2022 IEEE Power & Energy Society General Meeting (PESGM) | 978-1-6654-0823-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/PESGM48719.2022.9917224

Leveraging Distributed EVs and PVs to Assess Networked Microgrids Resilience Against Extreme Weather Event

Orlando Quezada Simental, *Student Member, IEEE,* Paras Mandal, *Senior Member, IEEE,* Eric Galvan, *Member, IEEE,* and Zongjie Wang, *Member, IEEE*

Abstract— **The development of new technologies is increasing transportation electrification and electric vehicles (EVs) are expected to become even more popular in coming years. High EV adoption rates can increase the potential to use EVs as an energy resource and operate in vehicle-to-grid (V2G) and vehicle-to-home (V2H). This paper focuses on the resilience analysis of using EVs and roof-top solar photovoltaic systems (PVs) to provide power support in network microgrids (MGs) experiencing an outage due to extreme weather conditions. To determine the effectiveness of using EVs and PVs as backup energy resources, a set of resilience metrics are evaluated for different cases and duration. Simulation results show that the management of EVs and PVs in residential networked MGs could provide power support for several hours during the restoration of a distribution system experiencing an outage.**

Keywords— **Distribution grid resilience, electric vehicles and roof-top solar photovoltaics, extreme weather event, networked microgrids, V2G and V2H operations.**

INTRODUCTION

Nowadays electric power grids are experiencing blackouts due to extreme weather at higher rates than ever before, leaving hundreds of customers without electric energy for hours and in some cases even for days. Extreme weather produces blackouts in the grid, while these events are considered as low-probability events, the socioeconomic costs and impacts are extensive [1]. For example, the Electric Reliability Council of Texas (ERCOT) system was impacted by a winter storm in February 2021, that left thousands of customers without electrical service for more than two weeks producing an estimated total cost of over $195 billion [2]. Improving the power distribution system resilience can be accomplished through the implementation of microgrids (MGs) throughout the grid, which can be constituted by distributed energy resources (DERs) such as, wind energy, energy storage systems, solar photovoltaic energy (PV), electric vehicles (EVs), and others. In recent years, MGs have received special attention as different research and pilot projects have shown the capability of MGs to make distribution networks more sustainable. MGs are considered a feasible method to operate and control demand-side DERs as they offer a variety of benefits, such as, increased power quality, zero-emissions energy sources, decrease costs in transmission and distribution, and enhance grid resilience due to extreme weather.

As it is discussed in the report by Adam Cooper [3], it is anticipated that more than 18 million EVs will be on U.S. roads by 2030. New developments in battery technology are allowing EVs to have superior battery energy capacity. An augmented battery capacity creates the potential to use EVs as an energy resource in vehicle-to-grid (V2G) mode of operation. There are several applications for V2G operation in power grids, such as, peak load shaving, smoothing generation from non-dispatchable wind and solar renewable energy resources, and energy storage support during unexpected outages [4]. V2G operation creates economic opportunities to provide different electricity market services (i.e., frequency and energy reserve and real-time trading) [5]. Therefore, due to the various benefits of EVs as aforementioned, it is expected that EVs could become an essential part for the reliable operation of MGs and power distribution grid of the future. EVs can also operate in other modes, such as, vehicle to home (V2H) in addition to V2G. In these modes of operation, EVs can significantly contribute to the energy management of the power system by providing ancillary services as well as demand response resources. During V2G operation, EVs can supply power to the main grid and receive power from the grid whenever necessary. Nunna *et al.* [6], reported that EV operation in V2G mode can be used for system peak reduction. Furthermore, EV in V2G operation can support large-scale renewable energy integration as reported in [7]. Also, in V2G operation EV owners can make profit by providing power to the grid by receiving rebates in their electric bill discount or other incentives [8].

V2H operation enables the users that own EVs to power their homes during high electricity price periods of time [9]. Such operation can shift the demand to decrease prices resulting in reduced energy costs [10]. Moreover, EVs can be used as backup power resource following a contingency [11]. The V2H operation can be properly incorporated in home energy management system (HEMS) as a flexible option [12], [13]. V2H mode is ideal for value stacking of EVs. V2H and V2G coupled with DER power management optimization can increase revenues by 30% [14].

The existing literature has very limited information regarding the utilization of EVs as an emergency backup during power outages under extreme events. Thus, there is still a great

---

O. Quezada Simental and P. Mandal are with the Power & Renewable Energy Systems (PRES) Lab, ECE Department, The University of Texas at El Paso, El Paso, TX 79968, USA (e-mail: oquezadasi@miners.utep.edu; pmandal@utep.edu).

E. Galvan is with the Load Research and Data Analytics Department, El Paso Electric, El Paso, TX 79901, USA (email: eric.galvan@epelectric.com).

Z. Wang is with the ECE Department, University of Connecticut, Storrs, CT 06269, USA (e-mail: zongjie.wang@uconn.edu).

This work is based in part upon work supported by the National Science Foundation (NSF) under Awards# 1941524 and 2021470.

978-1-6654-0823-3/22/$31.00 ©2022 IEEE

need to further explore on V2H/V2G operation during power grid emergencies and investigate the impacts of these events on power distribution networks. Highly motivated by the aforementioned issues, the major focus of this paper is to explore and investigate the possibilities of using distributed energy resources, in particular EVs and roof-top solar PV, as backup power supply for networked MGs during an outage under extreme weather (heat wave) event. This paper further provides an insight on evaluating resilience metrics to determine the potential grid resilience improvements. This paper aims to contribute to the current state-of-the-art in improving distribution grid resilience in the following manner: (1) Effective utilization of EVs and roof-top solar PVs in networked MGs during power distribution grid contingencies; (2) Resilience evaluation of distribution grid during short- and long-duration outages; (3) Demonstration of EVs and PVs for power restoration following a grid contingency; and (4) Evaluation of grid resilience by using resilience metrics in the context of electrical energy service and economic impacts.

The rest of the paper is organized as follows. Section II presents the system models and resilience metrics. Simulation results and analysis are presented in Section III, and Section IV concludes the paper.

Distribution System Outage Consequences and Resilience Metrics

In this paper, networked MGs with DERs are used to evaluate the resilience metrics using a Resilience Analysis Process [13].

A. Resilience Metrics and Outage Consequences

The potential hazards considered for simulation purposes are outages caused by weather of different duration, i.e., short duration and long duration. Under different cases the hazard scale is correlated, i.e., similar damages will be considered for both cases (short duration and long duration). The damages that are anticipated to occur in the distribution grid are feeder and transformer overload due to extreme temperature caused by a heat wave.

For the case studies, the consequence data of the hazards is obtained through power flow simulation [15]. Running the power flow analysis, the bus voltages and power outputs of the EVs/PVs are computed to determine which loads would be unserved during the outage. The power flow analysis was simulated for a 24-hour period under different cases that are described in the following section. These simulations permit the estimation and quantification of the effects the hazards will have on the distribution grid.

B. Resilience Formulas and Category Impacts

In this paper, the consequences and resilience metrics that are considered for the case studies were obtained from [16], [17]. In order to evaluate the resilience metrics, case studies have been assessed and accordingly presented in Section III. The resilience metrics formulation is as follows.

Total System-hours of outage

$$\sum_{t=1}^{n}\sum_{i=1}^{k} x_i * (t) \tag{1}$$

where $x_i * (t)$ is the number of buses-hours without power of user *i* for the duration of event *n*, for all user *k* experiencing an outage.

Total System energy not served

$$\sum_{t=1}^{n}\sum_{i=1}^{k} E_i * (t) \tag{2}$$

where $E_i * (t)$ is the total energy not served per bus.

Total and average number of buses experiencing outages

$$\bar{X} = \frac{\sum_{s=1}^{T_s}\sum_{i=1}^{K} x_{i,s}}{T_s} \tag{3}$$

where $\bar{X}$ is the average number of buses experiencing an outage during cases and *Ts* the total number of cases.

Total outage costs

$$C_{out,s} = C_o * \left(\sum_{t=1}^{n}\sum_{i=1}^{k} x_{i,s} * (t)\right) \tag{4}$$

where $C_{out,s}$ is the total outage cost ($) and C_o is the outage cost per hour ($/h).

Total Service loss of revenue

$$C_{LUR,s} = C_e * \left(\sum_{t=1}^{n}\sum_{i=1}^{k} E_{i,s} * (t)\right) \tag{5}$$

where $C_{LUR,s}$ is the loss of service revenue ($), C_e is the cost of energy ($/kWh), and $E_{i,s} * (t)$ is the total energy not served for the duration of the event.

Case Studies and Simulation Results

This section provides a detail description of the case studies, data collection, and simulation results.

A. Case Studies and Data Description

In this paper, the case studies are categorized in the following manner: (i) a base case where the power distribution system experiences a short-duration and long-duration outages with no DERs present, (ii) a short-duration and long-duration outages with PV and EVs operating in V2H, and (iii) a short-duration and long-duration outages with PV and EVs operating in V2H/V2G. The IEEE 33-bus radial distribution system with four MGs as shown in Fig.1 has been utilized for the simulation purposes. For EV modeling, three of the top selling battery electric vehicle (BEV) models in the U.S. market and their corresponding market share are considered, i.e., Tesla Model 3 (80%), Nissan Leaf (10%), and Chevrolet Bolt (10%) [18]. Furthermore, a future 60% BEV adoption share is considered based on the National Renewable Energy Laboratory (NREL) electrification futures study [19]. All MG data is summarized in Table I. The rest of the system data can be found in [17]. For the simulations, the BEVs were assumed to have the capability to operate in V2H and V2G. Load data for the test system is acquired from the U.S. Department of Energy Open Data Catalog, residential load at TMY3 locations for the surrounding region of El Paso, TX, and other locations in the U.S. Southwest [20]. Specifically, three load profiles are selected for the following locations, El Paso, TX, Las Cruces, NM, and Holloman AFB, NM. Below is a description of each case study conducted in this paper.

- **Case 1:** Base case with no EVs and PVs in the MGs, for (a) short duration outage and (b) long duration outage
- **Case 2:** PVs and EVs connected to MGs and operating in V2H, for (a) short duration outage and (b) long duration outage
- **Case 3:** PVs and EVs connected to MGs and operating in V2H/V2G for (a) short duration outage and (b) long duration outage.

Simulations are carried out for a day assuming the outages occur due to an extreme weather (heat wave) on a summer day. Moreover, the PV power profile is also considered for a sunny day to quantify the impact when maximum power production is achieved [21]. To calculate the price of energy not served, a fixed energy rate is assumed [22]. A value of 5.1 $/h is used to compute the total outages costs [23]. The following assumptions are made for the case studies:

- Short duration outage occurs for a 4-hour period.
- Long duration outage occurs for a 6-hour period.
- The outages occur at 5:00 PM.
- EVs initial state of charge is 90%.
- It is assumed that all necessary infrastructure (hardware and software) is available for the operation of the EVs in V2H and V2G.

B. *Resilience Analysis for Short Duration Outage*

In this case, it is assumed that an outage occurred affecting the feeders of the system, specifically, branches 2–19, 3–23, and 6–26 (see Fig. 1). In the US southwest, during the summer months (June-September) system peak hours usually occur in the late afternoon between 3pm to 5pm due to high temperatures and the buildup of heat throughout the day. Therefore, the contingency is considered to have occurred at 17:00 and the duration of the event is 4 h (17:00 to 21:00). The time-period is based on the average duration of an outage in the U.S. [24]. To alleviate the impact of the damaged branches, the normally-open tie lines 8–21, 12–22, 18–33, and 25–29 are closed. The use of tie-lines for network reconfiguration during contingencies is a normal practice in most power distribution systems, when available.

For the short duration outage, three sub-cases are considered Cases 1a to 3a as described in Section III-A. In order to simulate the operation of the power distribution system, power flow analysis is utilized. When power flow is executed, the power output of the EVs and PVs as well as the bus voltages of the distribution network are determined. For all scenarios, it is assumed that the load at any bus with a voltage below 0.9 p.u. will be curtailed because loads cannot work under normal conditions with voltages under this value. Fig. 2 shows the bus voltage profiles for Case 1(a) where the dark area indicates bus voltages below 0.9 p.u. From Fig. 2, it can be seen that the majority of the system buses are under 0.9 p.u when the outage occurs.

TABLE I. SYSTEM STUDY DATA FOR RESILIENCE ANALYSIS

	House holds	Load (kW)		PV	BEV	
			No. BEVs	Capacity (kW)	Capacity (kWh)	Input/Output (kW)
Microgrid 1						
Bus 23	10	60	10	40	767	102.4
Bus 24	12	77	12	48	927	124.4
Bus 25	17	60	17	60	1312	175.6
Microgrid 2						
Bus 19	10	60	10	40	767	102.4
Bus 20	11	71	11	44	847	113.4
Bus 21	12	48	12	48	927	124.4
Bus 22	12	73	12	48	927	124.4
Microgrid 3						
Bus 7	40	70	40	160	3086	413.4
Bus 8	40	100	40	160	3086	413.4
Bus 9	20	48	20	80	1552	208.6
Bus 10	20	48	20	80	1552	208.6
Bus 11	20	35	20	80	1552	208.6
Bus 12	25	45	25	100	1934	259.8
Microgrid 4						
Bus 29	48	290	48	192	3726	501.4
Bus 30	80	513	80	320	6187	830.6
Bus 31	60	239	60	240	4632	622
Bus 32	84	508	84	336	6507	874.6
Bus 33	24	154	24	96	1854	765.8

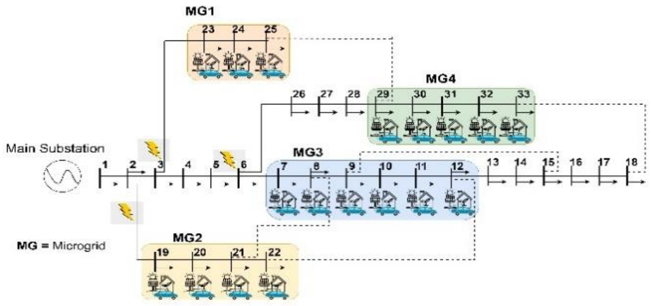

Fig. 1. IEEE 33-bus distribution system with networked microgrids, EVs and roof-top solar PV systems.

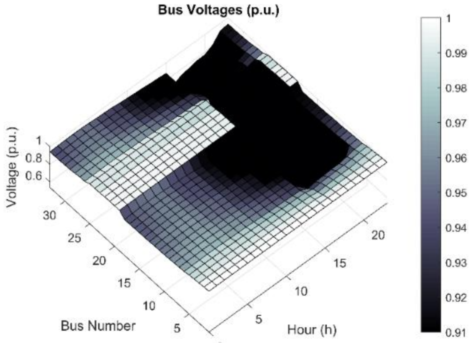

Fig. 2. Buses voltages Case 1(a) - EVs & PVs not connected to the system.

Table II presents the results of the energy service resilience metrics evaluation for the short duration outage. The resilience metrics provide a comprehensive measure of the resilience impacts that EVs and PVs can have on the power distribution grid. From Fig. 3 we can observe the economic impact for the three cases, i.e., case 3a has the best performance as the avoided outage cost is $15,728 compared to case 1a where the outage costs surpass $15,000. In the case of loss of service revenue, the best outcome was also obtained in case 3a. The loss of revenue only considers the energy not served during the outage. The customers using EV in V2H/V2G would not be

978-1-6654-0823-3/22/$31.00 ©2022 IEEE

consider a loss of revenue for the utility as the vehicle would be using energy drawn from the utility grid at a prior moment.

Fig. 4 shows the system demand for the three cases under the short duration outage, i.e., case 1a no EVs/PVs, case 2a EVs/PVs operating V2H, case 3a EVs/PVs operating in V2H/V2G. Also, from Fig. 4 it can clearly be seen that the solar PV cannot provide enough energy during the outage as a stand-alone resource. The system is under outage when the EVs and PVs are not connected, when the EVs are operating in V2H they provide voltage support and help the system improve its operating buses by 41% where only 42% of grid experience an outage. Furthermore, when the EVs are operating in the V2H/V2G, the distribution system operates in normal condition avoiding the outage.

TABLE II. RESILIENCE METRICS FOR ENERGY SERVICE: SHORT DURATION OUTAGE.

Case	1(a)	2(a)	3(a)
Total User Hours Outage (h)	3,084	1560	**0**
Total Energy Not Served (kWh)	23,001	3525	**0**
Total Number and Percentage of Users Experiencing Outage	771 (83%)	390 (42%)	**0** **(0%)**

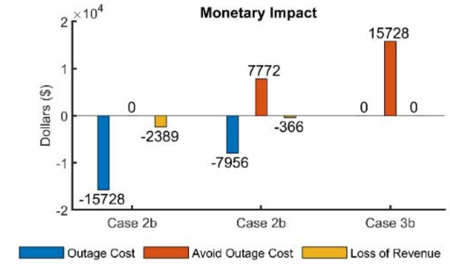

Fig. 3. Resilience metrics for economic impact short duration outage.

C. *Resilience Analysis for Long Duration Outage*

For the long-duration outage it is also assumed branches 2–19, 3–23, and 6–26 are affected as shown in Fig. 1. The contingency is assumed to have occurred at 17:00 and the duration of the outage is 6 h (17:00 to 23:00). The 6-hour time-period is based on the highest average duration of an outage in the U.S. due to extreme weather [24]. Three cases are also considered for the long duration outage. Table III presents the resilience metrics for the electrical service impact of the long duration outage. The average number of buses (case 2b and 3b) experiencing an outage is reduced by 41% when compared to case 1b (see Table III).

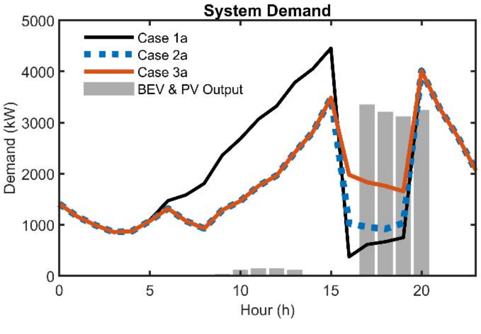

Fig. 4. System load demand under short duration outage.

Fig. 5 shows the economic impact analysis, where case 3b showed the best performance as the avoided outage cost was a $23,593 reduction compared to the base case 1b. Also, in Fig. 6 we can observe an improvement of the voltage profile for all buses in the system where dark area indicates bus voltages below 0.9 p.u. when EVs are operating in V2H/V2G. From Fig. 6, it can be seen that the majority of the system buses are above 0.9 p.u during the outage. Thus, improving the resilience of the system by avoiding a blackout of the distribution system.

TABLE III. RESILIENCE METRICS FOR ENERGY SERVICE: LONG DURATION OUTAGE.

Case	1(b)	2(b)	3(b)
Total User Hours Outage (h)	4,626	2070	**0**
Total Energy Not Served (kWh)	36,169	4879	**0**
Total Number and Percentage of Users Experiencing Outage	771 (83%)	390 (42%)	**0** **(0%)**

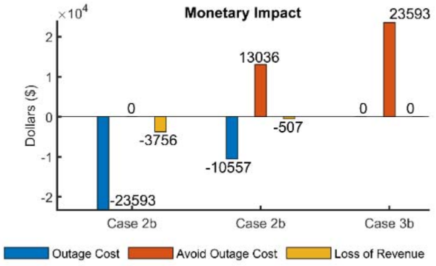

Fig. 5. Resilience metrics for economic impact long duration outage.

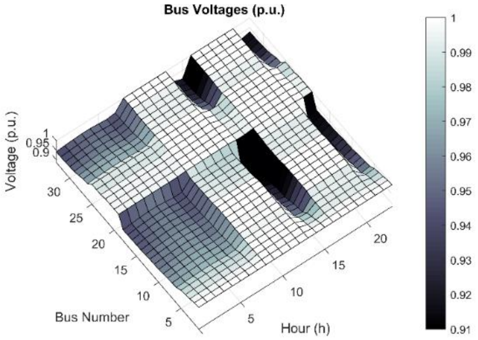

Fig. 6. Buses voltages case 3b – EVs & PV connected in network microgrid

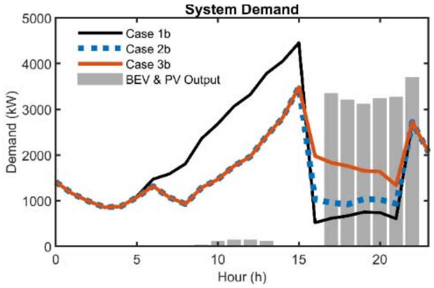

Fig. 7. System load demand under long duration outage.

Fig. 7 shows the system demand for the three cases under the long duration outage, i.e., case 2a no EVs/PVs, case 2b EVs/PVs operating V2H, case 3b EVs/PVs operating in V2H/V2G. The system is under outage where the EVs and PVs are not connected, once the EVs are operating in V2H/V2G they provide bus voltage improvement for the whole system as

978-1-6654-0823-3/22/$31.00 ©2022 IEEE

no bus experiences an outage. The results presented in Section III clearly show the benefits of using EVs and PVs to improve the resilience of power distribution networks to extreme weather events, in particular heat waves. The results presented in this paper were simulated and implemented in MATLAB R2019a using MATPOWER version 7.1 [15].

CONCLUSION

This paper presented an analysis on the use and efficient management of distributed EVs and PVs in residential networked MGs to improve the resilience of a power distribution system impacted by a heat wave. Three cases were presented considering different outage durations and evaluated under various resilience metrics in the context of electrical energy service and economic impacts. In addition, this paper presented an insight on the benefits that EVs and PVs operated in networked MGs can provide the distribution grid. Simulation results obtained using the IEEE 33-bus system demonstrated that EVs can provide power support up to 6 hours in V2H/V2G operation mode reducing the numbers of buses experiencing an outage by 41% whereas cases where solar PV and EV were not present 83% of the distribution system experienced an outage. Therefore, the analysis and results showed that DERs (EVs and PVs) managed in networked MGs can significantly help enhance resilience of the power distribution grid and can be beneficial for customers and utilities from technical and economic perspectives.

Future work would be interesting to evaluate the use of Medium- and Heavy-duty EVs considering random duration faults to test the capability of EVs from these classes to provide grid support services during an outage. It should be noted that the impact of extreme heat on EV battery efficiency was not considered for the case studies presented in this paper, and this could be a potential future work direction. Future work can also be focused on the development of monetary incentives for EV users to participate in energy market operations.

REFERENCES

[1] A. Gholami, F. Aminifar and M. Shahidehpour, "Front Lines Against the Darkness: Enhancing the Resilience of the Electricity Grid Through Microgrid Facilities," *IEEE Electrification Magazine,* vol. 4, pp. 18-24, 2016.

[2] I. Ivanova, "CBS News," 25 February 2021. [Online]. Available: https://www.cbsnews.com/news/texas-winter-storm-uri-costs/. [Accessed 3 October 2021].

[3] K. S. Adam Cooper, "Edsion Institute Electric," Novemeber 2018. [Online]. Available: https://www.edisonfoundation.net/-/media/Files/IEI/publications/IEI_EEI-EV-Forecast-Report_Nov2018.ashx. [Accessed 3 October 2021].

[4] S. B. Peterson, J. F. Whitacre and J. Apt, "The economics of using plug-in hybrid electric vehicle battery packs for grid storage," *Journal of Power Sources,* vol. 195, pp. 2377-2384, 2010.

[5] A. Jenn and J. Highleyman, "Distribution grid impacts of electric vehicles: A California case study," *iScience,* vol. 25, p. 103686, 2022.

[6] H. S. V. S. K. Nunna, S. Battula, S. Doolla and D. Srinivasan, "Energy Management in Smart Distribution Systems With Vehicle-to-Grid Integrated Microgrids," *IEEE Transactions on Smart Grid,* vol. 9, pp. 4004-4016, 2018.

[7] C. Liu, K. T. Chau, D. Wu and S. Gao, "Opportunities and Challenges of Vehicle-to-Home, Vehicle-to-Vehicle, and Vehicle-to-Grid Technologies," *Proceedings of the IEEE,* vol. 101, pp. 2409-2427, 2013.

[8] B. a. HaticeTekiner-Mogulkoc, "A comprehensive analysis of Vehicle to grid (V2G) systems and scholarly literature on the application on such sytems," *Renewable Energy Focus,* vol. 36, pp. 1-20, 2021.

[9] D. Borge-Diez, D. Icaza, E. Açıkkalp and H. Amaris, "Combined vehicle to building (V2B) and vehicle to home (V2H) strategy to increase electric vehicle market share," *Energy,* vol. 237, p. 121608, 2021.

[10] R. Hemmati, H. Mehrjerdi, N. A. Al-Emadi and E. Rakhshani, "Mutual Vehicle-to-Home and Vehicle-to-Grid Operation Considering Solar-Load Uncertainty," in *2019 2nd International Conference on Smart Grid and Renewable Energy (SGRE)*, 2019.

[11] B. Zhou, W. Li, K. W. Chan, Y. Cao, Y. Kuang, X. Liu and X. Wang, "Smart home energy management systems: Concept, configurations, and scheduling strategies," *Renewable and Sustainable Energy Reviews,* vol. 61, pp. 30-40, 2016.

[12] R. Hemmati and H. Mehrjerdi, "Non-standard characteristic of overcurrent relay for minimum operating time and maximum protection level," *Simulation Modelling Practice and Theory,* vol. 97, p. 101953, 2019.

[13] E. D. Vugrin, A. R. Castillo and C. A. Silva-Monroy, "Resilience Metrics for the Electric Power System: A Performance-Based Approach.," February 2017.

[14] T. Kern, P. Dossow and E. Morlock, "Revenue opportunities by integrating combined vehicle-to-home and vehicle-to-grid applications in smart homes," *Applied Energy,* vol. 307, p. 118187, 2022.

[15] R. D. Zimmerman, C. E. Murillo-Sánchez and R. J. Thomas, "MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education," *IEEE Transactions on Power Systems,* vol. 26, pp. 12-19, 2011.

[16] B. Chiu, A. Bose, S. Brown, B. Chalamala, D. Immerman, A. Khodaei, J. Liu, J. Mazurek, and D. Novosel, "Resilience Framework, Methods, and Metrics for the Electricity Sector," IEEE PES, 2020.

[17] E. Galvan, P. Mandal and Y. Sang, "Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters," *International Journal of Electrical Power & Energy Systems,* vol. 123, p. 106239, 2020.

[18] "U.S Department of Energy, Energy Efficiency & Renewable Energy (EERE) AFCD Maps & Data," 6 November 2020. [Online]. Available: https://afdc.energy.gov/data/10567. [Accessed 3 November 2021].

[19] T. T. Mai, P. Jadun, J. S. Logan, C. A. McMillan, M. Muratori, D. C. Steinberg, L. J. Vimmerstedt, B. Haley, R. Jones and B. Nelson, "Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States," June 2018.

[20] "U.S Department of Energy, Energy efficiency & Renewable Energy (EERE) Open Data Catalog.Residential load at TMY3.," [Online]. Available: https://openei.org/datasets/files/961/pub/ . [Accessed 11 November 2021].

[21] "PVWatts® Calculator," Alliance for Sustainable Energy, LLC, [Online]. Available: https://pvwatts.nrel.gov/. [Accessed 23 October 2021].

[22] "El Paso Electric Compamy," Rate service, 17 July 2018. [Online]. Available: https://www.epelectric.com/files/html/Rates_and_Regulatory/Docket_46831_Stamped_Tariffs/03_-_Rate_01_Residential_Service_Rate.pdf. [Accessed 10 October 2021].

[23] M. J. Sullivan, J. A. Schellenberg and M. Blundell, "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States," 2015.

[24] "U.S Energy Information Administration," 1 June 2020. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=43915. [Accessed 8 November 2021].