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Modeling of Electric Vehicle Charging Effects on Existing Grid Infrastructure

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Dr. Tony Kerzmann's higher education background began with a Bachelor of Arts in Physics from Duquesne University, as well as a Bachelor's, Master's, and PhD in Mechanical Engineering from the University of Pittsburgh. After graduation, Dr. Kerzmann began his career as an assistant professor of Mechanical Engineering at Robert Morris University which afforded him the opportunity to research, teach, and advise in numerous engineering roles. He served as the mechanical coordinator for the RMU Engineering Department for six years, and was the Director of Outreach for the Research and Outreach Center in the School of Engineering, Mathematics and Science. In 2019, Dr. Kerzmann joined the Mechanical Engineering and Material Science (MEMS) department at the University of Pittsburgh. He is the advising coordinator and associate professor in the MEMS department, where he positively engages with numerous mechanical engineering advisees, teaches courses in mechanical engineering and sustainability, and conducts research in energy systems.

Throughout his career, Dr. Kerzmann has advised over eighty student projects, some of which have won regional and international awards. A recent project team won the Utility of Tomorrow competition, outperforming fifty-five international teams to bring home one of only five prizes. Additionally, he has developed and taught fourteen different courses, many of which were in the areas of energy, sustainability, thermodynamics, dynamics and heat transfer. He has always made an effort to incorporate experiential learning into the classroom through the use of demonstrations, guest speakers, student projects and site visits. Dr. Kerzmann is a firm believer that all students learn in their own unique way. In an effort to reach all students, he has consistently deployed a host of teaching strategies into his classes, including videos, example problems, quizzes, hands-on laboratories, demonstrations, and group work. Dr. Kerzmann is enthusiastic in the continued pursuit of his educational goals, research endeavors, and engagement of mechanical engineering students.

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Robert Kerestes, PhD, is an assistant professor of electrical and computer engineering at the University of Pittsburgh's Swanson School of Engineering. Robert was born in Pittsburgh, Pennsylvania. He got his B.S. (2010), his M.S (2012). and his PhD (2014) from the University of Pittsburgh, all with a concentration in electric power systems. Robert's academic focus is in education as it applies to engineering at the collegiate level. His areas of interest are in electric power systems, in particular, electric machinery and electromagnetics. Robert has worked as a mathematical modeler for Emerson Process Management, working on electric power applications for Emerson's Ovation Embedded Simulator. Robert also served in the United States Navy as an interior communications electrician from 1998-2002 on active duty and from 2002-2006 in the US Naval Reserves.

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Abstract

The U.S. is rapidly electrifying its vehicle fleet. The electric vehicle (EV) market in the United States has grown from just over seventy thousand EV registrations in 2015 to more than 230,000 in 2020. That’s a U.S. market share jump from 0.8% to 2.0% in just 5 years, while Europe experienced a jump from 1.2% to 10.0% over the same timeframe [1]. There is no doubt that EV growth throughout the world will increase significantly over the next decade. With the U.S. Whitehouse goal of 50% EV sales by 2030, the grid is going to see some significant changes to its power consumption patterns [2]. The forecasted surge in the number of EVs elucidates the issue of rapidly increasing power loads from EV charging in residential and workplace applications. This rapid power variation on the existing grid infrastructure can have some important effects on the grid system and should be better understood. Many parts of the current electric grid date back more than 50 years and rapid changes to the power consumption curve could potentially have negative effects on grid reliability.

This research project focuses on the modeling of the effects of EV charging stations on the existing grid infrastructure. The modeling incorporates time-series and stochastic modeling approaches to identify key locations where the risk of failure may occur. A series of EV charging scenarios are modeled to evaluate the changes in grid voltage based on the localized grid power consumption. The nodal grid array that is simulated is modeled after data provided from Duquesne Light Company (DLC), a City of Pittsburgh electricity utility provider. The charging scenarios are modeled in the open-source OpenDSS software developed by the Electric Power Research Institute (EPRI) and utilize EV scenario data from the Department of Energy’s Electric Vehicle Infrastructure Projection Tool (EVI-Pro Lite). This research provides a successful example of an industry-academia collaboration of an engineering student research project. The findings from grid modeling will be presented along with the student educational components that were involved throughout the research and collaboration process.

Introduction

EV refers to an electric vehicle in which the propulsion system converts battery-stored electrical energy into mechanical energy to move the vehicle. One of the key drivers to mass-adoption of the EVs is the potential to greatly reduce the environmental impacts of the transportation sector by utilizing clean electricity to power the EVs. The adverse effects of global warming and climate change caused due, in part, to fossil fuel powered vehicles, has helped to bring awareness to the public about sustainable transportation technologies and has therefore led to the potential for a rapid transition to EVs on a global scale. EV charging is a major component to this transportation transition and has the potential to significantly change the electricity consumption strains on the exiting antiquated electric grid system in the U.S. The integration of a highly congested interdependent network may introduce several new challenges to electrified transportation from charging scheduling, traffic flow, charging load on power network, and cost perspectives [3].

In the coming years, the United States has the potential to emerge as one of the leading markets for electric vehicles globally. The US government goal of 50% electric vehicle sales share by 2030 is feasible through investments into EV manufacturing, incentives, and infrastructure. EV infrastructure needs to include charging stations and smart grid technologies, both of which must maintain electrical reliability. A major component to grid reliability is the understanding of potential reliability concerns which could be exacerbated by intermittent electricity generation caused by intermittent renewable energy sources as well as substantial spikes in electricity consumption due to EV charging. A prime example of a consumption spike would be when many EVs plug-in at once, like in the case of morning EV commuters in an urban environment. In this example, one can imagine thousands of EVs plugging into the grid to charge at the same time and in a relative proximity to one another. This considerable jump in power consumption would strain the local grid system, leading to the risk that the electrical reliability would be adversely affected. If many electric vehicles connect to the grid during peak load, it will further increase the burden on the power system and will result in a greater difference of peak power loading. The charging behavior of EV drivers provides a great deal of uncertainty to the charging load experienced by the grid as well. This can further increase the difficulty of stabilizing the grid while adding to the potential for negative effects to electrical reliability. At the same time, charging electric vehicles could cause problems with power quality [4].

Consideration must also be paid to the location of the EV charging. In most cases, the electrical infrastructure in an urban environment is more robust and has more redundancy to deal with variations in the load. On the other hand, there is typically less redundancy as the population decreases, such as in residential and rural areas. An EV owner would also charge their vehicle at home and therefore certain times during the day, such as after work hours, may also see a spike in power consumption. This can cause heavy loads to local residential areas and transformers, which would not typically see high power flow, could become overloaded. Therefore, accurate and reliable models for the behavior of electric vehicles are required due to the high penetration level of EVs and their complex charging behavior [5].

As seen in Figure 1, in 2020 the city of Pittsburgh saw a 2% EV share of new vehicle purchases. The city also enacted 19 promotional actions, which are strategies to facilitate the growth of the EV industry￼ The city also plans to add more than 200 new public charging plugs on city property and more than 2000 to total across the city by 2025 [7]. A large amount of charging load is connected to the distribution network, which significantly influences the load shape compared with the traditional power grid and affects the transportation network.

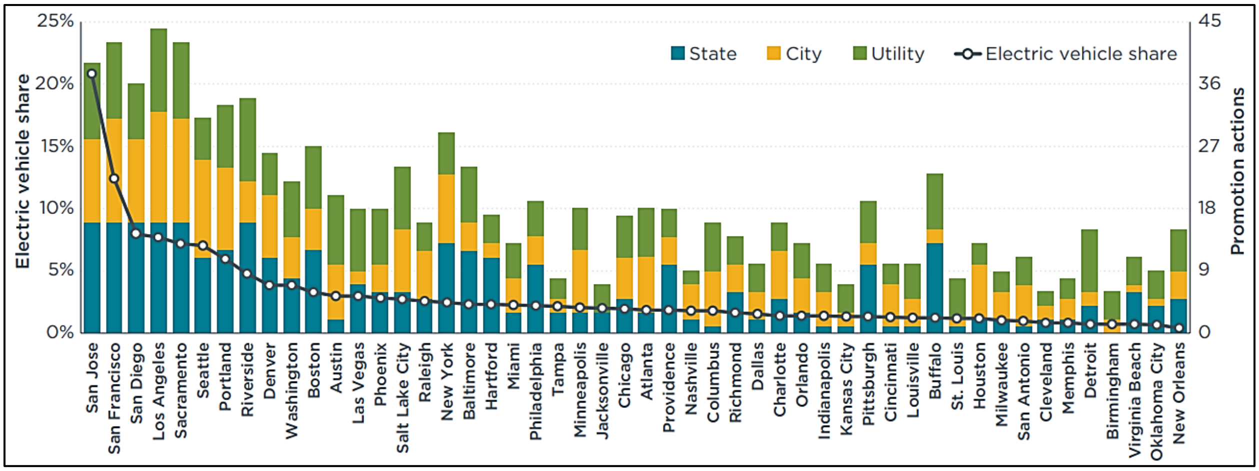


Figure 1: Electric vehicle shares of new vehicles and promotion actions in the 50 most populous U.S metropolitan areas. [6]

As discussed above, the forecasts for EV charging are projecting major increases to the EV electrical consumption in the next decade. This research project is a collaborative effort between the electrical engineering and mechanical engineering departments at the University of Pittsburgh, in collaboration a local utility. A master's student and undergraduate student are the contributors to the model developed in this research project. Both students used this research project to fulfill course credits toward their respective degrees. The following section will include a discussion of the educational benefits to undergraduate research. The research project is the first phase in working to better understand the effects that EV charging has on grid reliability. As such, the research group decided to focus our efforts on developing a model to simulate electrical performance under different EV charging scenarios. The team then used the model to evaluate a system of nodes that are meant to represent the consumption of a portion of the grid. Using this nodal system, the team introduced EV charging scenarios to see the effects on the grid power and voltage.

Educational Elements

Numerous studies have pointed to the idea that engineers work better in active-learning environments and therefore research experiences provide an important option for interested students [8]. Research allows students to focus their engineering knowledge in areas that interest them, while focusing on a particular subject on a deeper level than in typical engineering courses. The students are able to work for extended periods of time within the highest levels of Bloom's Taxonomy, where understanding and higher-level thinking are paramount [9]. The creation, evaluation and analysis of concepts utilizing high order thinking skills, as shown in Figure 2, are consistent and reoccurring skills that need to be exercised throughout the research process. A research experiences study, where 76 undergraduate students were interviewed, provided insight into additional benefits related to research experiences, including personal/professional gains, thinking, and working like a scientist, gains in various skills, clarification/confirmation of career plans (including graduate school), enhanced career/graduate school preparation, shifts in attitudes to learning and working as a researcher [10]. This research project not only incorporates the many positive components of undergraduate research into a team project, but also includes a topic that is highly interesting to most students, electric vehicles. Interest, authenticity of the project and the complexity of the project are all components that lead to increased student motivation, which in turn tends to lead to increased productivity [11].

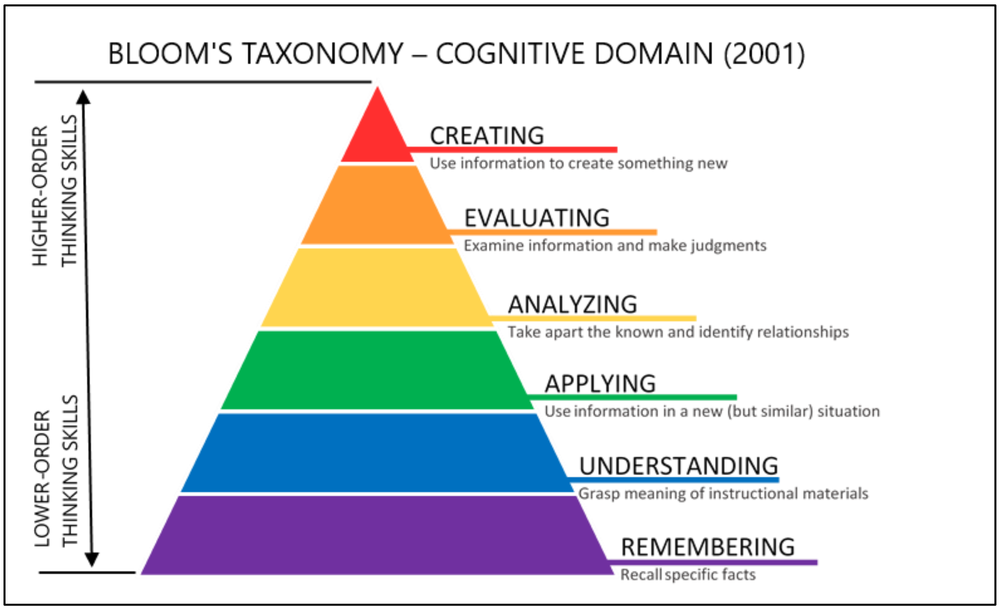


Figure 2: Diagram showing the Bloom's Taxonomy for the cognitive domain arranged as a pyramid from lower-order thinking skills to higher-order thinking skills. [12]

Throughout this process, the students were tasked with the goal of understanding how EV chargers will affect the grid. Preliminary research into how these two pieces operated separately was conducted as a team. This allowed the students to generate an understanding of the underlying concepts, as well as how to properly conduct background research. Furthermore, the students were given the opportunity to model energy systems in OpenDSS. Once the data was collected, they collaborated with the professors to draw conclusions based on the results. This process allowed the students to learn how to conduct research, as well as how to interpret data. The knowledge obtained by students when directly collaborating with professors allows them to develop an advanced understanding of the concepts covered during research. Additionally, the methodology with which to conduct research is an area where students typically lack experience. Working in a team environment with peers and professors allows students to get an understanding of how to properly perform research. It also gives them insight into whether research may be an area of interest with regard to future career path.

Research Methodology:

This research project is focused on the development and validation of an EV charging model which can evaluate charging scenarios to assess the effects on grid reliability.

Model Development

The first step was to design and build a simulation model. The IEEE Power and Energy Society provides a series of electrical distribution circuits called the IEEE Test Feeders. A realistic but convenient circuit that is commonly used for model validation is the IEEE 13 Node Test Feeder which is shown in the figure below

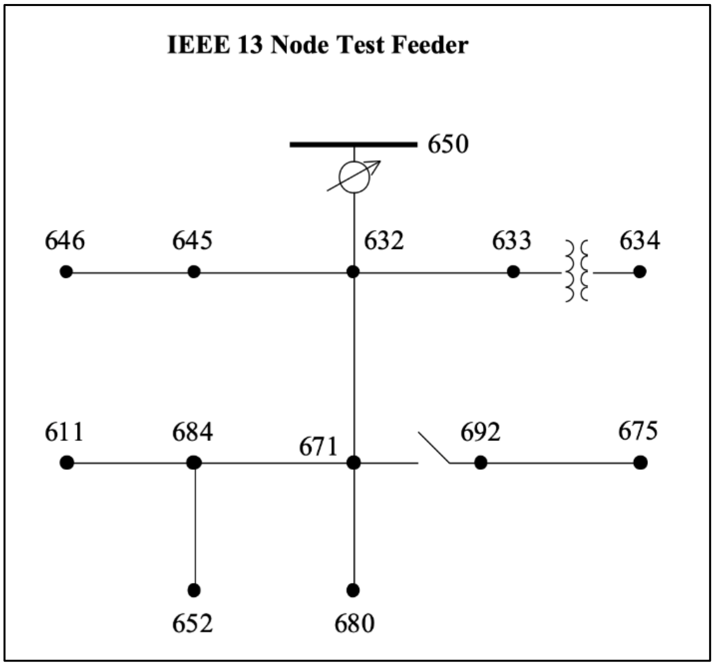


Figure 3: IEEE 13 Node Test Feeder Circuit [12]

This test feeder is a radial circuit with a combination of underground and overhead lines with single phase, two-phase, and three-phase connections that serve a series of single phase and polyphase loads. It has one in-line transformer and one voltage regulator.

The IEEE 13 Node Test Feeder model was built in OpenDSS which is an open-source software package that was developed by the Electric Power Research Institute (EPRI). OpenDSS was designed to support distributed energy resource grid integration and grid modernization [14]. OpenDSS uses load models which can be parameterized based on real, reactive, apparent power, and power factor. However, for a time series simulation to be conducted, loads need to vary over time rather than stay at a static power level. For this purpose, EPRI's Load Shape Library Tool 8.0 was used to produce realistic daily load shapes.

The EV charging model has a number of assumptions such as the number of EVs charging at a given time, the time at which electric vehicles would be charging during the day as well as the variation in the natural system load without EV demand. We paid special consideration to the uncertainty aspect of the rapid surge in demand load when the EVs charge, and the drastic drops in demand load when the EVs are removed from charging in circuit. These considerations are vital in planning for future distribution circuits to support EV charging. Using these assumptions, the load patterns on the grid experience significant fluctuations when all EVs charge at the same time upon arriving at the workplace. The same pattern can be observed in residential level circuits when all the EVs return home from the workplace and begin charging during the same window of time.

Results:

The simulation utilized EPRI's Load Shape Library Tool 8.0 to produce a realistic daily load shape. The load shape for an office space over a 24-hour period is shown in Figure 4. The load was normalized so that its maximum load is equal to 1.0.

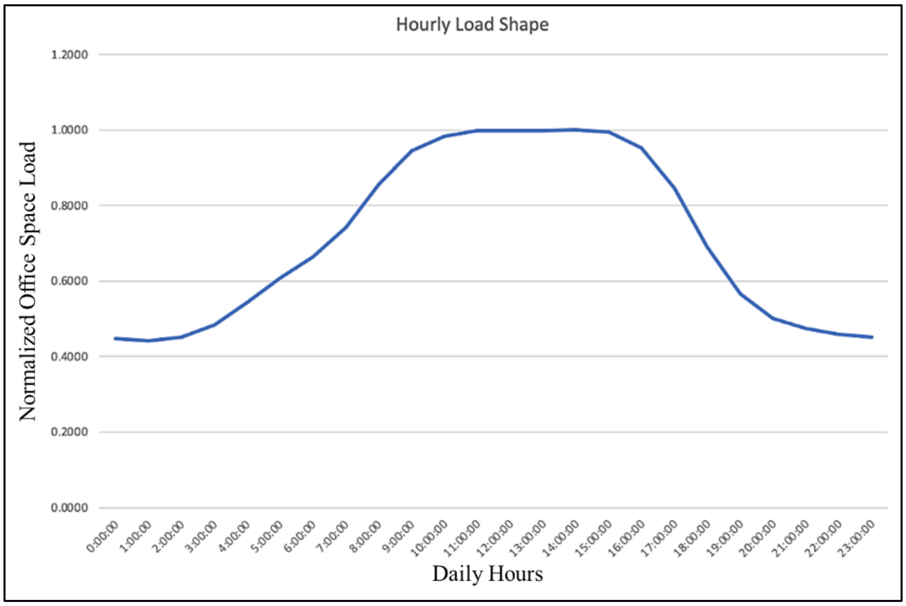
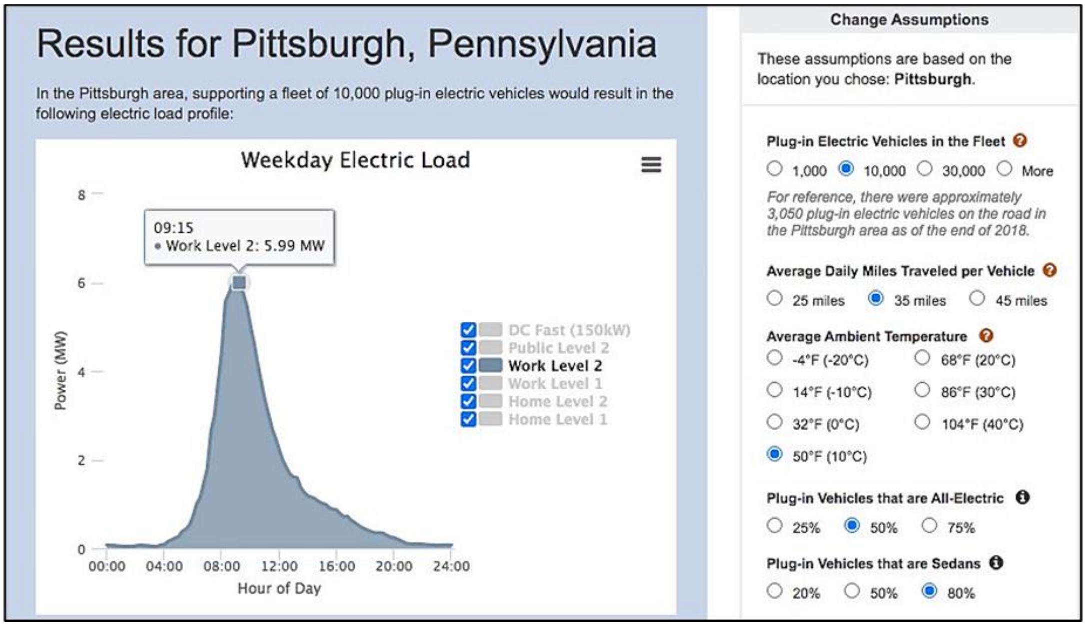


Figure 4: 24 Hour Load Shape for an Office Space

Data for EV charging was retrieved from the Department of Energy's Electric Vehicle Infrastructure Projection Tool (EVI-Pro Lite) [15]. EVI-Pro Lite is designed to provide the user with the electric vehicle charging power consumption. EVI-Pro Lite was used to determine the charging demand that would be introduced by a fleet of electric vehicles in the Pittsburgh, PA area. When the load data for a typical office is combined with the EV charging load data, the result was a representative load curve for the entire 24-hour period, including the added load due to EV charging. Using this representative combined load curve, a normalized model was developed so that the demand from a number of different office space scenarios could be simulated by simply scaling the load curve.


Results for Pittsburgh, Pennsylvania

In the Pittsburgh area, supporting a fleet of 10,000 plug-in electric vehicles would result in the following electric load profile:

Change Assumptions

These assumptions are based on the location you chose: **Pittsburgh.**

Plug-in Electric Vehicles in the Fleet
○ 1,000 ● 10,000 ○ 30,000 ○ More

For reference, there were approximately 3,050 plug-in electric vehicles on the road in the Pittsburgh area as of the end of 2018.

Average Daily Miles Traveled per Vehicle
○ 25 miles ● 35 miles ○ 45 miles

Average Ambient Temperature
○ -4°F (-20°C) ○ 68°F (20°C)
○ 14°F (-10°C) ○ 86°F (30°C)
○ 32°F (0°C) ○ 104°F (40°C)
● 50°F (10°C)

Plug-in Vehicles that are All-Electric
○ 25% ● 50% ○ 75%

Plug-in Vehicles that are Sedans
○ 20% ○ 50% ● 80%

Figure 5: EVI-Pro Lite Charging Power Curve for Office Spaces.

An example of the load curve for an office space in the Pittsburgh area is given in Figure 5. The assumptions for this curve are listed on the right side of the figure where the Level 2 charger represents a 240V charger charging at 40A, which equates to a 9.6 kW power demand per vehicle. We can see from the curve that the peak power consumption is almost 6 MW at 9:15am. We can infer that that this peak represents a substantial quantity of EVs that commute into the city for work and plug-in around 9am.

Monte Carlo Simulation

A Monte Carlo simulation was used to simulate the uncertainty of EVs charging throughout the day. From our MC simulations, we could predict the maximum number of charging EVs which gives insight into a worst-case scenario.

Based on the percentage of the Pennsylvania population that lives in the greater Pittsburgh area and the findings that there are 29,000 registered EV owners in PA, we are assuming that the City of Pittsburgh sees approximately 10,000 EVs travel into and out of the city limits each day [16]. The identification of the number of cars which are charging during a particular time interval within the city is the most critical assumption to the EV grid simulation. While some of the charging behavior is reasonably predictable, worst-case scenarios are important to understand for grid planning. The randomness associated with identifying the number of charging EVs is an important simulation component to consider when evaluating the accuracy of the simulation results. To introduce variability into our model, a Monte Carlo Simulation study was performed. A thousand simulations were performed and the average number of charging EVs was calculated based on the results. The average number of EVs charging at a given time, out of ten thousand, was 193 and the maximum was 392, as seen in Table 1.

Average number of cars	193
Median value	192
Maximum number of cars	392
Minimum number of cars	0
Standard Deviation	116

Table 1: Summary of Monte Carlo Simulation results.

Table 2 provides the MC simulation results based on the EVI-Pro Lite data. We can see that the maximum power consumption generated by 10,000 simulations at any point in a typical day is 6.23 MW. The MC simulation provides variability within the data, which results in a 0.24 MW increase from the maximum data point provided in EVI-Pro Lite load curve at 9:15 AM.

Average power consumption throughout the day (MW)	2.42
Maximum power consumption throughout the day (MW)	6.23
Minimum power consumption throughout the day (MW)	0.30
Median value of the power consumption (MW)	1.69
Variance value of the power consumption (MW)	3.53
Standard Deviation of the power consumption (MW)	1.88
Maximum number of cars being charged out of 10000 cars	392

Table 2: Important values from the retrieved normalized distribution curve used in performing Monte Carlo Simulation for the values

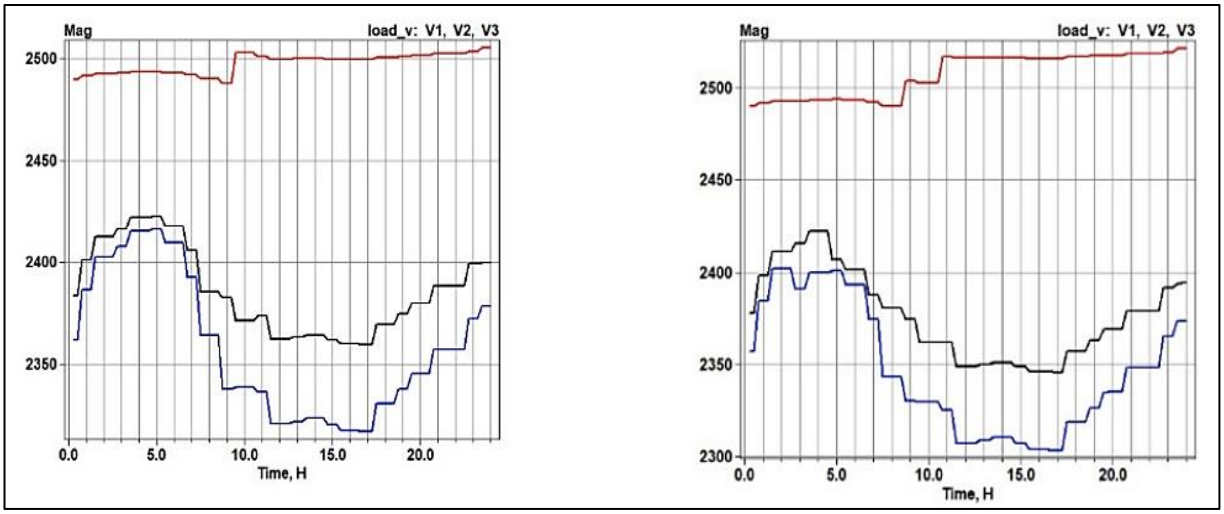


Figure 6: (Left) Voltage Profile for a 13 node Office Space Circuit with no additional power load. (Right) Voltage Profile for a 13 node Office Space Circuit with 76 kW of additional EV charging load

For the combined IEEE 13 node system simulation, we combined the EPRI load curve, the EVI-Pro Lite load curve, and the results from the Monte Carlo simulation. This provided us with our input load for the OpenDSS simulation. The OpenDSS simulation for a small-scale 13 node office complex was simulated throughout a 24-hour period. In Figure 6, we see the results from the Open DSS simulation where the left chart shows the three phase voltage curves for a typical load curve as compared to the voltage curve with additional EV charging, as shown on the right chart. This value was calculated from the assumption that a type 2 EV charger will consume 9.5 KW per EV. The graph on the right depicts a scenario where we have 8 additional electrical vehicles charging. This amounts to a total power consumption increase of 76 kW per node. Each of the curves represents a different phase in the three-phase voltage supply. The black line is V1, the red line is V2, and the blue line is V3. The results at this point in the research are preliminary, but we can plainly see that the voltage curve is affected by the additional EV power consumption, especially when the EV power consumption is the highest. These results are still preliminary and further work needs to be done to validate the model and apply the model to different EV charging scenarios.

Conclusion:

In the coming years, electric vehicles will not only vastly change the transportation landscape but will increasingly affect the electric grid. As EV markets grow, it becomes increasingly important to understand grid power management, and the necessary grid upgrades, to keep the grid stable under highly fluctuating power demand cycles. This research is the first step in developing a grid reliability model that is highly adaptable to many different grid scenarios. Although the current results are still preliminary, the research team plans to build upon the existing model as well as continue the engagement of undergraduate research students in this stimulating research space. The future work includes validating the existing model and building upon the model to account for a number of different scenarios. We hope to build a model that has the flexibility to simulate grid systems as small as few buildings and as vast as a portion of a town grid system. An important aspect of future work will incorporate the capability of adding Distributed Energy Resources (DER), such as solar or wind, which adds another layer of variability to the system, but unlike EVs which increase the variance of the consumption side, DER increases the variance of the electricity production side. DER would also include the simulation of energy storage systems and future work could include the incorporation of a vehicle-to-grid concept where EVs provide power to the grid during demand response periods.

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