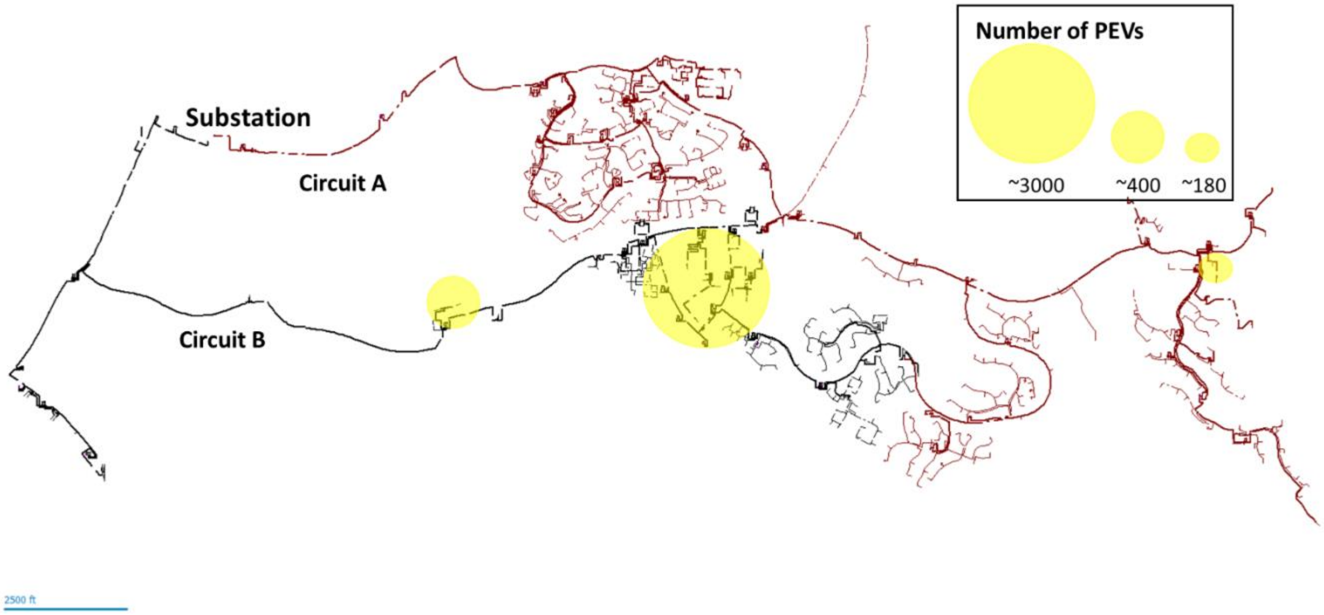


**Figure 10. PEV Lots in Circuits A & B**

The parking lots identified are all next to a large building which, for the purpose of this study, are considered to be shelters and thus critical loads. Note that the lots themselves can be used as emergency shelters and designated meeting areas in case of an emergency. Using the same PEV characteristics previously used, the power capacity and energy capacity of each PEV lot location were determined. Note that level 2 bidirectional chargers were assumed to be integrated at the PEV lots.

In Table 2, the available energy and power are shown for each lot, assuming that the PEVs are at 50 percent state of charge (SOC) and the lots are full. However, without replacing the current transformers, there is a limit to the available power as shown in the 'Transformer Size Limit' column in Table 2. This shows that the three transformers could supply power for 7, 32 and 27 hours respectively for Lots 1, 2, and 3.

**Table 2. PEV Lot Energy Availability**

| PEV lot location | Size of lot (# of PEV) | Available Energy (MWh) | Available Power (MW) | Transformer Size Limit (MVA) | Hours |
|---|---|---|---|---|---|
| 1 | 180 | 9 | 1.3 | 2 | ~7 |
| 2 | 400 | 20.5 | 2.95 | .65 | ~32 |
| 3 | 3000 | 173 | 24.77 | 6.5 | ~27 |

## 1.2 Grid Restoration

In these simulations, the PEVs are discharged to facilitate grid restoration by blackstarting a utility asset such as the substation transformer. Due to transformer size and inrush current, several PEVs are required to be able to restart the substation transformer. Two scenarios are studied: (1) PEVs located in parking lots, and (2) residential PEVs.

### 1.2.1 PEV Lots

In these simulations, PEVs parked at the same location and connected to the same transformer were aggregated to provide the required power and energy to restart the substation transformer. The same parking lots identified in Figure 10 were used in these simulations. Their corresponding size and cable length from the substation are listed in Table 3.

**Table 3. PEV lot size and distance**

| PEV lot location | Size of lot | Cable length from Substation (mi) |
|---|---|---|
| 1 | 180 | 5.26 |
| 2 | 400 | 2.14 |
| 3 | 3000 | 3.26 |

PEV lots were studied to examine their capability to energize the distribution transformer during a grid outage. Two factors were analyzed to assess the capability of aggregated PEVs located at the same lot to energize the 12kV/66kV transformer at the substation: 1) the energization inrush current of the transformer, and 2) the power loss associated with the cable impedance. The energizing path to the substation is shown in Figure 11. The opened circuit breakers depicted in red close in consecutive order from the right to left when energizing the transformer.

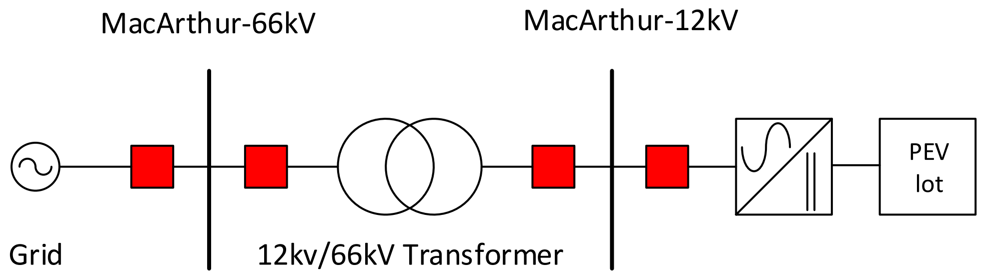


**Figure 11. Transformer Energizing Path**

The same energization path was modeled in MATLAB/Simulink as shown in Figure 12. The PEV lot and the inverter are depicted as a three-phase source, 12.47kV source feeder in the model since the inverter capabilities are not analyzed in this project. The details and characteristics of the transformer were collected from the utility. At t = 0.6 seconds, the 12kV side circuit breaker closed, and at t=2 seconds the 66kV side circuit breaker was closed. On the 66kV side, a three-phase load, 66kW is connected as part of the larger grid.

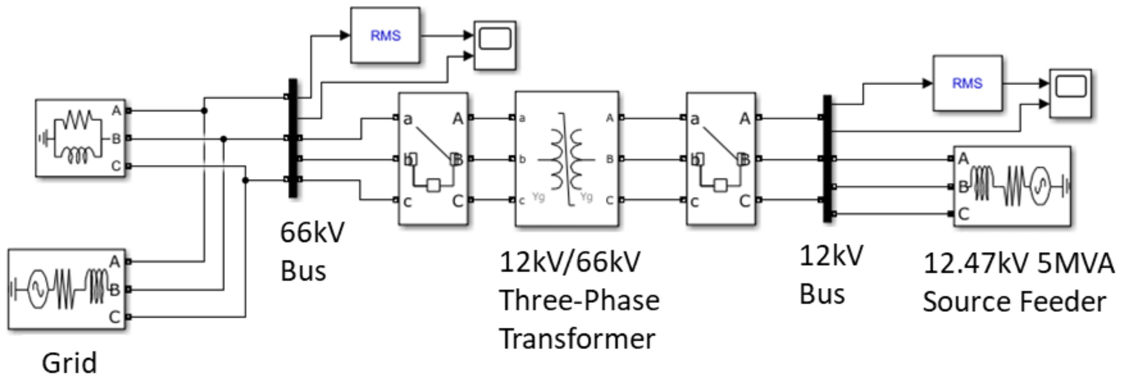


**Figure 12. Transformer Energizing Simulink Model**

The transformer energizing model was simulated for a total of 3 seconds and the results are shown in Figure 13. When the first circuit breaker closes on the 12kV side to energize the transformer at t = 0.6s voltage sag and inrush current are observed. The peak Inrush current of 170A and 197.7A were observed on phase A and phase C, respectively and converges in about 0.5 seconds. Respective to the voltage and current, Figure 14 shows the power associated with energizing the transformer. It indicates that the maximum power peaks at 880kW. Considering the different inrush currents for different switching times, 25 simulations with different switching times were ran as shown in Figure 15. A maximum of 1.3MW was observed among the 25 simulations which was used as the transformer energizing power peak.

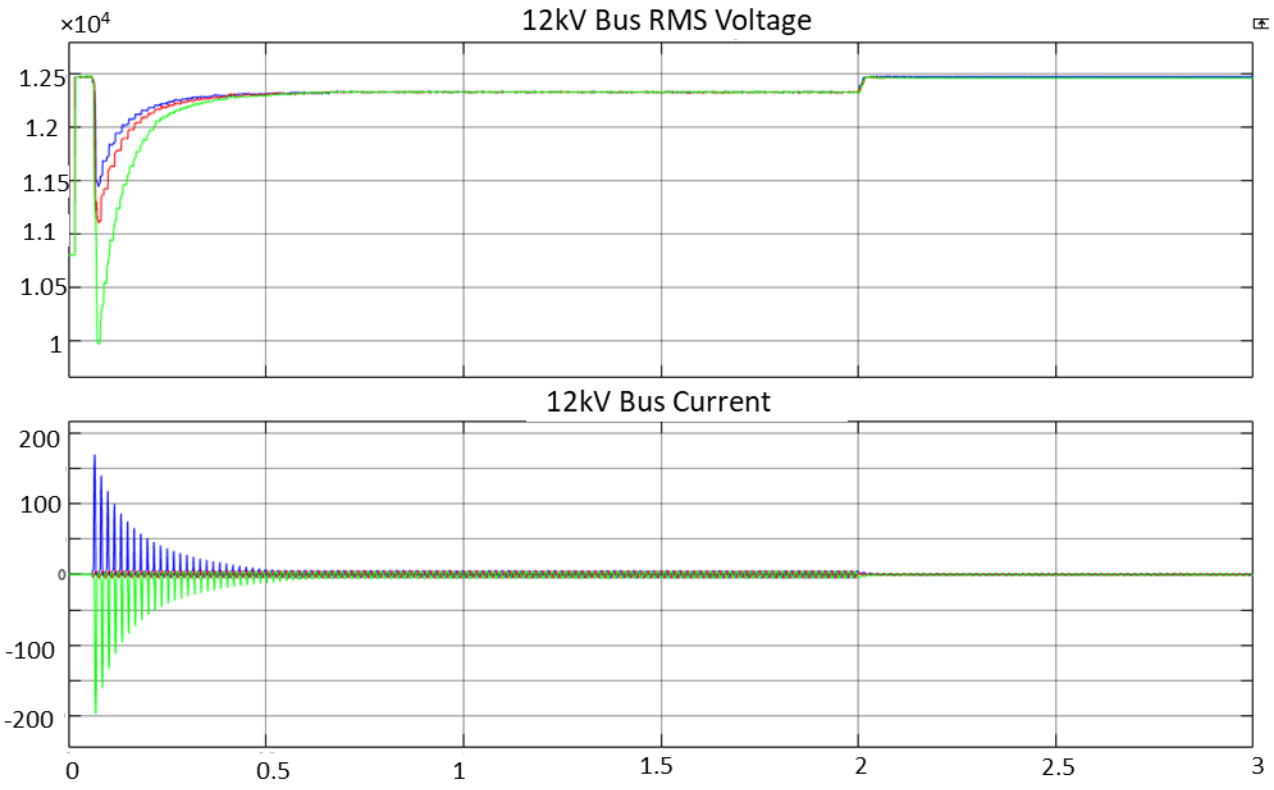


Figure 13. Transformer Energization Results: V & I

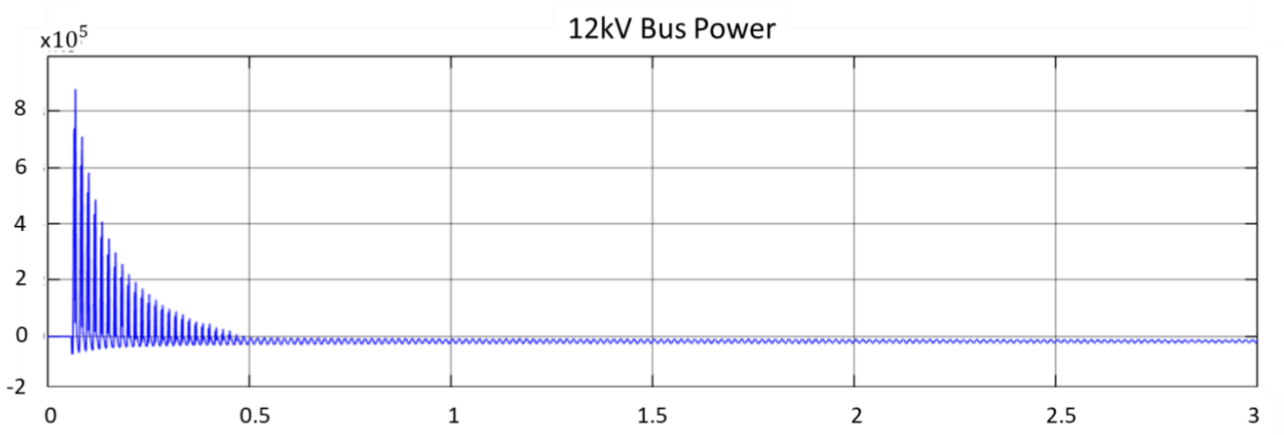


Figure 14. Transformer Energization Power

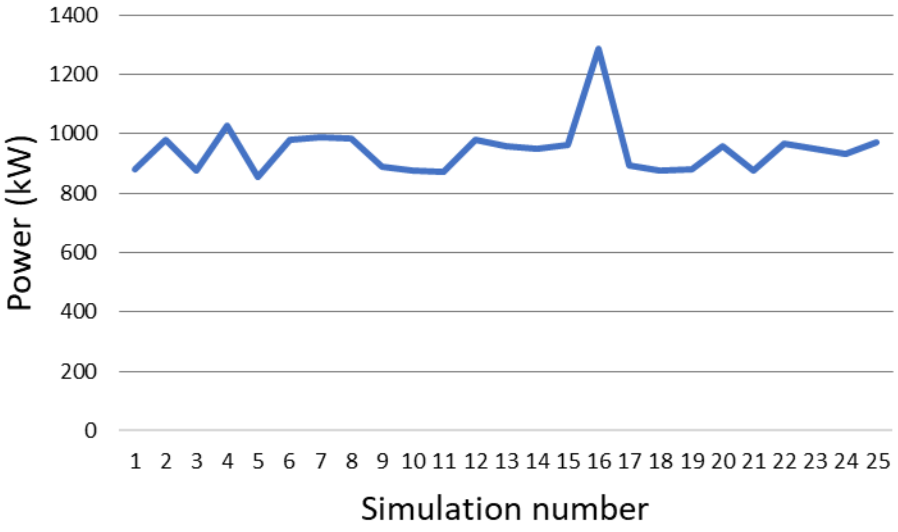


**Figure 15. Statistical Power for Energizing Transformer**

Next, the loss of power was calculated with the circuit cable impedance R and X as shown in Eq (1) and Eq (2).

$$P(loss) = I * I * r/L * L \qquad \text{Eq (1)}$$

$$Q(loss) = I * I * x/L * L \qquad \text{Eq (2)}$$

The length of the cable from Table 3 was used and the impedance values, R and X, were retrieved from the distribution data that were provided by the utility. The active power loss and reactive power loss for the instant inrush current during energizing of the transformer are shown in Table 4.

**Table 4. Power Loss**

| | Ph A | Ph B | Ph C | Total |
|---|---|---|---|---|
| R (Ω/m) | 0.3867 | 0.2054 | 0.2054 | |
| X (Ω/m) | 0.2211 | -0.0016 | -0.0016 | |
| Lot 1 P loss (kW) | 58.786 | 0.027 | 42.229 | 101.0 |
| Lot 1 Q loss (kVar) | 33.612 | -0.00021 | -0.329 | 33.3 |
| Lot 2 P loss (kW) | 23.930 | 0.0110 | 17.190 | 41.1 |
| Lot 2 Q loss (kVar) | 13.682 | -0.00008 | -133.91 | 13.5 |
| Lot 3 P loss (kW) | 36.386 | 0.0167 | 26.139 | 62.5 |
| Lot 3 Q loss (kVar) | 20804.33 | -0.13 | -203.6 | 20.6 |

After accounting for the loss in power, the power needed for energizing the transformer and supplying the inrush current is 1.5 MW. However, this power is needed for less than 1 second before it converges to 25kW until connection to a load or greater grid. This is equivalent to .42kWH in energy for the peak power and 25kWH for the rest of the hour. This can be provided by PEVs in lot 1 and lot 3. While the PEV lot 2 has the PEV capability, the transformer is limited to 650kVA.

### 1.2.2 Residential PEVs

Use of residential PEVs for energizing the transformer was considered as well. Theoretically, it is possible for the scattered PEVs at residential homes to be discharged and supply power, starting from vehicle to home, then to the larger grid. As discussed in Section 1.1, a V2H would be integrated with a central home management system for the consolidation of many different DERs in the home. Under an interconnection agreement with the utility/ISO, the home would be able to participate in exporting power to the grid. For this section, only the PEV connected to a residence was examined as a DER that can export to the grid in order to analyze the impact of PEVs and not the combined DERs in the nanogrid. The home is assumed to be equipped with bidirectional and grid forming chargers/inverters. Over 1,000 switches on the two circuits allow the disconnection of every secondary transformer and, as a result, the corresponding load. These are manual switches which require field crews to switch on and off, but for this study, it was assumed that these switches are remote switches which can be operated from a central controller at the substation. The use of URCIs (Universal Remote Current Interrupters) was demonstrated in Yinger [7] and the ISGD report [10].

Using the required power needed for energizing the substation transformer which was determined in Section 1.2.1, it was concluded that at least 250 PEVs are required to reach 1.5 MW, assuming that they all discharge at 6kW. There are 2,000 residential homes in the system under study and assuming a 50 percent PEV penetration, each home will include a PEV. The number of available PEVs is showed in Figure 16 with yellow bubbles. Almost 50 percent of the total PEVs are in the closest radius from the substation as shown in Figure 16 with the cable lengths between 1.89 miles and 3.21 miles.

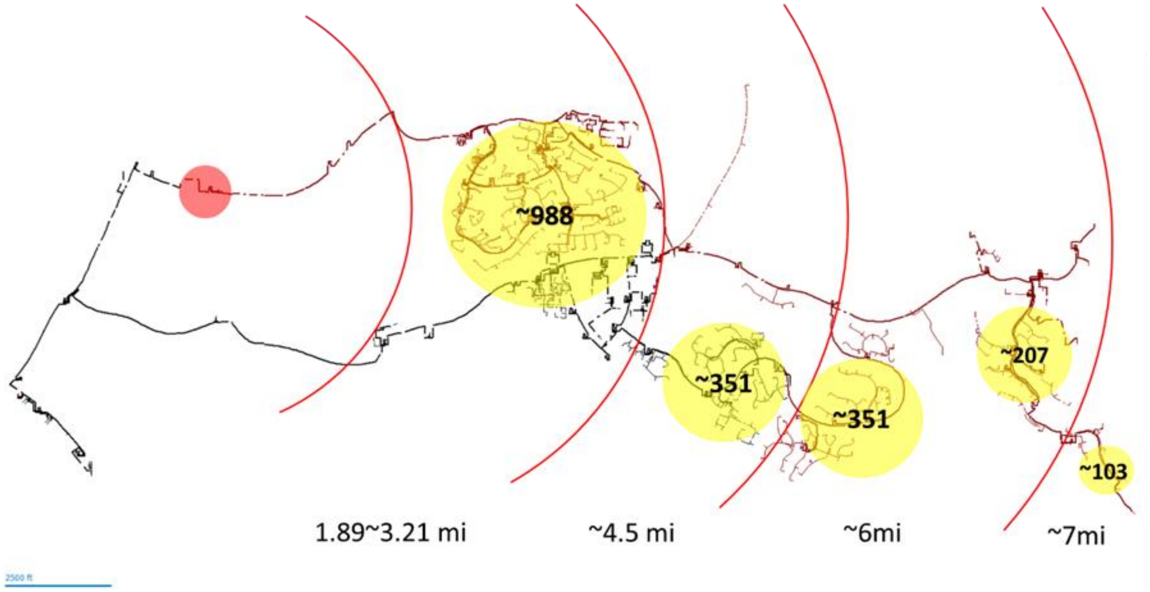
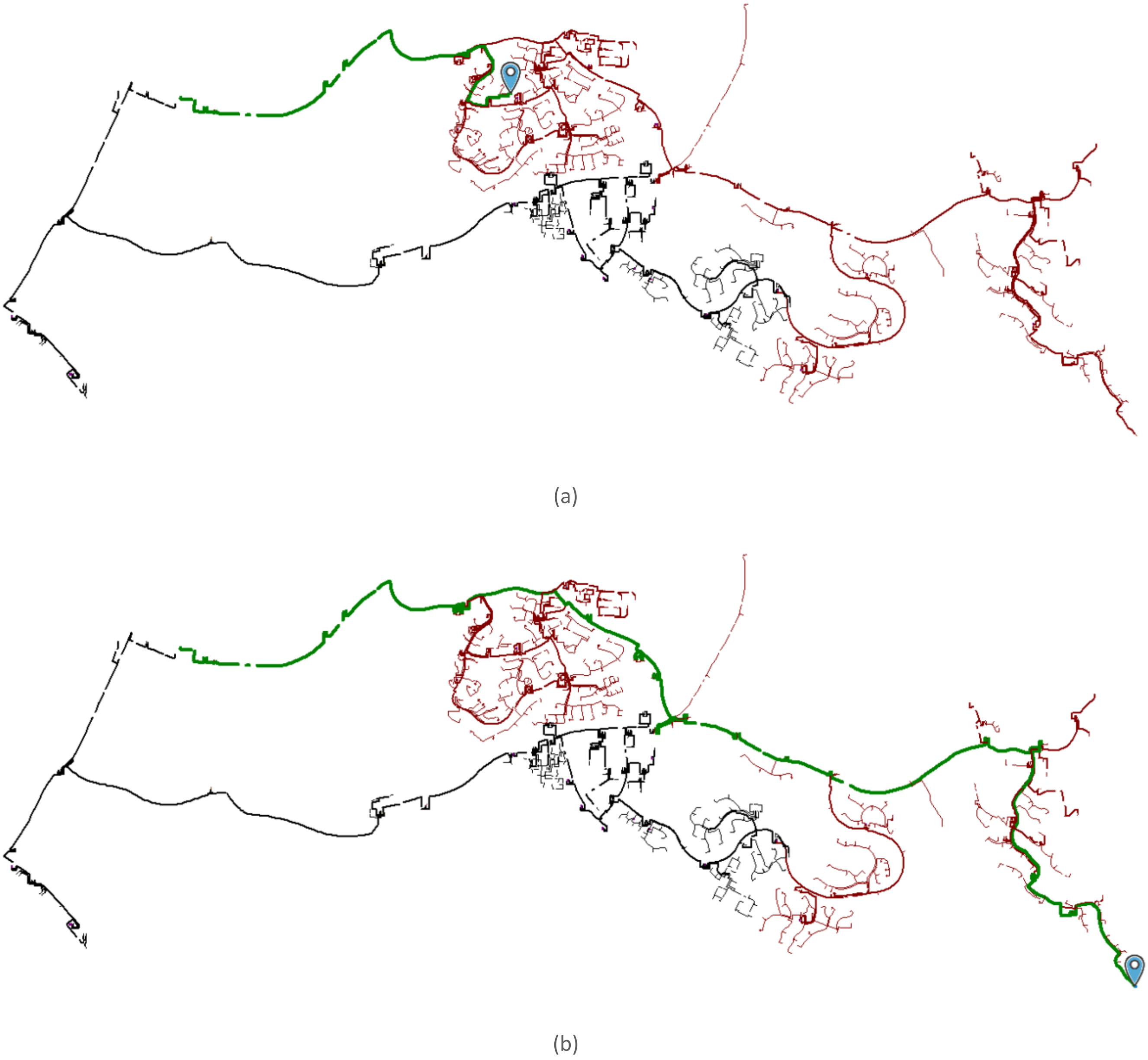


**Figure 16. Residential PEV Locations**

Out of the 282 secondary transformers on the circuit, the two secondary transformers shown in Figure 17 (by the blue "eyedrops") were selected to demonstrate the route (highlighted in green) to the substation which needs to be cleared by opening/closing switches to ensure that other loads on the route are not energized. The first, shown in Figure 17a is one of the closest secondary transformers to the substation with a total cable length of 1.89 miles and the second, shown in Figure 17b, is the furthest with a total cable length of almost 7 miles.



(a)

(b)

**Figure 17. Power Route to Substation**

Given that all the PEVs are located in residential homes, the following two factors were considered to determine which PEVs should be selected for energizing the substation transformer: (1) power loss, and (2) the number of switching actions.

First, it is reasonable to choose PEVs based on location which would result in the lowest power loss, which is directly proportional to the length of the cable and the magnitude of power. For the nearest radius with 3 miles of cable (Figure 16), the power loss is 60 kW, and 150kW for the longest cable of 7 miles. Secondly, to route power to the substation, a switching sequence needs to be implemented in order to disconnect every load and clear the route between the PEV and the substation. This should not be of concern since it is assumed that switches can be controlled remotely. However, it can be advantageous to select PEVs with minimum switching requirements for systems with manual switches so that the field crew can implement the required switching more quickly. Thus, the 250 PEVs can be selected from the closest residential area shown in Figure 16. If 250 PEVs are not available or do not have sufficient SOC to provide 1.5MW, PEVs from the next closet radius will be selected.

For the selected PEVs and switching to successfully deliver power to the substation, the following steps need to be implemented from the central substation controller:

1) De-energize and isolate the system:
2) Open all switches including the substation upstream circuit breaker as shown in Figure 11.
3) Identify PEVs:
4) Identify the availability of the scattered PEVs through communication between the grid or substation controller, and the PEV with either the EVSE or HEMS.
5) Select grid-forming inverter:
6) Identify one main inverter, or EVSE, to grid-form or operate all inverters in parallel as grid forming.
7) Perform switching:
8) Implement the appropriate switching sequence to route electricity from PEVs to the substation
9) Implement grid restoration:

Note that the feasibility of this concept depends on (1) the capability of a central controller at the substation to communicate with the PEVs, control the PEVs output and switching, and (2) overcome the technical challenges associated with autonomous and stable operation of the many home inverters. To this end, one inverter, or EVSE, would have to be identified to grid-form both the voltage and frequency and have the remaining inverters grid follow or operate all inverters in parallel as grid forming. Details on the technical interactions and communication between multiple inverters and the grid should be studied in the future to further validate the feasibility of this.

When comparing the use of PEV parking lots to the residential PEVs, the PEV lots offer a more practical resiliency option. With the current infrastructure, all switches are manual. The PEV lot case would have a designated route to the substation and would require fewer switches to be upgraded than the residential PEV case. In addition, the technical challenges in communicating with numerous individual homes can be reduced to one communication line with the PEV lot. This further simplifies the actions by the central controller which now includes configuring the controls for one PEV lot instead of individual PEVs across the system.

# 2. Impacts of PEVs on a Smart Grid

In the previous section, use of single PEVs as well as aggregated PEVs as resiliency resources was assessed and studied in multiple scenarios for a grid outage. While PEVs can help enhance the resiliency of the community, clustered PEVs during grid-connected operations might result in negative impacts on the distribution system infrastructure including transformers under normal operation of the grid. In this section, the impact of high penetration of PEVs in the two circuits previously discussed, is assessed. Furthermore, impacts of distributed energy resources and smart charging implementation on mitigating the possible negative impacts of PEVs are assessed. Reducing the impact of PEVs on the distribution grid reduces the required investment in system upgrades and thus helps reduce/avoid costs.

## 2.1 PEV Load

Data were collected from the National Household Travel Survey (NHTS) [10] and from the Irvine SCAG report [11] on the travel patterns and population statistics associated with the system and area under study. It was determined that there were approximately 2000 households in the system under study (two circuits) as well as businesses, schools, religious buildings, and workplaces. Based on SCAG population data from 2016, an average household has 2.65 residents which result in a total of 5300 residents among the 2000 households. Based on the number of vehicles per household from the NHTS, there would be a total of 3493 vehicles. The PEV load used in this study includes workplace and home charging with 50 percent PEV market penetration. The data available include three categories of vehicles:

1) Live and Work: Both workplace and home charging occur in the system under study,

2) Commute Out: Live in the area but commute out (charging at home but workplace charging occurs elsewhere), and

3) Commute In: Those who commute into the system to work (only workplace charging occurs in the system under study).

Once the number of PEVs was determined, specifications of several popular PEV models which included the Tesla Model S, the Chevrolet Volt, Chevrolet Bolt, Tesla Model X, Nissan Leaf (ZE1), and BMW i3 were analyzed and it was determined that these PEVs have an average energy consumption of 0.293 kWh/mile. The Tesla Model S was chosen for this study due to its battery size and performance and since it has an efficiency of 0.294 kWh/mile close to the average PEV. Note also that it is assumed that the range of PEVs does not significantly impact the typical day to day commuting and traveling of the average person in California since 95 percent of the drivers have a daily vehicle miles traveled (VMT) of 100 miles and the majority have a daily VMT of 40 miles or less as shown in Figure 18.

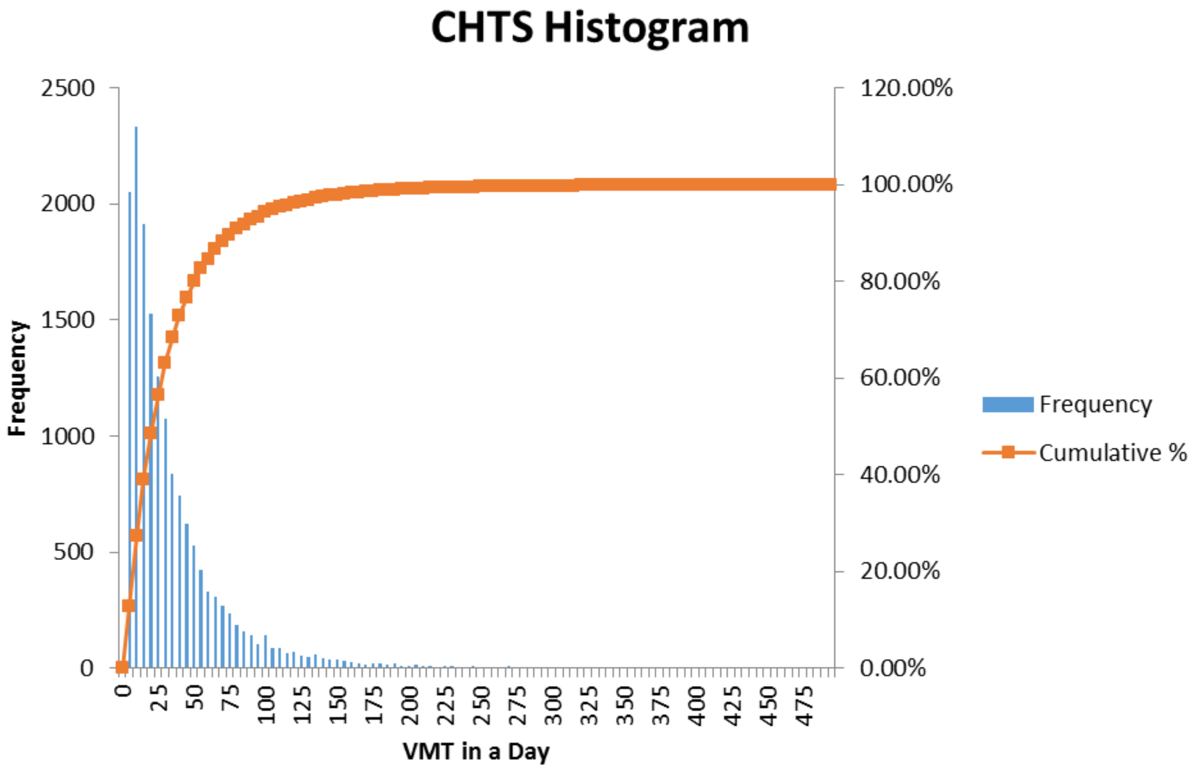


**Figure 18. Daily VMT Histogram in CA**

To establish the charging needs of this fleet of PEVs, NHTS data were used. These data suggest that trips to home make up 34.4 percent of total trips, with trips to work at 16.6 percent, and trips to other locations (largely shopping, recreational, school, and religious) make up 49.1 percent of the daily trips. The average mile per trip is 9.93, 11.98, and 8.47 miles for home trips, work trips, and other locations, respectively. Finally, based on the average trips per day per household and vehicles per household, an average trips per vehicle per day was calculated to be 2.92 trips. A MATLAB script was created to generate the number of trips from 0-6 for each PEV with selected percentages for each likelihood of each number of trips to statistically regenerate the average 2.92 trips per vehicle a day. Similarly, several trip profiles were created for each trip. This was undertaken to simulate normal driving patterns as well as to recreate the trip destination averages (home, work, and other locations). Distances for these trips chosen in a manner that the averages match the average for each trip destination.

Once the trips for each PEV were generated, the arrival times at each destination were determined. Probabilities for work arrival times were based on data from the US Census Bureau [13]. If the PEV had work as a destination for one of its trips, the time they arrive at work is determined as well as the dwell time (how long they stay at work). Dwell time at work was determined using data from Lombardi, et al. [14]. Arrival and departure times associated with other destinations are then based on the work arrival and dwelling time with a time resolution of one hour. If daily trips of a specific PEV do not include a work trip, the schedule was based on the last trip home. Home arrival time probabilities were based on data collected from the PEVs in the previous ISGD project. The PEVs in that project were mostly used for local driving, and not as commuter vehicles, and thus the data are a good representation for home arrival times for a day without a work trip. A PEV charging and travel profile was generated which included locations, arrival/departure times, and SOC of the PEV which was determined by the distance of each trip. The PEV charging load was then added to the home loads previously discussed in order to assess the impact of 50 percent PEV market penetration on the distribution system infrastructure.

For the purposes of analyzing the impact on transformers, only home charging occurring on Circuit A was considered, and it was assumed that the vehicles did not have access to charging at their workplace. This characterized a worst-case scenario regarding the impact on distribution system infrastructure and planning. The resulting daily VMT for PEVs in Circuit A used to determine the PEV charging needs is shown in Figure 19. Note that 12 percent of the vehicles have a daily VMT of 10 miles or less including the vehicles that are not driven at all on a specific day. This is consistent with the input data used. Workplace charging in included when assessing the environmental impacts.

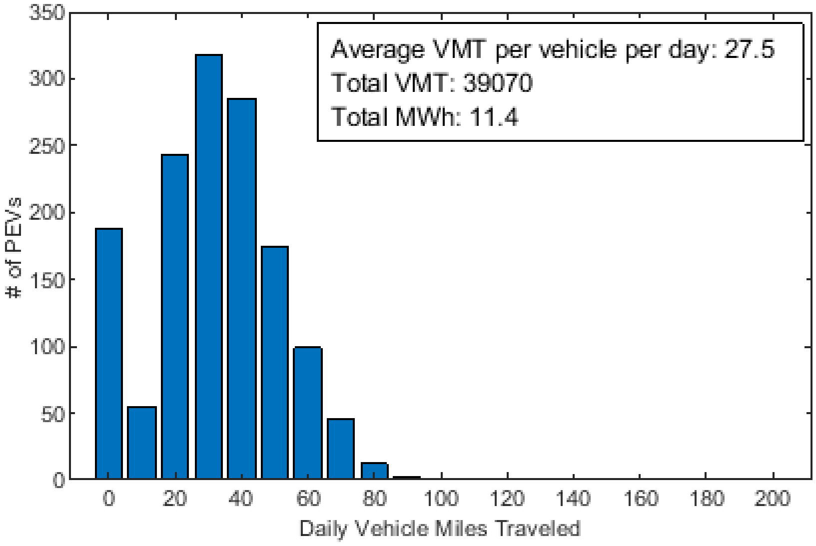


**Figure 19. Daily VMT for PEVs on Circuit A**

A summary of home arrival and departure times for the PEV set developed is shown in Figure 20. This figure shows the distribution of home arrival and departure times which was used to determine the home charging requirements of the PEV fleet.

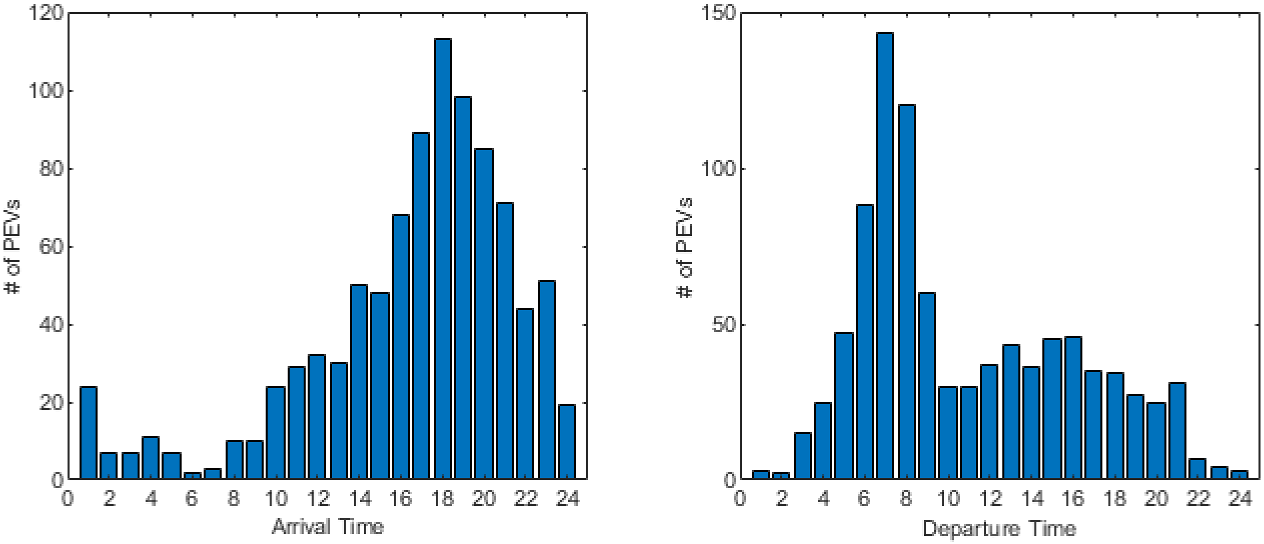


**Figure 20. Home Arrivals and Departure Distributions**

## 2.2 Smart Charging

In the previous section, PEV fleet electricity demand was determined based on the arrival/departure times at various destinations, as well as the SOC and required SOC for the next trip assuming that the PEV starts charging right away when plugged in. This will be referred to as *uncontrolled* charging. A smart charging strategy previously developed by APEP [6], was used to develop optimized charging profiles for the PEV. This smart charging strategy is based on valley-filling. The objective of the optimization is shown in Equation (3). This equation represents the energy cost. C($t_i$) is the most recent broadcasted cost of electricity at timestep $t_{i,}$ (\$/kWh) and $x_n$(ti) is the energy consumed by the $n^{th}$ PEV during timestep $t_i$. In this study, the circuit loads are used as an indication for the cost. When a PEV plugs in, the C($t_i$) is updated for the next time step and the next PEV.

$$\boldsymbol{minimize}\left\{\sum\nolimits_i \left(\boldsymbol{C}(\boldsymbol{t_i}) \times \boldsymbol{x_n}(\boldsymbol{t_i})\right)\right\} \qquad \text{Eq(3)}$$

The main constraint of the optimization is shown in Equation (4). In this equation, $b_n$ is the total charging energy required for the $n^{th}$ PEV for 24 hours or for the duration that the PEV is connected to the charger, and Δt is the timestep duration.

$$\Delta \boldsymbol{t} \times \sum\nolimits_i \boldsymbol{X}\,(\boldsymbol{t}[\boldsymbol{i}]) = \boldsymbol{B} = \sum\nolimits_n \boldsymbol{b}[\boldsymbol{n}] \qquad \text{Eq(4)}$$

Other constraints include departure time of the PEV as well as the required SOC at the end of the charging session.

The smart charging was modified to minimize the GHG emissions from the charging of the vehicles. This was done by replacing the C($t_i$) in Equation (3) with the CA grid GHG emission factor at time $t_i$. This will be referred to as *Emission Smart Charging.*

## 2.3 Load on Transformers

For all the residential transformers on Circuit A, the load was determined by adding the PEV loads. This circuit includes sixty-nine 50kVA transformers, one hundred and eight 75kVA transformers, and three 100kVA, transformers. Based on the data collected from the system, it was assumed that 6, 9, and 12 homes are located on each 50kVA, 75kVA, and 100kVA transformer, respectively. With 50 percent PEV market penetration, each home includes a PEV. The travel and trip plans for each PEV were determined using the strategy previously discussed. For *uncontrolled charging,* the PEV load was added to the home loads. For *smart charging* and *emission smart charging,* the optimization was implemented on each transformer and was used to determine the charging profiles. For home base electricity demand, two scenarios were simulated: (1) Low load condition based on the ZNE home loads with energy efficiency measures and smart appliances, and (2) High load condition based on control block load without the aforementioned measures. Furthermore, for each scenario, three DER configurations were simulated: (1) No DER, (2) CES, and (3) RESU. Note that for the CES and RESU, the maximum allowable PV and battery energy storage previously determined in Lee, Razeghi, and Samuelsen [8] are assumed to be deployed on the home and on the overall circuit. In the CES configuration, a 25kW/50kWh community storage device (battery energy storage) is deployed on each block. In the RESU configuration, each home includes a 4kW/10kWh battery energy storage device. The results of the simulations are provided below.

### 2.3.1 Low Load Condition

For the low-load condition, it is assumed that the homes have implemented energy efficiency measures and include smart appliances. Data from the ZNE block were used for this purpose. The sum of the load on all 180 transformers under study is shown in Figure 21 for the case with no DER deployed on the circuit. The results show that both smart charging strategies help reduce the peak demand significantly (by almost 1 MW). The sharp peaks and valleys in the figure, especially for the uncontrolled charging are due to hourly resolution of the PEV travel plan both for arrival and departure. Time resolution for running the smart charging strategies was one minute; however, the hourly resolution departure times resulted in the sharp valleys. Also note that optimization was done for each transformer using the specific load on that transformer.

Results for the CES and RESU circuit configurations are provided in Figure 22 and Figure 23. Smart charging strategies in circuits with DERs with different configurations (CES and RESU) also help reduce the peak demand, as well as shifting the PEV load to times when PV is available. Note that all the PEV load cannot be shifted to the times when extra PV is available because of home arrival and departure constraints. This is depicted in Figure 24 showing two 50kVA transformers. For one of these transformers shown in Figure 24a, the PEV arrival and departure times do not allow for charging during excess PV times, while for the other transformer shown in Figure 24b, some of the PEV load is shifted to high-PV times. Larger community or residential batteries can help further take advantage of excess PV which is otherwise exported to the larger grid or curtailed depending on the interconnection agreements.

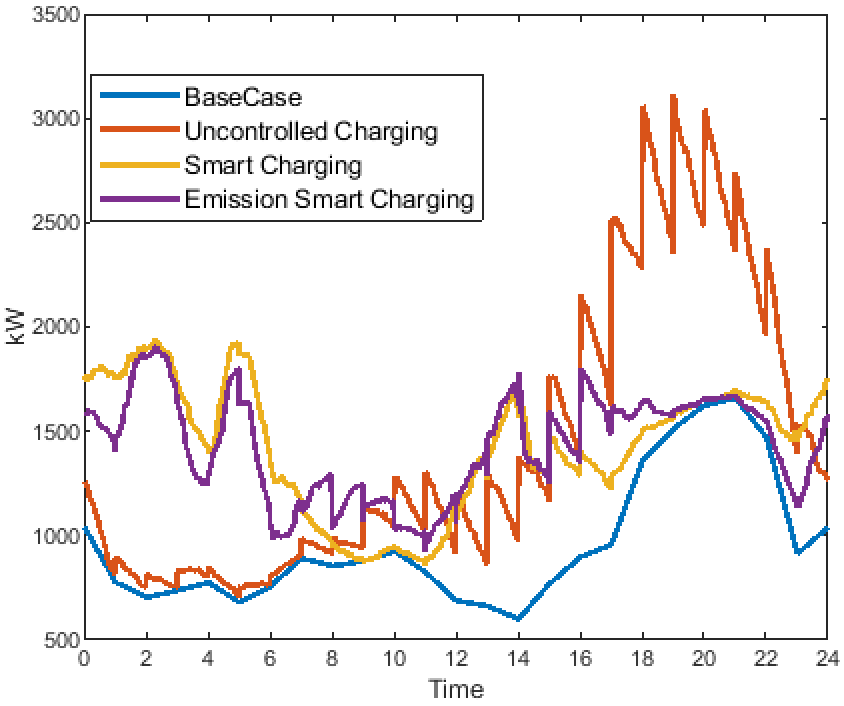


Figure 21. Load on All Residential Transformers-Low Load Condition Without DERs on Circuit A

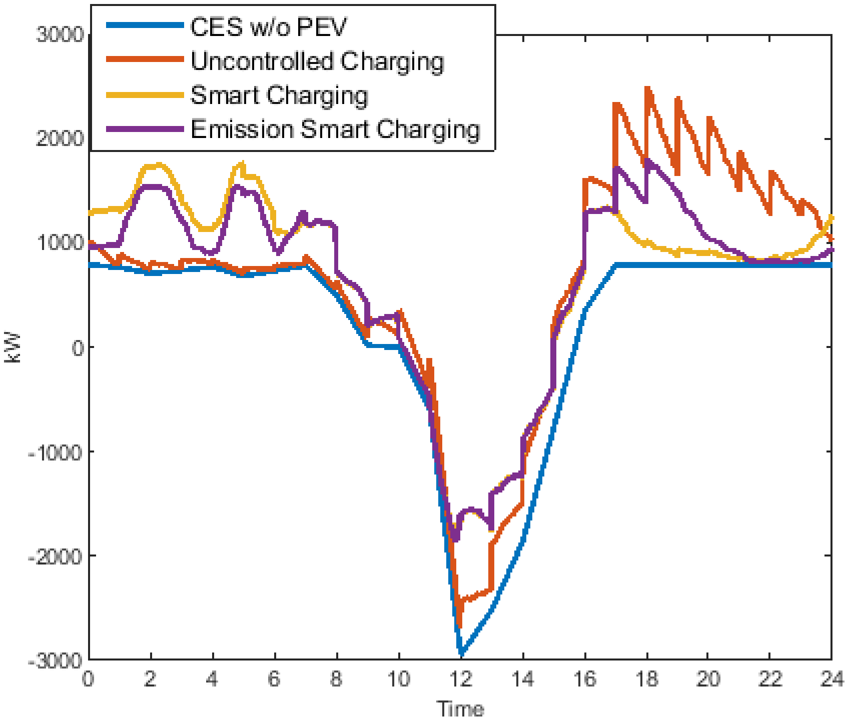


Figure 22. Load on All Residential Transformers- Low Load Condition, CES

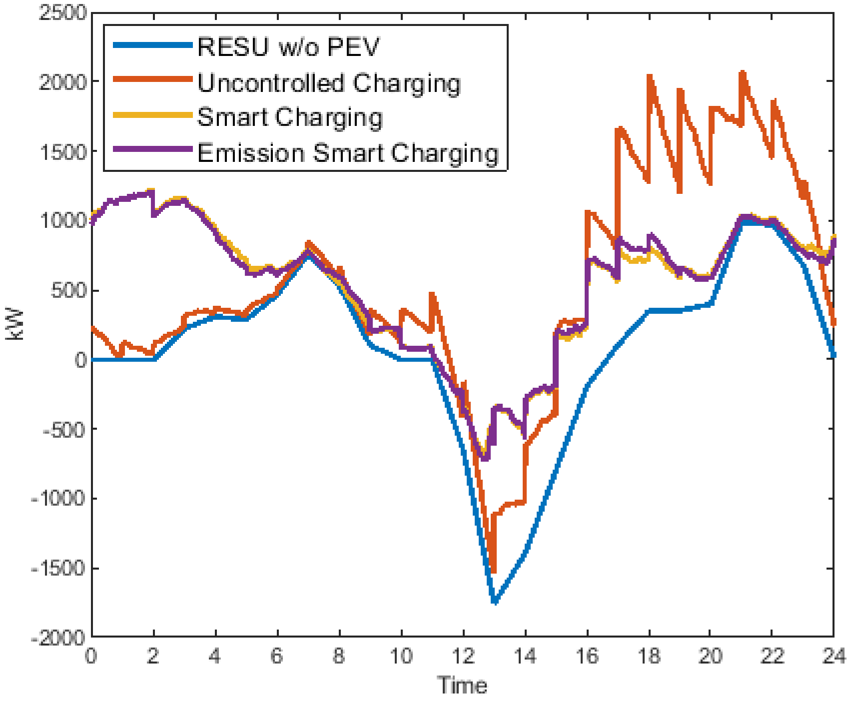
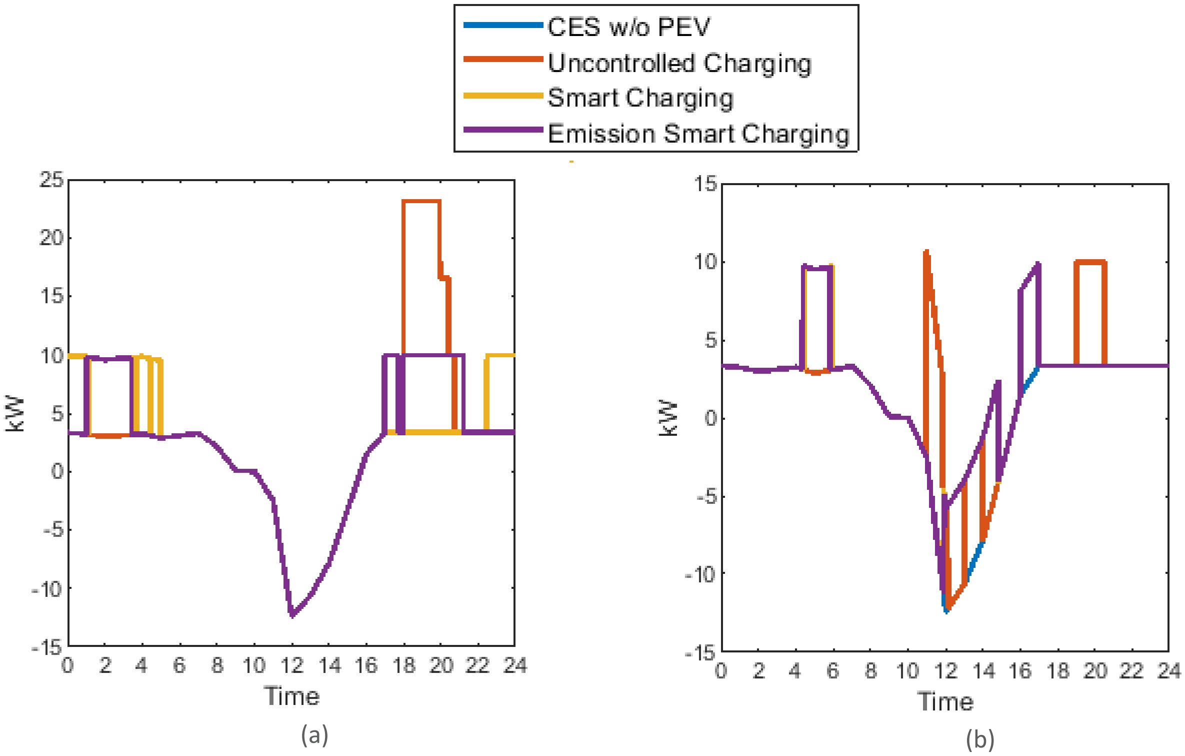


Figure 23. Load on All Residential Transformers- Low Load Condition, RESU



(a)

(b)

Figure 24. Load on Specific 50 kVA Transformers- Low Load Condition, CES. (a) T12, (b) T65

### 2.3.2 High Load Condition

For the high-load condition, it is assumed that the homes have not been retrofitted with energy efficiency measures and smart and more efficient appliances. For this purpose, the home loads from the control block are used. All the simulations are repeated which include three circuit configurations (no DER, CES, and RESU) and three charging strategies (uncontrolled, smart, and emission smart charging). The resulting load on all 180 transformers for the case without any DERs is shown in Figure 25. As expected, the overall load is higher for this scenario because the baseload is higher. Both smart charging strategies result in significant reduction in peak load demand (more than 1 MW) and shift the PEV load to times with low demand or low GHG emission factors.

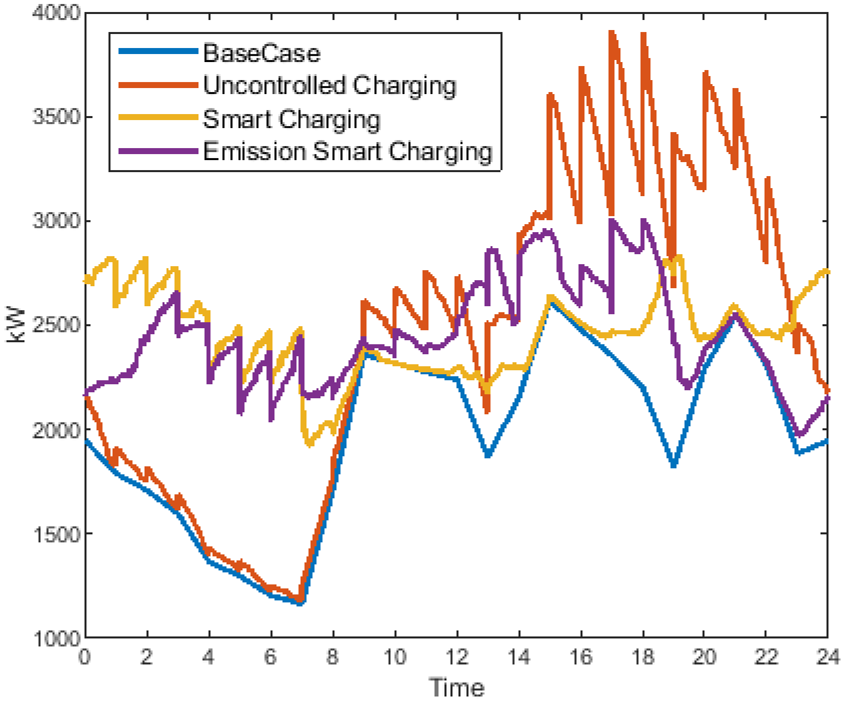


**Figure 25. Load on All Residential Transformers-High Load Condition Without DERs on Circuit A**

The simulations were repeated for the CES and RESU circuit configurations and the results are shown in Figure 26 and Figure 27. Smart charging strategies result in lower peak demand and they help shift the PEV load to times when PV is available and thus increase the renewable energy usage at the local level. These strategies can further help integration of additional renewable resources in the distribution system without violating system constraints such as voltage limits. The load on two 50 kVA transformers (T12 and T65) for the CES circuit configuration is shown in Figure 28. This figure shows that the success in use of renewable energy for PEV charging depends on the travel plan of PEVs. Changes in driver behavior as well as increasing the size of energy storage — community storage or residential storage — both can help further increase the use of renewable energy in the distribution system and reduce the impact of PEVs on the grid as a result.

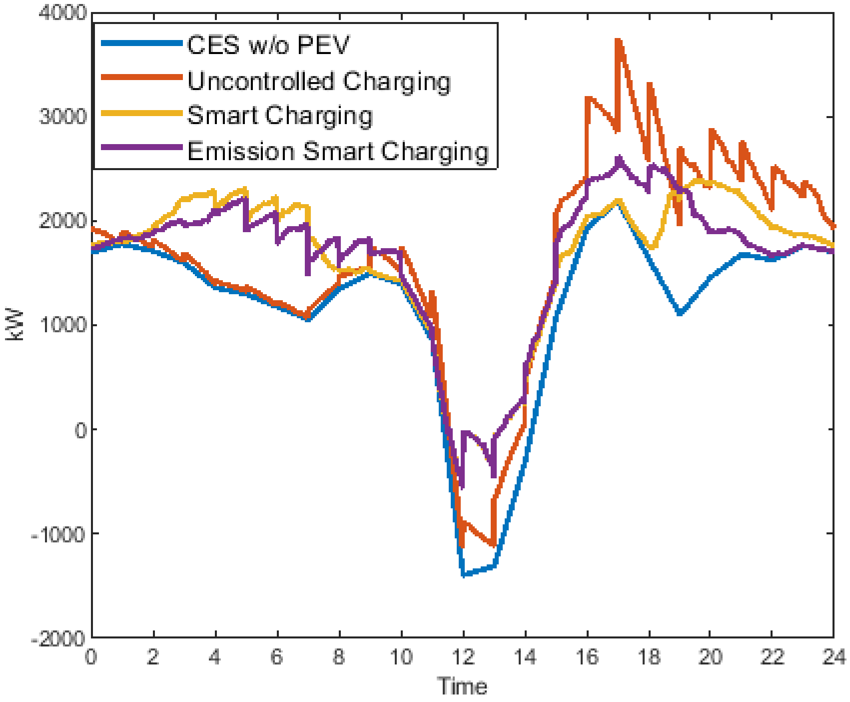


Figure 26. Load on All Residential Transformers-High Load Condition, CES

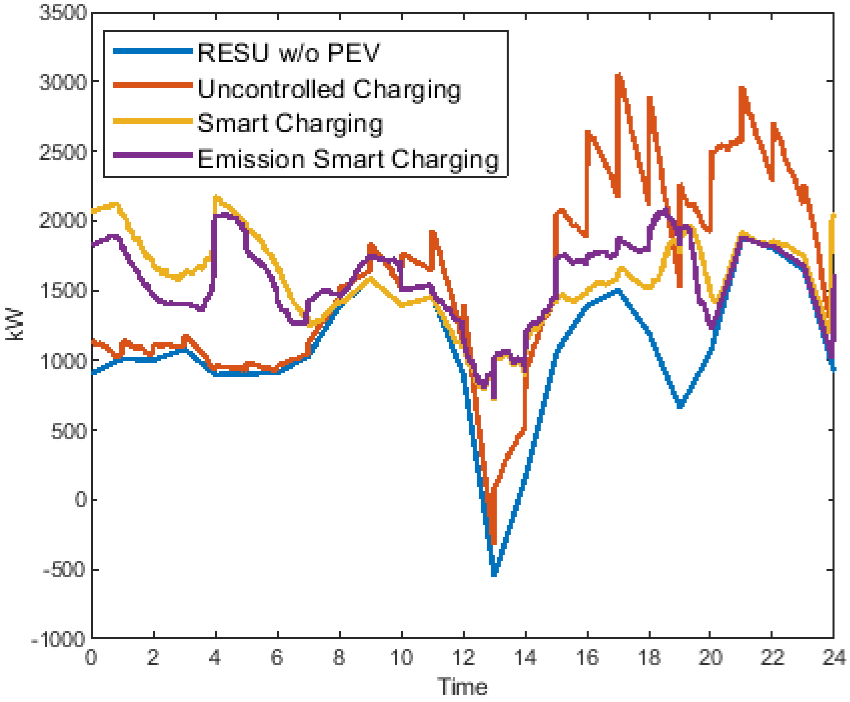
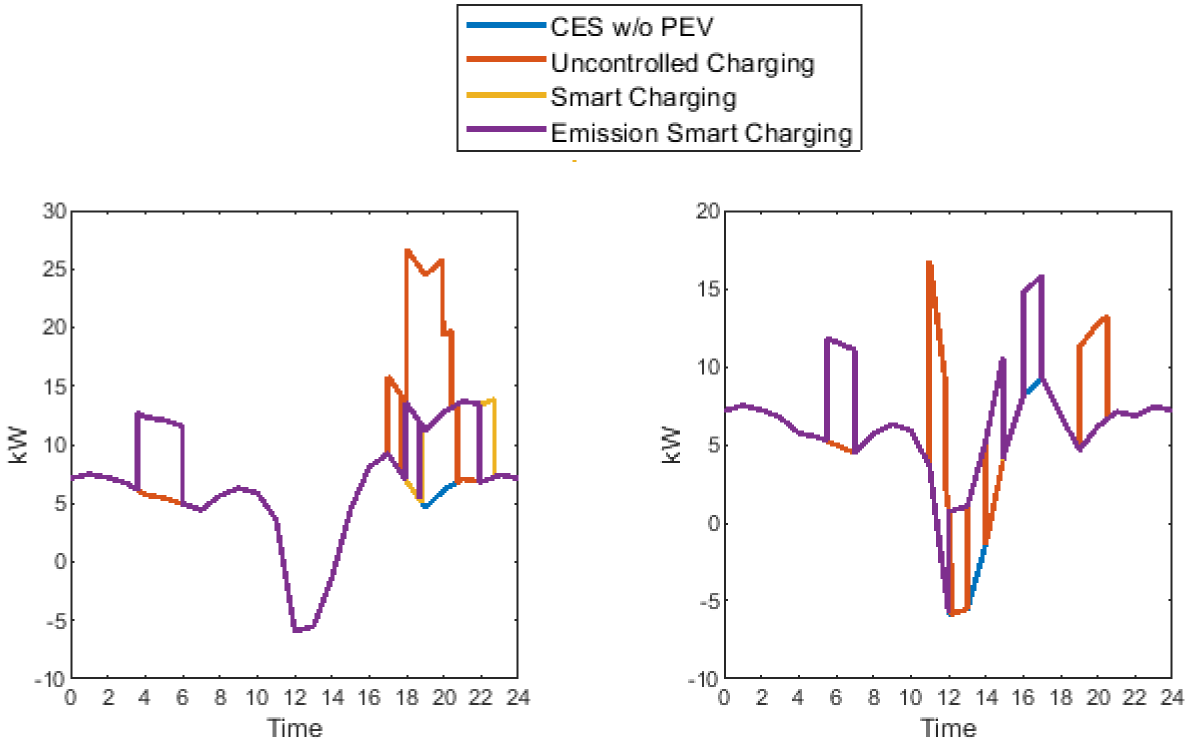


Figure 27. Load on All Residential Transformers-High Load Condition, RESU



(a) (b)

Figure 28. Load on Two 50 kVA Transformers- High Load Condition, CES. (a) T12, (b) T65

## 2.4 Impact on the Infrastructure

The major factor in transformer loss of life is the degradation of the winding insulation due to thermal stress which can be predicted by estimating the Hot Spot Temperature (HST), the highest temperature observed in the winding. A heat transfer model for oil-immersed transformers, previously developed by Razeghi et al.[15], was used to determine the HST of the transformers in each of the scenarios that was simulated. The model assumed a constant ambient temperature of 30°C. In this analysis, ambient temperatures derived from the daily temperature profile for a summer day in southern California are used.

First the load factor and the HST are compared to the limits recommended by IEEE C.57.91 (Table 5). If any one of these three limits is reached, the transformer is highly likely to fail. The IEEE standard is then used to determine the Equivalent Aging Factor (EAF) and loss of life based on the dynamic HST calculations.

**Table 5. Recommended limits of temperature and loading for a distribution transformer**

| | |
|---|---|
| Oil temperature | 120°C |
| Winding hot spot temperature | 200°C |
| Short time loading (30 minutes or less) | 200% or 300 % |

As previously mentioned the model previously developed by Razeghi et al. [15], was used in this project. For an oil-immersed transformer the HST is calculated from Equation (3).

$$\theta_{HST} = \theta_{amb} + \Delta\theta_{Oil} + \Delta\theta_{HST} \tag{Eq(3)}$$

Temperature rise of the oil over ambient ($\Delta\vartheta_{oil}$) for each time step can be calculated from Equations (5)-(6).

$$\Delta\theta_{Oil} = \left(\Delta\theta_{Oil,U} - \Delta\theta_{Oil,i}\right)\left\{1 - \exp\left({-t}/{\tau_{oil}}\right)\right\} + \Delta\theta_{Oil,i} \tag{Eq(4)}$$

$$\Delta\theta_{Oil,i} = \Delta\theta_{Oil,R}\left[\frac{(K_i^2\, R + 1)}{R + 1}\right]^n \tag{Eq(5)}$$

$$\Delta\theta_{Oil,U} = \Delta\theta_{Oil,R}\left[\frac{(K_U^2 R + 1)}{R + 1}\right]^n \tag{Eq(6)}$$

Similarly, the hot spot temperature rise over the oil can be calculated from Equations (7)-(9).

$$\Delta\theta_{HST} = \left(\Delta\theta_{HST,U} - \Delta\theta_{HST,i}\right)\left\{1 - \exp\left({-t}/{\tau_w}\right)\right\} + \Delta\theta_{HST,i} \tag{Eq(7)}$$

$$\Delta\theta_{HST,i} = \Delta\theta_{HST,R}\, K_i^{2m} \tag{Eq(8)}$$

$$\Delta\theta_{HST,U} = \Delta\theta_{HST,R}\, K_U^{2m} \tag{Eq(9)}$$

The Aging Acceleration Factor (AAF) is determined using Equation 10. Empirical formulas suggest that the insulation degradation with time and temperature follows the Arrhenius reaction rate theory. The reference temperature is assumed to be 110°C (at rated power) for which the aging acceleration factor is unity. For temperatures over 110°C, the aging acceleration factor is greater than 1 showing that the aging accelerates as the temperature rises.

$$AAF = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_{HST} + 273}\right) \tag{Eq(10)}$$

After AAF calculation the EAF is calculated using Equation (11) for a specific time period. For the purposes of this study, 24 hours is chosen.

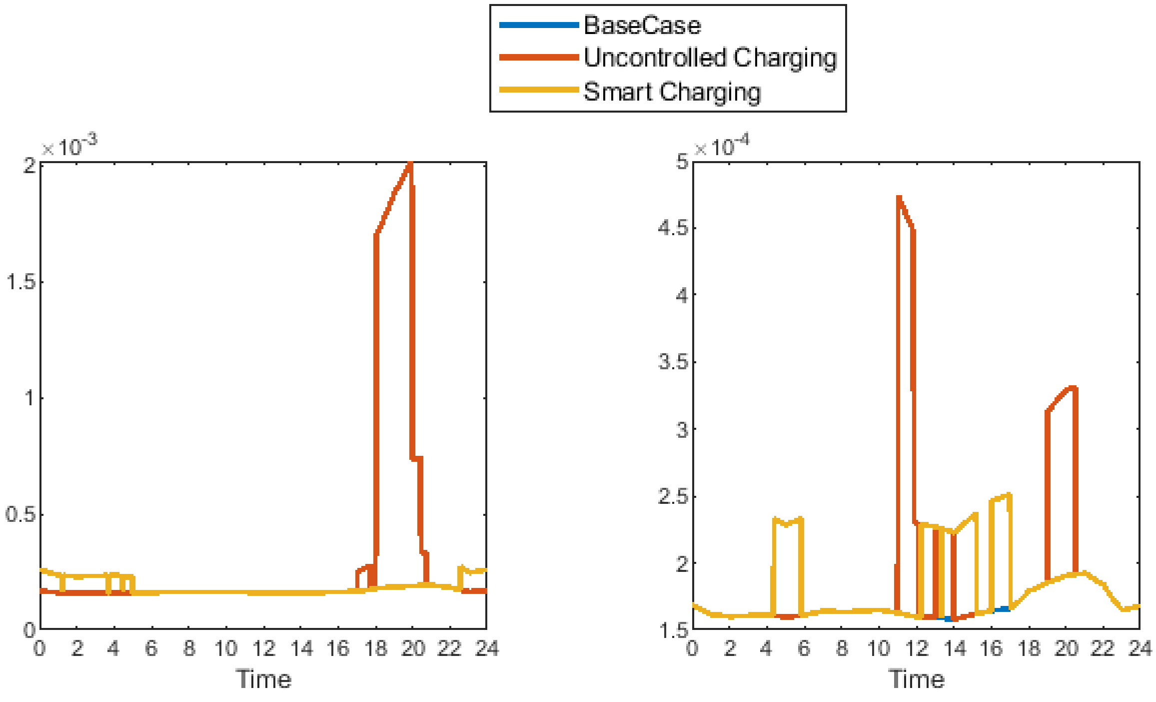
$$EAF = \left(\sum_{i=1}^{N} AAF_i\, \Delta t_i\right) \Big/ \sum_{i=1}^{N} \Delta t_i \tag{Eq(11)}$$

The model described was applied to all the 180 residential transformers under study for all scenarios and circuit configurations. The results for the BaseCase (i.e., without PEVs and without DERs) are summarized in Table 6 for the low-load condition as well as the high load condition. Small equivalent aging factors imply that these transformers are well designed and oversized for the circuit. As expected, the high load condition results in greater EAF.

**Table 6. Equivalent Aging Factor for a Period of 24 h- BaseCase**

| Case Description | 50 kVA | | 75 kVA | | 100 kVA | |
|---|---|---|---|---|---|---|
| | Avg | Max | Avg | Max | Avg | Max |
| Low-load condition | 1.674E-4 | 1.674 E-4 | 1.674 E-4 | 1.674 E-4 | 1.611 E-4 | 1.611 E-4 |
| High-load condition | 2.140 E-4 | 2.140 E-4 | 2.140 E-4 | 2.140 E-4 | 1.859 E-4 | 1.859 E-4 |

Simulations are repeated for the low-load scenario with three circuit configurations (No DER, CES, and RESU) and three charging strategies (uncontrolled, smart and emission smart charging). The resulting AAF for two 50 kVA transformers for cases without DERs is shown in Figure 29 for uncontrolled and smart charging. This figure shows that smart charging prevents accelerated aging of the transformer due to PEV load.



(a) (b)

**Figure 29. AAF for Specific 50 kVA Transformers- Low Load Condition, No DER. (a) T12, (b) T65**

In Table 7, EAF results for the low-load scenarios are summarized. This table shows the percent change in average and max EAF compared to the low-load BaseCase shown previously in Table 6. None of these cases under the low-load condition resulted in transformer failure or high HST. The addition of PEVs without any charging strategy (uncontrolled charging), with different circuit configuration resulted in a 10-18 percent increase in average EAF and up to a 64 percent increase in max EAF was observed among 180 transformers. Smart charging strategies were shown to help mitigate the increase in aging of the infrastructure. Simulating various smart charging strategies resulted in a 7-14 percent decrease in average EAF and an 8-40 percent reduction in max EAF compared to uncontrolled charging.

**Table 7. Percent Change in Equivalent Aging Factor for a Period of 24 h-Low Load Condition**

| Case Description | Charging Strategy | 50 kVA | | 75 kVA | | 100 kVA | |
|---|---|---|---|---|---|---|---|
| | | Avg | Max | Avg | Max | Avg | Max |
| PEV (w/o DER) | Uncontrolled | 33.57 | 109.62 | 23.48 | 74.25 | 26.82 | 35.69 |
| | SC | 13.80 | 24.61 | 11.23 | 22.76 | 15.95 | 20.48 |
| | EmSC | 14.04 | 25.51 | 11.29 | 20.25 | 15.64 | 20.73 |
| | | | | | | | |
| CES w/o PEV | NA | 1.55 | 1.55 | 1.55 | 1.55 | 0.62 | 0.62 |
| CES | Uncontrolled | 19.12 | 65.89 | 13.02 | 43.07 | 18.68 | 23.71 |
| | SC | 7.11 | 19.06 | 4.54 | 13.62 | 9.75 | 12.85 |
| | EmSC | 7.35 | 20.13 | 4.60 | 12.84 | 9.81 | 13.04 |
| | | | | | | | |
| RESU w/o PEV | NA | -5.32 | -5.32 | -5.32 | -5.32 | -3.17 | -3.17 |
| RESU | Uncontrolled | 9.74 | 40.44 | 4.54 | 29.45 | 8.63 | 13.53 |
| | SC | -0.84 | 6.75 | -2.57 | 2.63 | 1.74 | 3.91 |
| | EmSC | -0.84 | 6.81 | -2.57 | 2.45 | 1.74 | 3.91 |

The simulations were repeated for the high-load scenario. The AAF results for two 50 kVA transformers (T12 and T65) are provided in Figure 30. As expected, the AAF for the high-load scenarios are greater compared to the low-load scenarios, and thus the addition of PEVs results in even faster aging of the transformers and they will need to be replaced earlier than they were designed for. The EAF results for all cases of the high-load scenario are summarized in Table 8. This table shows the change in average and max EAF (%) compared to the high-load BaseCase provided in Table 6. None of these cases under the high-load condition resulted in transformer failure or high HST.

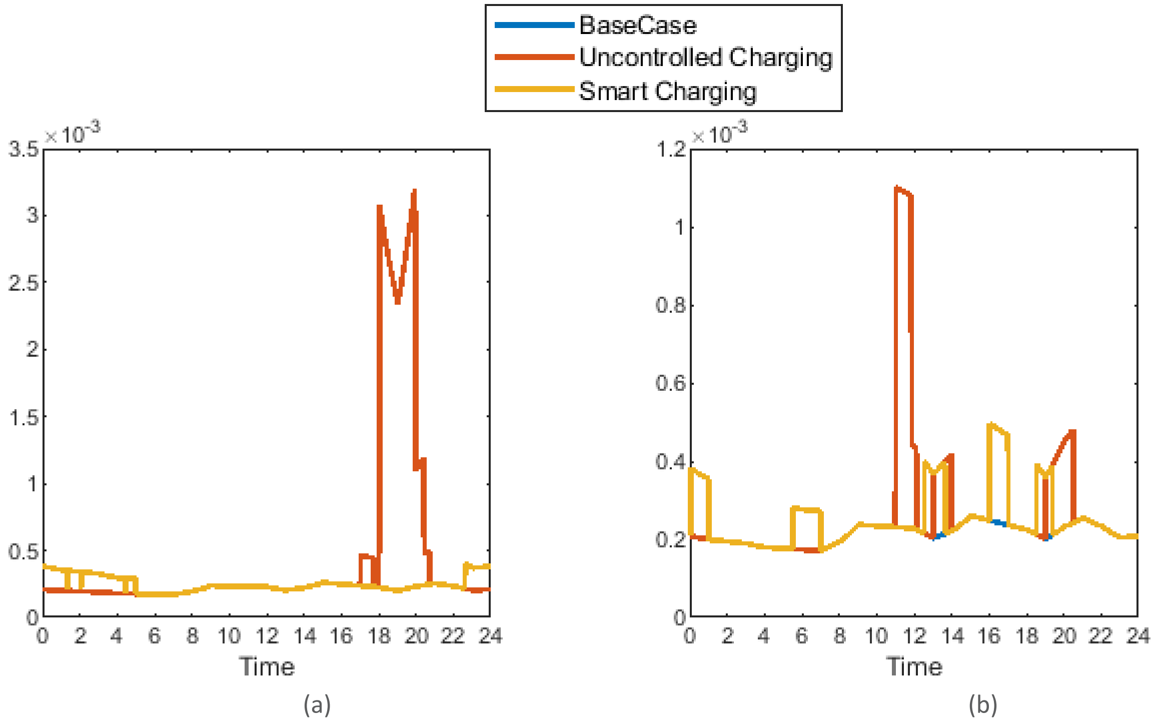


**Figure 30. AAF for Two 50 kVA Transformers- High Load Condition, No DER. (a) T12, (b) T65**

**Table 8. Percent Change in Equivalent Aging Factor for a Period of 24 h-High Load Condition**

| Case Description | Charging Strategy | 50 kVA |  | 75 kVA |  | 100 kVA |  |
|---|---|---|---|---|---|---|---|
|  |  | Avg | Max | Avg | Max | Avg | Max |
| PEV (w/o DER) | Uncontrolled | 53.41 | 153.41 | 38.13 | 118.79 | 55.35 | 74.13 |
|  | SC | 20.37 | 38.46 | 17.29 | 31.96 | 37.22 | 43.14 |
|  | EmSC | 22.10 | 41.68 | 18.50 | 39.07 | 36.79 | 45.45 |
|  |  |  |  |  |  |  |  |
| CES w/o PEV | NA | -14.39 | -14.39 | -14.39 | -14.39 | -8.66 | -8.66 |
| CES | Uncontrolled | 15.33 | 78.13 | 7.34 | 70.19 | 24.21 | 36.36 |
|  | SC | -1.92 | 10.89 | -4.53 | 5.75 | 11.30 | 16.35 |
|  | EmSC | -1.26 | 14.30 | -3.97 | 6.92 | 11.40 | 17.00 |
|  |  |  |  |  |  |  |  |
| RESU w/o PEV | NA | -19.07 | -19.07 | -19.07 | -19.07 | -11.62 | -11.62 |
| RESU | Uncontrolled | 6.26 | 47.15 | -0.70 | 36.26 | 13.77 | 24.74 |
|  | SC | -7.99 | 2.66 | -10.05 | -0.51 | 3.98 | 8.45 |
|  | EmSC | -7.48 | 3.64 | -9.72 | -0.84 | 4.20 | 8.77 |

The addition of PEVs without a charging strategy (uncontrolled charging) results in a 23-55 percent increase in the average EAF depending on the circuit configuration and transformer size, and up to a 150 percent increase in the max EAF indicating that at least for a few transformers, the accelerated aging in significant. The transformer most impacted is a 50 kVA transformer -T60. For this transformer, the AAF is shown in Figure 31 indicating that the AAF is an order of magnitude greater for this transformer compared to other transformers such the ones shown previously in Figure 30. To avoid service interruptions in practice, this transformer needs to be replaced sooner than the other transformers in the system.

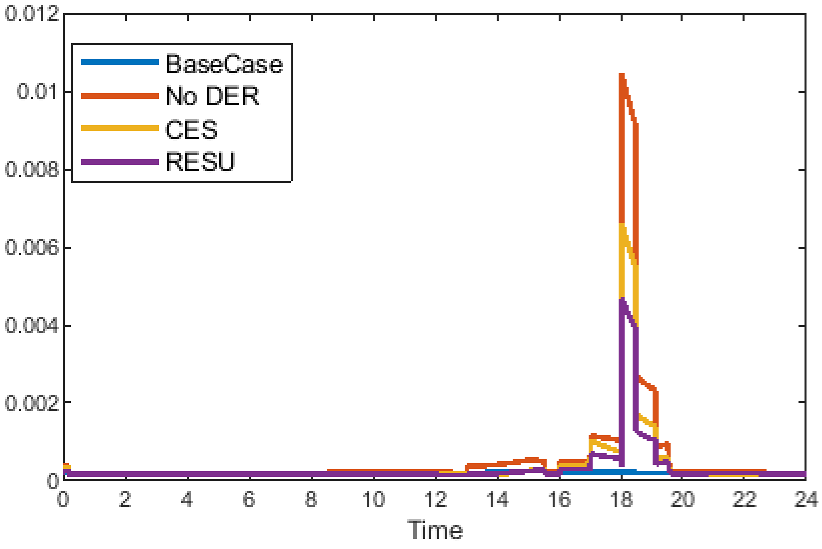


**Figure 31. AAF for T60, High Load, Uncontrolled Charging**

Implementing smart charging strategies, results in a 5-21 percent reduction in average EAF and a 7-45 percent reduction in max EAF compared to uncontrolled charging depending on the circuit configuration (No DER, CES, and RESU) and the transformer. For the transformer most impacted by PEVs (T60), the AAF with smart charging is provided in Figure 32. This figure shows that implementing smart charging significantly decreases the rate of aging of this transformer and thus it will not need to be replaced earlier with the addition of PEVs charging load in the circuit.

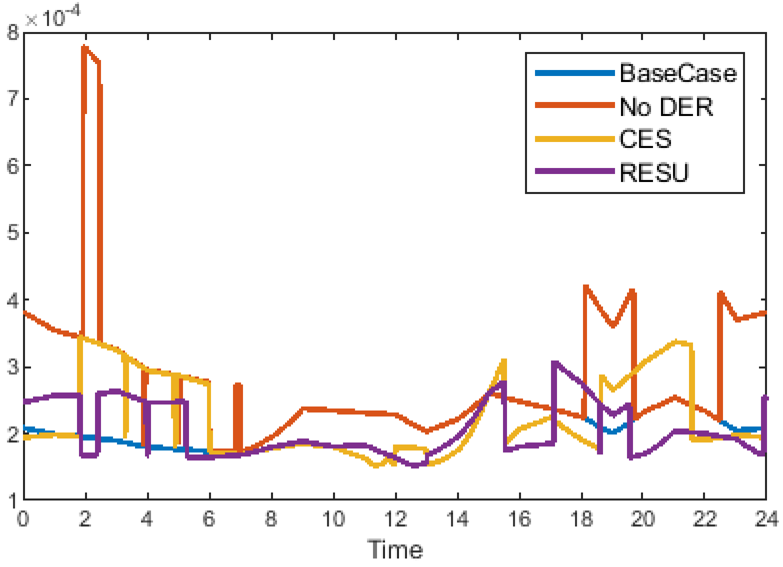
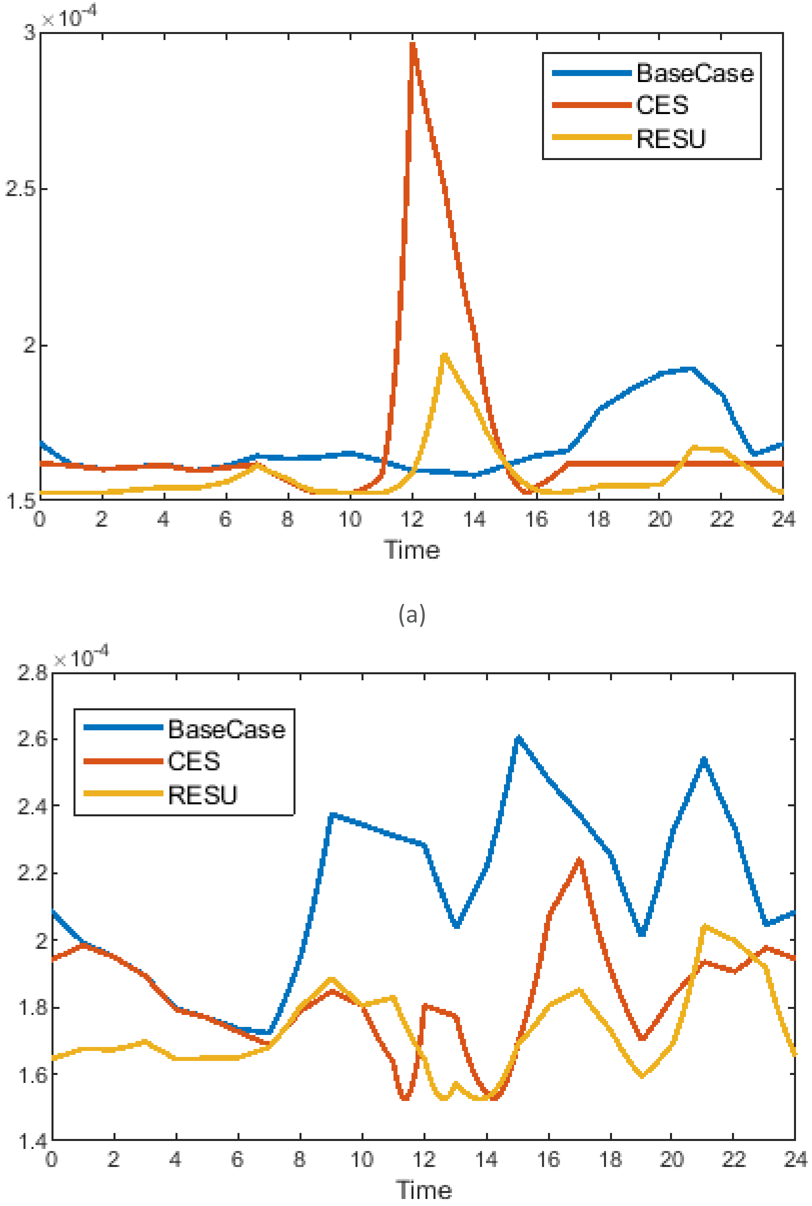


**Figure 32. AAF for T60, High Load, Smart Charging**

It is interesting to note that although the RESU configuration results in slowing the aging of the transformers on average, the CES configuration results in a slight increase in aging (compare CES w/o PEV and RESU w/o PEV in Table 7) for the low-load scenario. This is due to the fact that in the CES configuration, significant reverse power flow in the transformer results in high HST and faster aging, where RESU results in smaller export to the grid. This can be seen in results provided in Section 2.3 and is further shown in Figure 33. For the high-load scenario, both CES and RESU slow the aging of the transformers. Because of the greater load demand during high PV times, the export to the grid and the reverse power flow going through the transformer is lower resulting in lower HST.



(a)

(b)

**Figure 33. Transformer AAF Without PEVs: (a) Low Load, and (b) High Load**

# 3. Environmental Impacts

In this section, the environment impacts and benefits of the strategies discussed in this project are assessed. First, the environmental benefits of using PEVs during grid outages as resiliency resources are studied by comparing the $NO_x$ emissions to that of backup generators including diesel and gasoline backup generators. Next, the impact of using PEVs and different charging strategies during normal grid operations are assessed.

## 3.1 Grid Outages and Events

In this subsection, the benefits of using PEVs as resiliency resources during grid outages and events are assessed. A recent report by the California Air Resources Board (ARB) [16] addressed the 2019 PSPS occurrences and indicated that the backup generators emitted a significant amount of $NO_x$ and PM during these events. The report also included a survey of backup generators showing that the majority of the gasoline backup generators were between 2-5 hp with a $NO_x$ emission factor of 1.484 g/bhp.hr (~4.363 lb/MWh). For the V2H scenarios, the energy supplied by the PEVs during a 24-hour outage is shown below in Figure 34 for homes with ZNE and control block loads. In the absence of V2H, and in order to avoid dropping any loads, this energy would be supplied using backup generators. Assuming that the PEVs are charged using the California grid with a $NO_x$ emission factor of 0.377 lb/MWh, use of PEVs instead of gasoline backup generators results in reduction of 40-100 lb of $NO_x$ per day for the entire 2000 households depending on the home electricity base demand.

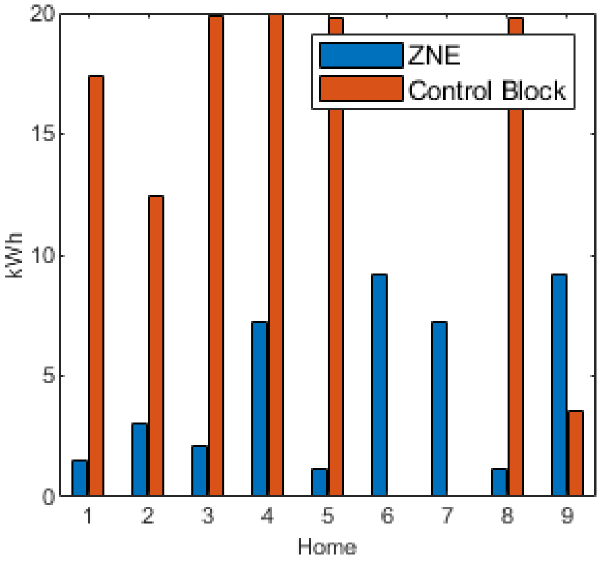


**Figure 34. Energy Supplied by PEV in a 24-hr Outage**

Note that the $NO_x$ reduction mentioned is associated only with the portion of the home loads supplied by the PEVs and does not include power generation from the PV panels nor electricity supplied by the battery energy storage. If the output of PV and battery is considered, the overall home nanogrids result in a $NO_x$ reduction of 145-250 lb per day for the entire 2000 households compared to backup generators.

For PEV lots serving critical loads, the emission reduction depends on the size of the critical load. For critical loads and facilities, larger diesel back-up generator would be used which have an average $NO_x$ emission factor of 6.7 b/bhp.hr. For a 1MW critical load, using PEVs results in $NO_x$ reduction of 450 lb per day.

For grid restoration using PEVs, the maximum power (1.5 MW) determined to overcome the inrush is required only for a very short time. However, to achieve this using blackstart or backup generators, a large (1.5-2 MW) blackstart generator is still required or several smaller ones fired in order to supply the inrush current of the transformer. Assuming that the cold start-up of the back-up generator takes 30 minutes to 2 hours, and using an emission factor of 18.9gr/sec for $NO_x$ [17] to account for start-up emissions, using PEVs for this purpose results in a 77- 300 lb/event $NO_x$ reduction.

## 3.2 Normal Grid Operations

Deploying PEVs results in a significant reduction in emissions from the transportation sector since these vehicles have zero tailpipe emissions. To determine temporal emissions from the vehicles, the daily VMT distribution derived from the California Air Resources Board. Emission Factor database [18] was used (shown in Figure 35). For the baseline, all light-duty vehicles were assumed to be conventional internal combustion or diesel engines, and for the baseline fleet, tailpipe emission factors were derived from EMFAC [18]. For cases with PEVs, depending on the PEV market penetration (50 percent in this study), it was assumed that a similar percentage of the VMT is associated with PEVs with zero tailpipe emissions.

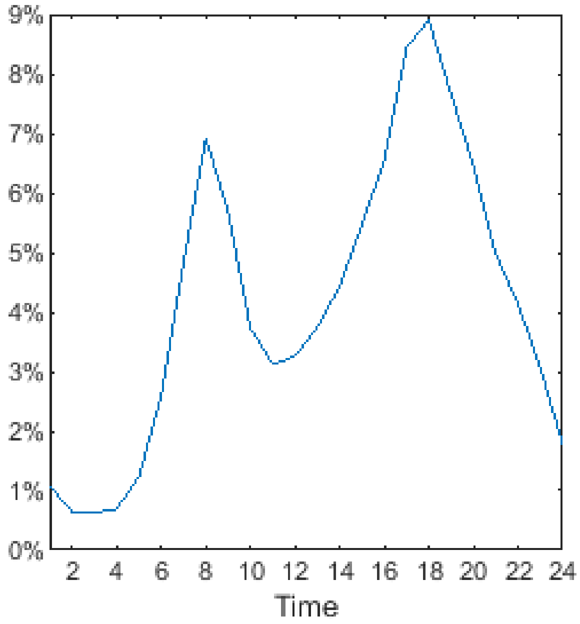


**Figure 35. Average Daily VMT Distribution**

However, to fully understand the impact of PEVs, the interaction of PEVs with the grid and emissions associated with PEV charging must be taken into account. For the scenarios studied in this project, the resulting GHG emissions from electricity generation for PEV charging are estimated by determining the import from the grid for each case and multiplying it by the grid emission factor (shown in Figure 36). Note that electricity generated by the DERs (PV+energy storage) has no GHG emissions.

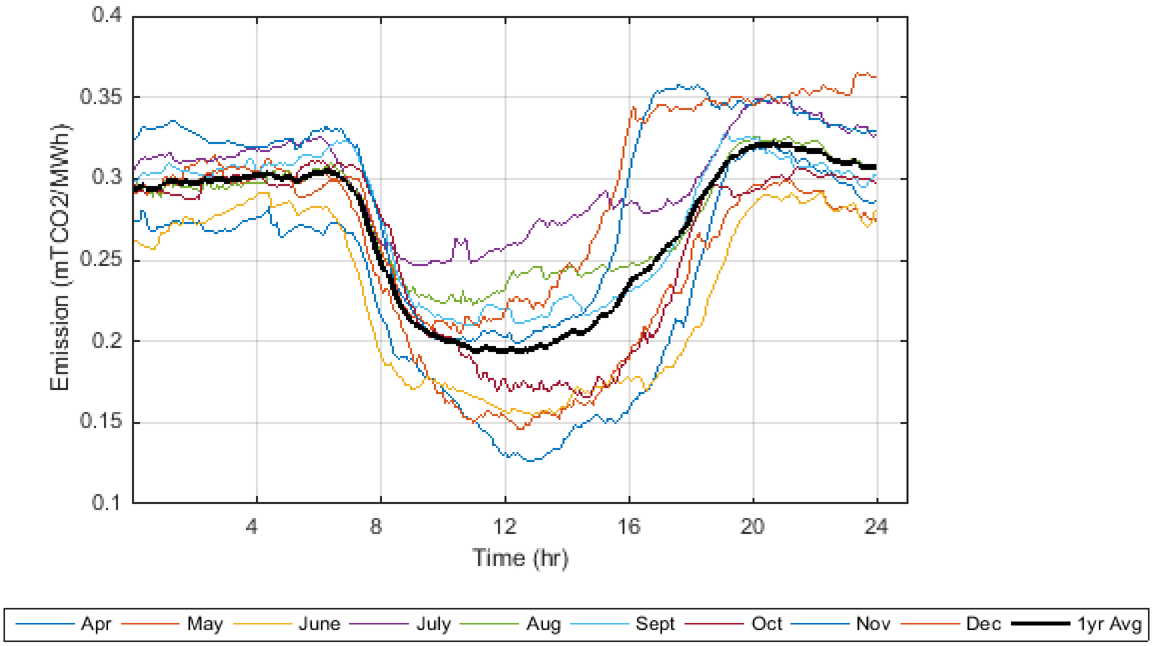


**Figure 36. CA Grid Average GHG Emission Factor[19]**

Daily GHG emissions from the grid associated with electricity demand on 180 residential transformers discussed in the previous subsection, are shown in Table 9. As expected, the deployment of PEVs results in increased emissions from the electric grid. This increase can be reduced by integrating DERs in the distribution system as well as implementing energy efficiency measures that will result in the excess PV or battery being used for PEV charging instead of serving other home loads. Implementing smart charging in some cases results in a slight increase in emissions compared to uncontrolled charging. This is expected because in this strategy the objective is to minimize the load on specific transformers. Emission smart charging, on the other hand, results in a small reduction in GHG emissions from the grid. Note that these results only include home charging which limits the use of PV (in the distribution system or larger grid) for PEV charging).

**Table 9. Grid GHG Emission (mTCO$_2$/day)**

| Case Description | Charging Strategy | Low-Load | | High-Load | |
|---|---|---|---|---|---|
| | | | | | |
| BaseCase | | | 5.74 | | 11.32 |
| PEV (w/o DER) | Uncontrolled | | 8.51 | | 14.09 |
| | SC | | 8.66 | | 14.47 |
| | EmSC | | 8.48 | | 14.18 |
| | | | | | |
| CES w/o PEV | NA | | 3.36 | | 7.88 |
| CES | Uncontrolled | | 5.71 | | 10.46 |
| | SC | | 5.43 | | 10.34 |
| | EmSC | | 5.36 | | 10.15 |
| | | | | | |
| RESU w/o PEV | NA | | 1.79 | | 6.56 |
| RESU | Uncontrolled | | 4.14 | | 9.28 |
| | SC | | 3.94 | | 9.43 |
| | EmSC | | 3.92 | | 9.27 |

The overall emissions (electricity generation+tailpipe) for three circuit configurations (No DER, CES, and RESU) and for the low-load scenario are provided in Figure 37. These figures are associated with PEVs and electricity load on the 180 residential transformers (total of 1422 homes) that were studied in the previous subsection, with only home charging included. The BaseCase refers to the case without any DERs and without PEVs. These results indicate that the reduction from the transportation sector from PEV deployment are greater than the increase in grid emissions and thus there is an overall GHGs decrease with the deployment of PEVs. Emission smart charging can help reduce emissions slightly, but arrival and departure times limit the benefits of this strategy in further reducing emissions. Results for the high-load scenario are provided in Figure 38. For the high-load scenario, similar trends are observed.

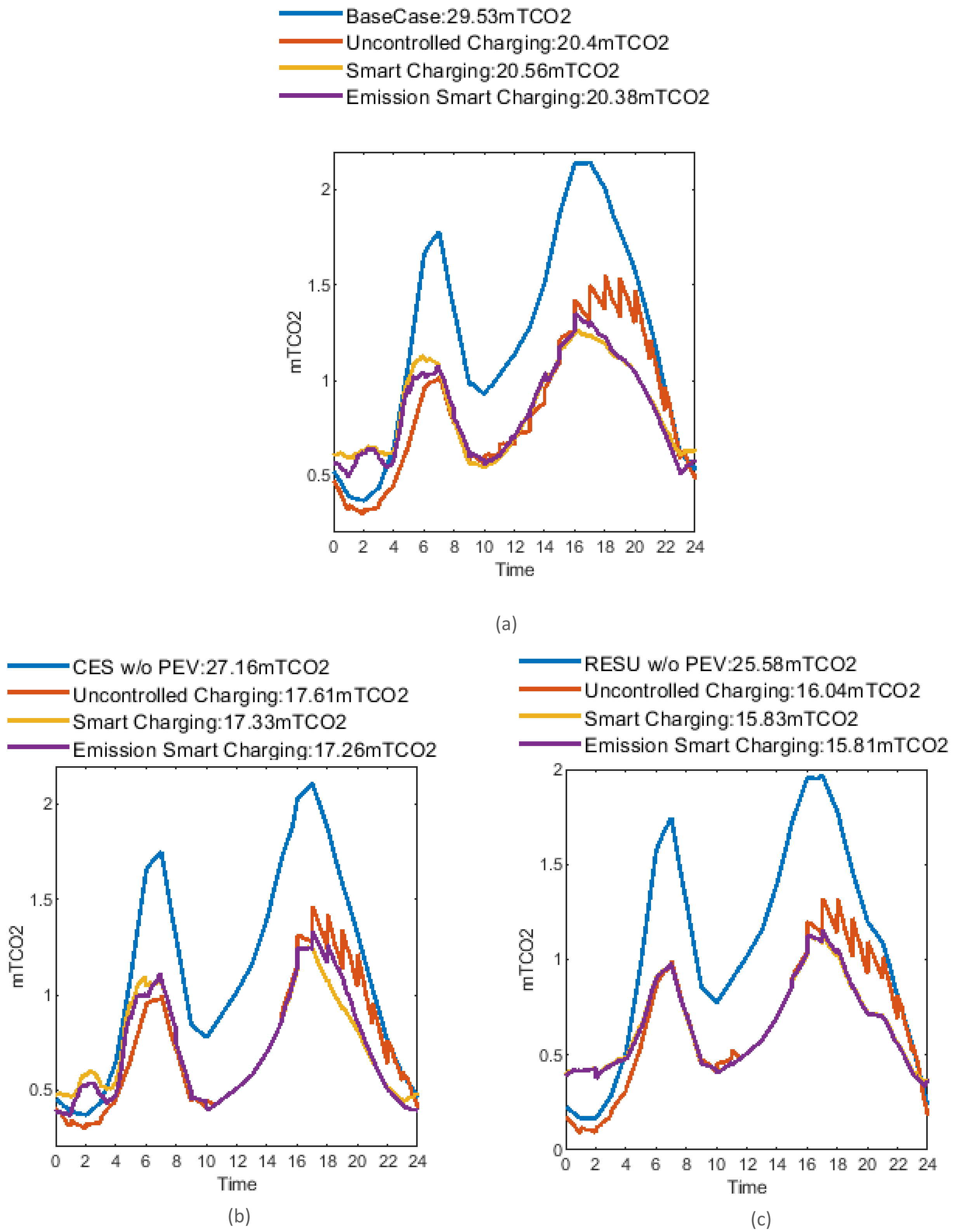
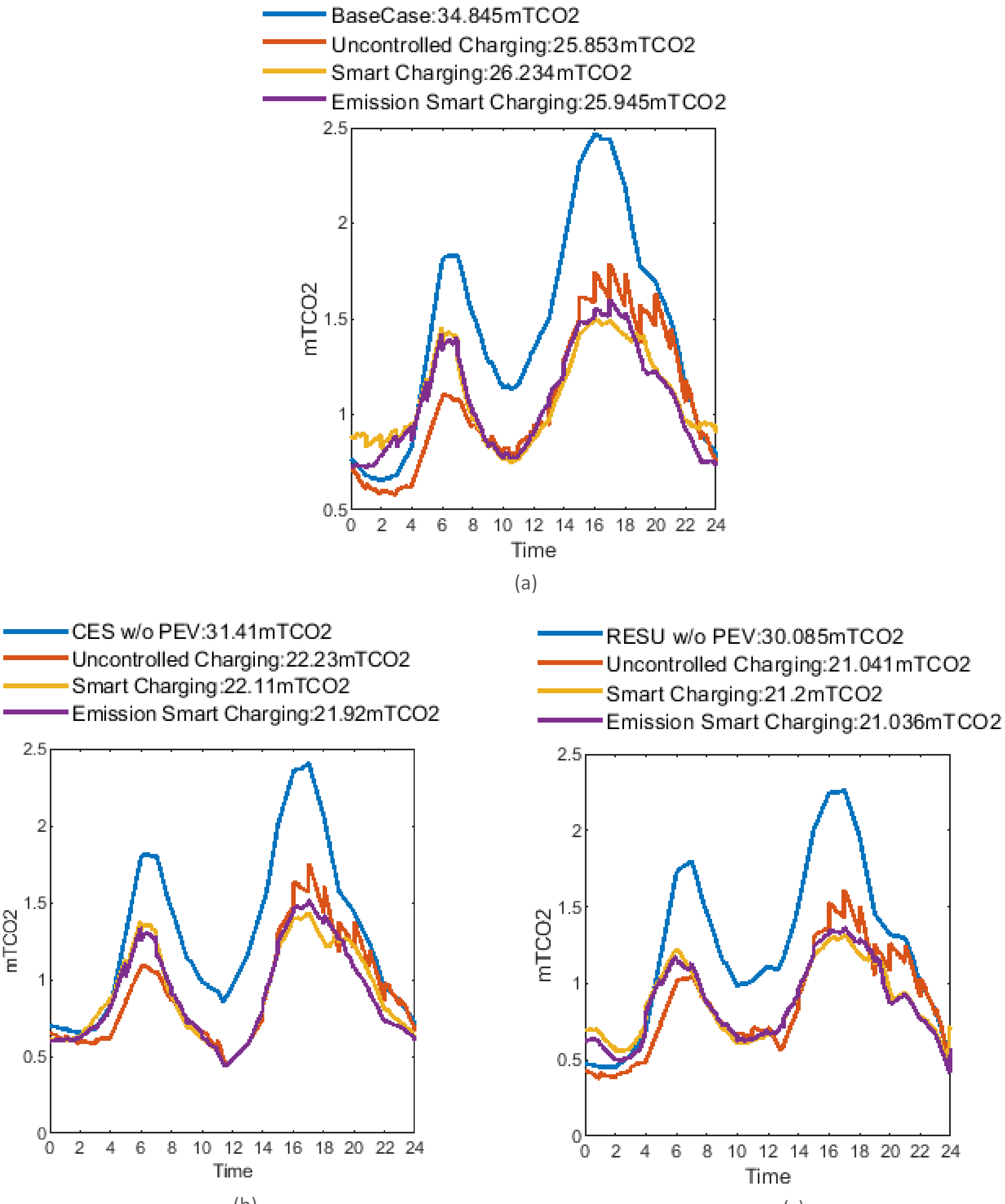


**Figure 37. Overall GHGs, Circuit A. Low Load Condition: (a)No DER, (b) CES, and (c) RESU**



(a)

(b)

(c)

Figure 38. Overall GHGs, Circuit A. High- Load Condition: (a)No DER, (b) CES, and (c) RESU

The overall emissions from the two circuits are provided in Figure 39 and Figure 40 for the low-load scenario and CES and RESU circuit configurations, respectively. These figures include the addition of workplace charging for PEVs that commute in the system under study as well as PEVs that both live and work in the system. These figures indicate that with the addition of workplace charging, smart charging strategies can be more effective due to more flexibility of travel plans as well as coinciding workplace charging with high-PV intervals.

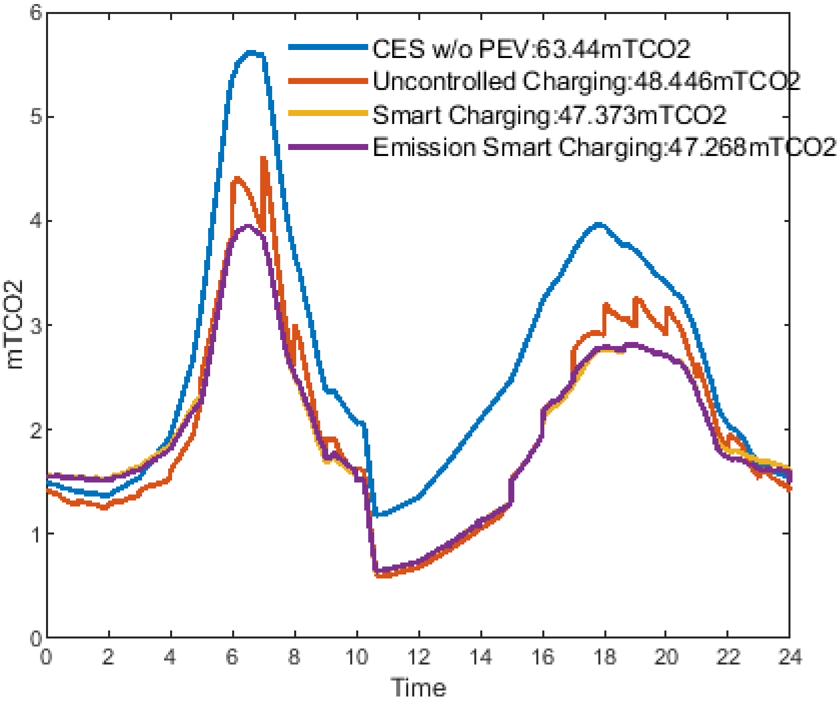


**Figure 39. Overall GHG from the Entire System-CES**

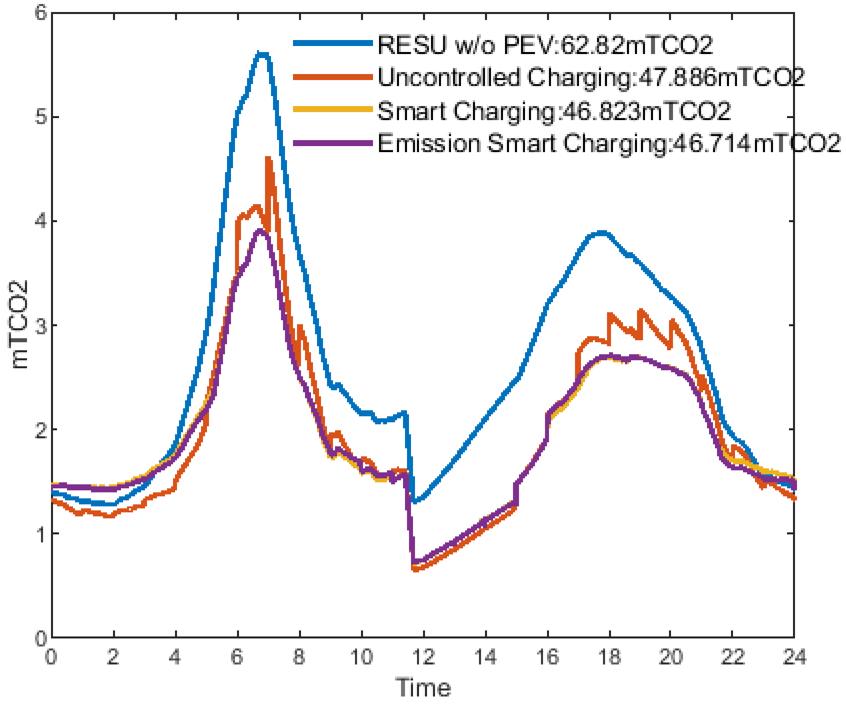


Figure 40. Overall GHG from the Entire System-RESU

# 4. Conclusions

This project examined the feasibility of using PEVs to supply electricity to homes and to the grid during power outages and other unforeseen occurrences. To this end, a model of two distribution circuits that had previously been developed was modified to include V2H and V2G power supply and used to simulate the use of PEVs in restoring the grid after a power interruption. Furthermore, the impact of linking large numbers of PEVs capable of serving as energy storage during non-emergency operations was assessed by developing travel plans for a set of connected PEVs. Several different smart charging strategies were developed and assessed.

Below are the major conclusions of this study:

- **Under normal electric grid operation**
    - **While PEVs with uncontrolled charging can stress the electrical infrastructure, accelerate the degradation of utility assets such as transformers, and overall degrade the resiliency of the grid, smart charging strategies can significantly mitigate the negative impact of increased PEV use on the grid infrastructure.** The simulated use of PEVs in this study did not result in residential transformer failure or dangerously high increases in transformer hot spot temperatures since the system was modeled based on a well-designed smart grid. However, uncontrolled charging of PEVs during the day did result in accelerated aging of the 180 transformers studied on average, and in significant increases in other factors which could result in transformers and other system components needing to be replaced sooner, as well as increased operating and upgrade costs. In all the scenarios and circuit configurations simulated, smart charging strategies reduced the negative impact of PEVs on transformers.
    - **A combination of distributed energy resource (DER) systems, energy efficiency measures and smart charging provides the best results in terms of reducing both infrastructure impacts and emissions.** Results of the study showed that the addition of distributed energy resource (DER) systems and energy efficiency measures (to reduce base electricity demand) to smart charging helped eliminate the negative impact of PEVs on the distribution grid infrastructure.
    - **Smart charging enables an increase in renewable penetration in the distribution system.** Smart charging helps facilitate the use of available renewable energy in the distribution system without any required infrastructure upgrades.
    - **Flexible travel plans and additional charging stations can increase the effectiveness of charging strategies.** The effectiveness of smart charging strategies and the advantages of increasing the use of renewable resources were limited by the fact that most PEVs left home around the same time. Flexible travel plans and providing additional charging opportunities such as workplace charging and charging at other destinations would help increase the effectiveness of smart charging strategies.

- **Under grid outages**
    - **Properly controlled, plugged-in PEVs can be an effective and environmentally friendly resiliency resource for V2G and V2H.** In this study, PEVs were shown to be able to serve critical loads during a grid outage and facilitate grid restoration by providing necessary power and energy to restart utility assets while emitting substantially less criteria pollutant and greenhouse gases compared to gasoline and diesel back-up generators.

    - **PEVs can serve local critical loads with minimal system upgrades.** PEVs are essentially mobile energy storage resources and their batteries can be discharged to provide electricity directly to home nanogrids using a home energy management system in order to avoid service interruptions. Furthermore, power from PEVs attached to charging stations in a parking lot can be aggregated to serve larger critical loads adjacent to the parking lot such as emergency shelters. A minimum of standard electrical switches would need to be upgraded to smart or remote-controlled switches to automate this process. In the absence of automation, a field crew could manually implement the required switching.

    - **To increase resiliency with both service to critical loads and grid restoration through PEVs, system upgrades are required**. For service to critical loads beyond single homes (e.g., groups of homes, large buildings, a microgrid), system upgrades are required including energy management systems, communication links, smart switches, and grid-forming inverters.

    - **Clustered PEVs (e.g., in a parking lot) are more suitable to facilitate grid restoration compared to residential PEVs randomly scattered throughout the system.** While PEVs scattered across the distribution system that are plugged into home nanogrids have sufficient power and energy to help startup the local substation transformer after a shutdown. This would require upgrading all system switches to smart switches, ensuring that all inverters across the system are capable of operation in absence of the grid, and providing communication links between the substation central controller and individual home energy management systems. Using PEVs clustered in a parking lot, would only require upgrading the switches that are in the specific route between the parking lot and the substation, and the substation central controller would only need to communicate with a single inverter. Furthermore, fewer chargers would need to be upgraded, and only the parking lot inverter would need to be able to operate in the absence of the grid.

# References

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