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Electric vehicles for improving resilience of distribution systems

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ABSTRACT

In this study, improving the resilience of residential customers through employing Electric Vehicles (EV) is investigated. This solution is especially effective in case of unavailability of distribution systems for a considerable amount of time. An example of this situation is the aftermath of a hurricane when existing grid infrastructure may be fully or partially disabled. In this paper, specific attention is paid to hybrid electric vehicles, as their gasoline can be used as a sufficient source of energy during such conditions. In order to have a fair comparison, selected models of both hybrid and non-hybrid electric vehicles are considered. Moreover, based on available data from reliable literature, this paper has generated different load profiles for various consumption scenarios to model the severity of conditions and estimate the required energy. Moreover, two seasonal conditions are considered and the load profiles are developed based on characteristic curves of major household appliances, instead of their rated powers. Then, the selected electric vehicles are considered as the main power supply and the available serving time of each electric vehicle is computed. Results show that a typical hybrid electric vehicle can supply power to residential units for a reasonable amount of time during a power outage.

1. Introduction

Disasters are inevitable, and so are power outages due to storms that affect the distribution network; the only variables are location and severity. Super storm Sandy caused billions of dollars of damage and spawned a power outage for millions of people from several days to weeks (Blake, Kimberlain, Berg, Cangialosi, & Beven, 2012; Sullivan and Uccellini, 2013). The issue could lead to a life-threatening situation during severe weather outbreaks or during medical emergencies, which require special equipment. However, in most cases, power outages cause mere temporary inconvenience. Therefore, a range of different engineering solutions can be considered for different situations, and in the end, it will be a trade-off between capital investment, maintenance expenses and reliability.

While improving the performance of existing structures and increasing their capability to withstand probable extreme weather events can be a solution (Willis and Novosel, 2017; Choobineh, Ansari, & Mohagheghi, 2015), resilience cannot be ensured and a solution is required to restore power locally until service is restored at the large grid level (Gholami, Aminifar, & Shahidehpour, 2016; Choobineh and Mohagheghi, 2016). Hence, while reducing the number of outages is of interest, resilience of the system is also dependent on how the grid will respond to such events. Employing the existing infrastructure has the potential to reduce the capital investment and maintenance expenses significantly. The objective of this paper is to mitigate the issue of supplying power to residential customers while the distribution network is unavailable by employing Electric Vehicles (EV).

Although there are other types of power supplies in emergency cases such as diesel generators, deep-cycle batteries, and other Distributed Energy Resources (DER), in this work EVs are selected since they are now widely available and offer a cost-effective solution to the problem. In September 2014, the governor of California set a goal of placing at least one million zero- and near zero- emissions vehicles on the road in California by January 2023 (Gholami et al., 2016). According to the International Energy Agency, electric vehicles will reach a market penetration of approximately 20 million by 2020 (Trigg et al., 2013). Moreover, scheduled maintenance of EVs (probably by dealerships) can omit any extra Operation and Maintenance (O & M) costs and makes the solution even more economical in comparison to other solutions.

Another advantage of employing electric vehicles is their rapid rate of growth and penetration. Society is also showing more interest in EVs in recent years. Prominent presence of EVs can also be due to the political will behind the deployment of EVs, reducing dependence on fossil fuels and carbon emission. Moreover, environmental and economic benefits of enhanced utilization of EVs make them an impressive player in smart grid structure. As a result, the Department of Energy (DOE) has introduced and highlighted EVs as one of the 20 metrics in measuring the status of smart-gird deployment and impacts (U.S.

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Department of Energy (DOE), 2009).

Valuable research has been performed on different aspects of the Vehicle to Grid (V2G) concept; such as frequency and voltage regulation (Liu, Hu, Song, & Lin, 2013a; Falahi, Chou, Ehsani, Xie, & Butler-Purry, 2013), as well as storage and renewable energy integration (Ma, Houghton, Cruden, & Infield, 2012; Saber and Venayagamoorthy, 2010; Saber and Venayagamoorthy, 2011). However, in this work, it is assumed that the distribution network has been rendered unavailable due to a natural disaster, and the V2G concept is modified to the vehicle to home (V2H) concept. Being isolated from the grid in the V2H scheme relaxes the criteria set by IEEE standards for interconnecting DER with electric power systems (IEEE 1547) (IEEE, 2017). This makes the use of EVs even more economical.

In (Liu, Chau, Wu, & Gao, 2013b), opportunities and challenges of V2H technology are discussed, which highlights the simplicity of the configuration, high cycle efficiency and assistance in the deployment of smart grid. Online optimization control strategy of a Plug-in Hybrid Electric Vehicle (PHEV) connected/disconnected to a home has been studied in (Berthold, Blunier, Bouquain, Williamson, & Miraoui, 2012). The objective of (Berthold, Blunier, Bouquain, Williamson, & Miraoui, 2011) is to minimize the cost function for a V2H configuration. (Xu and Chung, 2016) has evaluated reliability of distribution systems including V2H and V2G, and has shown superior reliability of distribution system with local V2G in case of centralized EV charging as well as distributed EV charging with the V2H concept. In (Alirezaei, Noori, & Tatari, 2016), a combination of solar panels and a battery energy storage system with the V2H concept has been utilized to supply power to a building in order to reduce dependency on the grid. Results have shown the possibility of reducing the energy required from the grid by up to 68% on average. (Shimizu, Ono, Hirohashi, & Kumita, 2016) has used V2H concept in a coordinated scheme with home energy management systems for demand response purposes. Two configurations of combining a photovoltaic system and a PHEV have been studied in (Rahimi and Chowdhury, 2014) to supply power to residential customers. In (Khalghani, Khushalani-Solanki, & Solanki, 2016), optimal integration and location of PHEV aggregators in distribution systems has been assessed. (Jalilzadeh Hamidi and Livani, 2017) has studied real-time decentralized charging management of plug-in hybrid electric vehicles. However, to authors' best understating, no study has considered the use of gasoline energy of Hybrid Electric Vehicles (HEV) in V2H schemes, especially for continuity of service while distribution grid is not available. Moreover, in this work, several top selling and popular PHEVs are selected and a comparison based on the amount of energy they can provide in a V2H scheme is provided.

Even though there have been past reports and research on residential appliance characteristics in detail (Pipattanasomporn, Kuzlu, Rahman, & Teklu, 2014), different objectives are sought such as demand response or residential load control. In this paper, results of previous studies are incorporated into the concept of V2H to investigate the feasibility of the proposed solution. To provide realistic and practical results, three scenarios are developed to consider different severity conditions and the simulations are performed during two different seasonal conditions. Moreover, in most studies, a constant power (rated power) is considered for an appliances power consumption without any cycle or variation. However, in this work, detailed power characteristics are used for each appliance which increases the accuracy.

The main contributions of this work are:

- Use of gasoline energy of HEVs in a V2H scheme.
- Employing detailed power characteristics of major household appliances in order to have an accurate total daily consumption for a typical home.
- Employing a scenario-based approach to calculate energy consumption in different emergency situations based on the severity of the situation.

Moreover, a comparison between different types of EVs in terms of the amount of energy they can supply to a residential customer while distribution grid is not accessible is also presented in this work to analyze the presented concept with real-world examples.

The rest of the paper is organized as follows. Section II is devoted to motivation and a brief review of historical US power outages. Section III explains how electric vehicles can be used as emergency backup power supplies. Section IV discusses the developed scenarios to estimate energy consumption for different situations. In section V, simulation results of two seasonal conditions are presented and discussed. Finally, section VI concludes the paper.

2. Motivation

Power outages always happen, due to the fact that human errors, equipment failures and especially natural disasters are inevitable. Hurricane Sandy caused billions of dollars in damage (in excess of $50 billion) and power outage for millions of consumers (approximately 8.5 million) (Blake et al., 2012; Sullivan and Uccellini, 2013). Another recent example is the northeast snowstorm of October 2011 which caused power outage for more than 3.2 million homes and businesses and a damage estimated approximately between $1 billion and $3 billion (FERC and NERC, 2011).

Fig. 1, (Amin, 2008), shows the number of power outages between 1991 and 2005 which are over 100 MW in size or impacting over 50,000 consumers, revealing an increasing trend over the recent years. An assessment of data from the North American Electric Reliability Council (NERC) has shown that the frequency of blackouts increased during 1984–2006 (North American Electric Reliability Corporation (NERC), 2015). More specifically, a statistically significant increase in blackout frequency was observed during peak hours of the day and during late summer and mid-winter months (Hines, Apt, & Talukdar, 2008).

Severity risk index (SRI) is defined as a stress index, measuring risk impact from events resulting in transmission, generation, and load loss (North American Electric Reliability Corporation (NERC), 2017a). Table 1 shows the top ten severity risk index (SRI) days between 2008 and 2016, which are the days the system was highly stressed (North American Electric Reliability Corporation (NERC), 2017b). As seen in Table 1, all events are caused by weather-related events such as hurricanes or thunderstorms. Another important point seen in this table is the considerable amount of SRI due to the load loss, which in reality means millions of customers without power.

According to data from NERC and analyses from the Electric Power Research Institute (EPRI), average outages from 1984 to 2008 have affected nearly 700,000 customers per event annually (Amin, 2008).

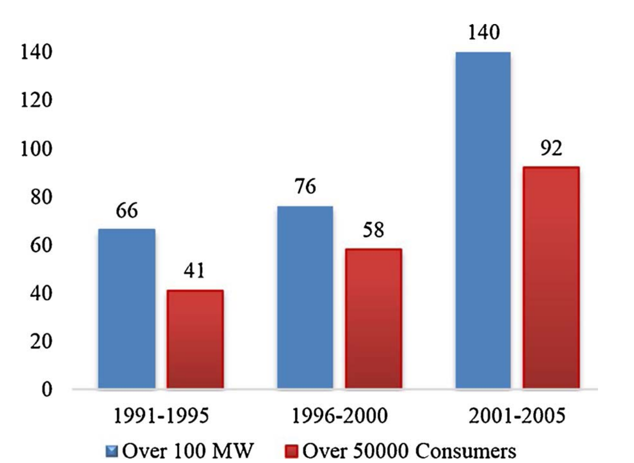

Fig. 1. US Outages over 100 MW and impacting over 50000 consumers (North American Electric Reliability Corporation (NERC), 2015).

Table 1
Top 10 SRI Days (2008–2016) (North American Electric Reliability Corporation (NERC), 2017b).

Rank	Date	SRI	Generation	Transmission	Load Loss	Weather Influenced	Event Type
1	9/8/2011	14	1.2	0.8	12.0	No	Southwest Blackout
2	1/7/2014	11.1	9.8	0.9	0.4	Yes	Polar Vortex
3	2/2/2011	10.8	3	0.5	7.3	Yes	Cold Weather Event
4	6/29/2012	8.9	2.6	1.4	4.9	Yes	Thunderstorm Derecho
5	1/6/2014	8	6.7	1.2	0.2	Yes	Polar Vortex
6	10/30/2012	7.2	2.9	3.4	0.9	Yes	Hurricane Sandy
7	10/29/2012	7	2	1.8	3.2	Yes	Hurricane Sandy
8	4/27/2011	5.8	1.9	3.5	0.4	Yes	Tornadoes Severe Storm
9	8/28/2011	5.6	0.8	1.6	3.2	Yes	Hurricane Irene
10	1/4/2008	5.3	1.2	0.8	3.2	No	Pacific Coast Storm

Therefore, any approach to improve the continuity of the service to the customers is valuable. Due to the fact that natural disasters are inevitable, resilience is of paramount importance. Power system resilience is based on three major elements; prevention, recovery and survivability. This paper introduces a realistic and cost-effective solution to increase survivability.

3. Electric vehicles as emergency backup power supplies

Even though the invention of the EV can be traced to the mid-nineteenth century, mass production of EVs started in the twenty first century as seen by the production of the Toyota Prius in 2001. Sources of energy in an EV can be just batteries or internal combustion engines (ICEs) or fuel cells plus batteries. Recent advances in technology has increased the efficiency of EVs in terms of power consumption, capacity and emissions (Hybrid Cars, 2016).

In this section, the reasons why some types of EVs can be more efficient than others as an emergency power supply are discussed. To select an appropriate option, a comparison between top-selling electric vehicles is performed. Toyota Camry hybrid, Toyota Prius and Chevrolet Volt from hybrid electric vehicles and Nissan Leaf and Tesla model S from battery electric vehicles are chosen. The comparison can be seen in Table 2. Note that BEVs denotes Battery Electric Vehicles and HEV denotes Hybrid Electric Vehicles. MSRP (manufacturer's suggested retail price) is also shown in this table which reflects the affordability of each electric vehicle.

All the electric vehicles mentioned in Table 2 are considered as case studies in this paper, and further comparison of their capability to act as potential electrical energy resources in case of emergencies will be discussed later on. However, it is useful to have an overall understanding of our expectations based on data provided in Table 2. When the distribution network is disabled, BEVs cannot be an effective power supply since their only source of energy is the remaining charge in their batteries. Fully electric cars are dependent on the grid for charging and they are not fully charged often. Moreover, their battery capacity is limited and they are not capable of providing substantial amounts of energy during emergencies. Therefore, Nissan Leaf and Tesla model S which are in the category of BEVs might not be the best choices. Although Tesla model S has a decent battery capacity (85 kWh) in comparison with Nissan leaf battery capacity (24 kWh), since it is a luxury vehicle, it is not an affordable option, nor popular. Another solution can be Fuel Cell Vehicles (FCVs) which use hydrogen to generate electricity but due to the issues of hydrogen production, storage and technical limitations of fuel cells, they are not yet in large scale commercial use (Chan, 2007; Spink and Saathoff, 2013; Roman, 2006). Hybrid Electric Vehicles (HEVs) and their plugin version, Plug-In Hybrid Electric Vehicles (PHEVs), do not have the mentioned disadvantages of BEVs and FCVs. Moreover, their internal combustion engine (ICE) makes them capable of supplying power even when they are isolated from the grid. Therefore, the remaining charge on their batteries plus the energy obtained by their ICE propulsion system can supply a residential load for a reasonable amount of time. It is then expected to find the HEVs more efficient in the scope studied in this paper.

4. Consumption scenarios under study

Focus of this paper is to study the benefits of EVs for residential customers and compare their serving times in emergency conditions, and for this purpose, the total energy consumption of a typical residential customer in such scenarios needs to be known. In this section, first, the load profile of a typical residential customer is created in summer and winter conditions under normal operation of distribution system, referred as the first scenario. Then, by modifying the usage durations and/or not utilizing some appliances, emergency and extreme emergency scenarios, later on referred as second and third scenarios respectively, are developed, which enables us to calculate the daily load consumption in kWh. Note that the residential consumption records may be available during normal conditions, but by creating the load profiles in emergency scenarios, energy consumption can be estimated during emergency and extreme emergency conditions.

Major residential appliances and loads are limited, but since different manufactures make different types, there is a great variety in their characteristics. Measuring appliances characteristics needs real appliances and data acquisition devices and software; therefore, most published studies have used the rated power for each appliance. This assumption makes the computation simple but decreases the accuracy. This paper has used the results of (Pipattanasomporn et al., 2014) and (Oak Ridge National Laboratory, 2011) and employed the detailed characteristics of major electric appliances to develop the required consumption scenarios. In this research, air conditioner/heat pump, water heater, oven/stove, clothes washer, clothes dryer, dishwasher, refrigerator, lights, and electronics are considered as major household

Table 2
Comparison of some of the top-selling electric vehicles (prices acquired in 2017).

Vehicle (2017 model)	BEV/HEV	Tank size (Gallons)	MSRP From ($)	Popularity	Sales in 2016 (#) (Hybrid Cars, 2016)
Toyota Prius	HEV	11.9	23475	Yes	98,863
Toyota Camry Hybrid	HEV	17	26790	To some extent	22,227
Chevrolet Volt	HEV	9.3	33220	To some extent	24,739
Nissan Leaf	BEV	NA	30680	To some extent	14,006
Tesla model S	BEV	NA	68000	To some extent	29,156

Table 3
Details of the proposed scenarios.

Appliance	Time of Use and Duration		
	Normal	Emergency	Extreme Emergency
Refrigerator	whole day	whole day	whole day
AC	whole day	whole day	whole day
Water Heater	7:30 AM (15 min) 12:30 PM (15 min) 8:00 PM (60 min)	7:30 AM (15 min) 12:30 PM (15 min) 8:20 PM (30 min)	7:30 AM (15 min) 12:30 PM (15 min) 8:20 PM (30 min)
Clothes Washer	6:00 PM (50 min)	1:45 PM (50 min)	No Use
Dryer	7:00 PM (65 min)	2:45 PM (65 min)	No Use
Dish Washer	8:00 PM(100 min)	9:00 AM (100 min)	No Use
Range/Oven	7:00 AM (15 min) 11:30 AM (45 min)*2 6:00 (45 min)*2	7:00 AM (10 min) 11:30 AM (30 min) 6:00 (30 min)	7:00 AM (10 min) 11:30 AM (30 min) 6:00 (30 min)
lighting	6–11:00 PM (300 min)	6–11:00 PM (300 min)	6–11:00 PM (300 min)
Electronics	TV 8:00AM (20 min) TV 11:00PM (30 min) TV 07:00PM (60 min) Laptop 8:00 PM (30 min)	TV 8:00AM (20 min) TV 11:00PM (30 min) TV 07:00PM (60 min)	TV 8:00AM (15 min) TV 11:00PM (15 min) TV 07:00PM (15 min)

appliances. Since air conditioning allocates a large portion of consumption, all three scenarios are developed in two seasonal conditions (summer and winter). It makes the study more comprehensive and detailed. Note that this work does not try to develop mathematical models of the loads and appliances, but estimates the energy consumption based on the results of previous studies (Pipattanasomporn et al., 2014; Oak Ridge National Laboratory, 2011).

The scenarios have been utilized to consider and study different consumption patterns during a day and it helps to come up with practical results. Some assumptions have been employed to develop the scenarios; however, since detailed load characteristics have been used, all assumptions in each scenario can be modified (the time of day each appliance is used and the amount of use). Note that if only required energy is the main concern and usage durations are kept constant, time of use of appliances does not make a difference in total energy consumption, since energy consumption is defined as the integral of power over time. Having a Building Energy Management System (BEMS) for the house can be very useful for optimal utilization of available energy and preventing damage to appliances. The whole point of using a BEMS is to monitor and control the major appliances, their time of use and the available energy to have the optimal performance of electric system. By employing a BEMS, it is possible to control when to turn on a high-consumption appliance and when to turn it off. In some cases, reasonable amount of energy may be available from EVs, but rate of consuming energy, i.e. power, is very high and it can cause overloading the wiring and the batteries. The BEMS can save the system form those situations by defining the right time to turn on high-consumption appliances.

In normal condition, all major appliances are used in a normal day. In the emergency condition, a BEMS controls the time to turn on high-consumption appliances with a flexibility in their time of use, such as washer/dryer and dish washer; while other appliances such as lighting or range are not controlled in this scheme. The BEMS tries to find the best times to turn on the flexible appliances (clothes washer/dryer and dish washer) to achieve the least maximum power seen in the total load profile of the household. In order to do so, in this paper, it is considered that the BEMS solves an optimization problem to find the best times to turn on the flexible appliances in order to achieve the least amount of peak power during the periods those appliances are being used. This is performed in order to prevent the system from overloading; in other words, although enough energy might be available from EVs, but rate of its consumption (power) should be limited in order to avoid damaging the wiring and battery. Hence, the BEMS optimizes the usage time of flexible appliances such as washer and dryer to minimize the peak power, which is the maximum of the sum of all turned-on appliances' powers. The objective function is hence defined as follows:

$$\min[\max \sum_{i=1}^{n} Pi(t)] for t \in T_C \tag{1}$$

where:

n: Number of appliances

$Pi(t)$: Power consumed by appliance i at time t

Moreover, $T_C$is the time durations of the day in which the flexible appliances are controlled, and is calculated as:

$$TC = [t_1: t_1 + T_1] \cup [t_2: t_2 + T_2] \cup [t_3: t_3 + T_3]$$
$$s.\ t.\ t_2 > t_1 + T_1 \tag{2}$$

where:

t_1: Start time of use for clothes washer

t_2: Start time of use for clothes dryer

t_3: Start time of use for dish washer

T_1: Duration of use for clothes washer

T_2: Duration of use for clothes dryer

T_3: Duration of use for dish washer

Genetic Algorithm (GA) is used in this paper to solve the optimization problem (Goldberg, 1989); however, other optimization techniques may also be used to achieve the same goal. Each string consists of 6 values which define the hour and minute of the starting times. For each string, the fitness value is computed and then selection, crossover and mutation are performed on the population. The parameters of the employed GA are shown the Appendix Table A1.

In extreme emergency conditions, an approach is needed that saves the amount of available energy and uses it for the essential needs such as cooking and air conditioning. Therefore, in the third scenario, clothes washer and dryer as well as dishwasher are not used to increase the amount of time in which the vehicle can deliver power to the essential loads. However, the usage pattern of other appliances are the same as the second scenario.

Table 3 shows the consumption scenarios, denoting when and how much each of the major appliances are utilized in them. It is obvious that the refrigerator and air conditioner may work all day. It is important to note that the proposed scenarios have been developed just to have different but realistic consumption patterns, and since residential consumers might follow different lifestyles, many other scenarios can be developed. Interested readers may hence consider different scenarios, but the concept of using EVs to increase the resilience of residential customers would be the same.

5. Simulation results

In this section, first, the power characteristic of household appliances are considered to create the load profile for each aforementioned scenario in both summer and winter condition. The operating characteristics of appliances used in this paper are derived from (Pipattanasomporn et al., 2014), (Oak Ridge National Laboratory, 2011) with a data resolution of one minute. Then, based on the total consumption in each scenario, the duration of time when the EV can help in the continuity of service to the residential customer is determined.

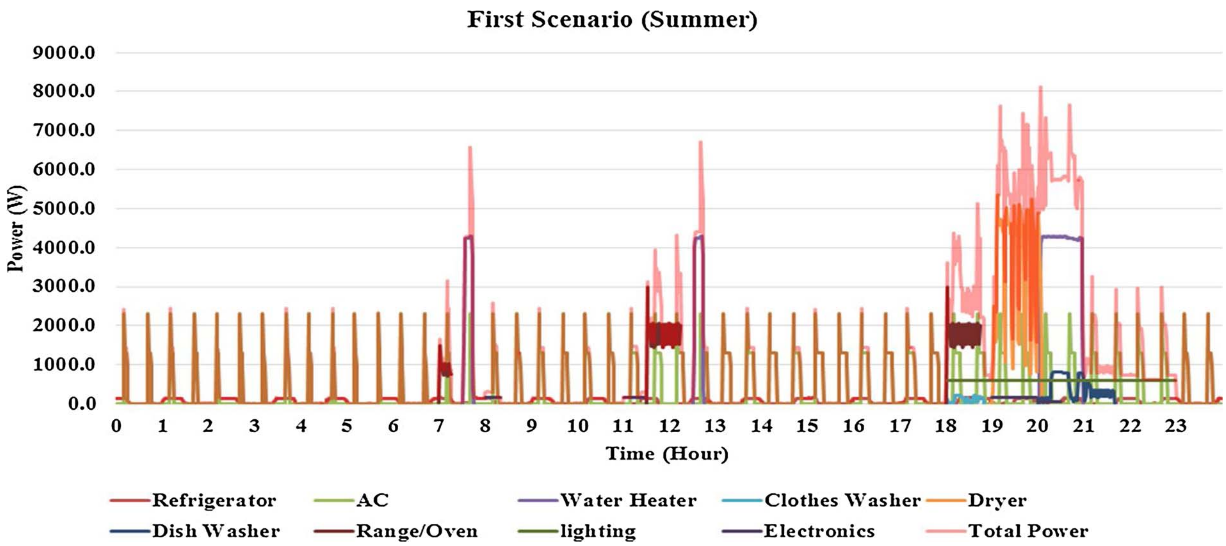

Fig. 2. Appliances characteristics and total power in the normal scenario, summer.

5.1. Summer condition

The first set of simulations is performed in summer when the AC is supposed to work. Fig. 2 presents the power characteristics of each appliance and total power during the first scenario, and Fig. 3 shows the hourly load-profile of the same scenario. It can be seen that the AC works the most during afternoon, and the effect of using the clothes washer and dryer and dishwasher can be clearly seen between 6 and 9 PM when the consumption could reach 2.5–3 times that of around noon.

In the emergency scenario, to prevent overloading, the BEMS turns on the dishwasher, clothes washer and dryer during the time periods which provide the least amount of peak power. Time of use for some appliances is decreased to save energy. Figs. 4 and 5 present the total power and power characteristics of each appliance as well as the hourly load profile for the emergency scenario, respectively. The effect of turning on the dish washer and dryer can be seen in these figures between 9 and 11 AM and 3–4 PM, respectively.

Finally, in the extreme emergency scenario, the BEMS does not let the dishwasher, clothes washer, and dryer operate. Fig. 6 and 7 present the total power and power characteristics of each appliance as well as the hourly load-profile for this scenario. The effect of temperature on ACs on-off cycles can be seen in Fig. 6 during the afternoon hours.

Total consumption in normal scenario depicted in Fig. 2 is calculated to be 35.5 kWh. Note that the characteristics of major household appliances were achieved from (Pipattanasomporn et al., 2014), in which the study was performed in Maryland. This is close to the average summer daily consumption of a residential customer in the state of Maryland (EIA, 2017), i.e. 37 kWh. Selection of the state of Maryland for this study is solely based on the available data for the major household appliances, and the proposed approach is independent of the geographical location of the residential customers.

Based on the normal load profile, the emergency and extreme emergency load scenarios depicted in Fig. 4 and Fig. 6 have a total consumption of 27.4 kWh and 20.7 kWh, respectively.

5.2. Winter condition

The second set of simulations is performed in the winter when the heat pump is supposed to operate. Fig. 8 shows the power characteristics of each appliance and the total power in normal scenario, while Fig. 9 presents the hourly load profile of this scenario, both in winter season. As expected, the peak load is seen in the evening for the residential load curve under study.

In the same manner, Fig. 10 and 11 show the power characteristics of each appliance, total power and hourly load profile of the emergency scenario, respectively. Dishwasher, washer and dryer were turned on by the BEMS at the optimal times, found by employing GA, to prevent overloading the wiring and battery modules. The temperature affected the on-off cycles of the heat pump and it can be seen in Fig. 10.

Finally, Fig. 12 and 13 show the power characteristics of each appliance, total power and hourly load profile of the extreme emergency scenario, respectively. Since a heat pump generally consumes more energy than an AC, it is expected for the energy consumption in winter

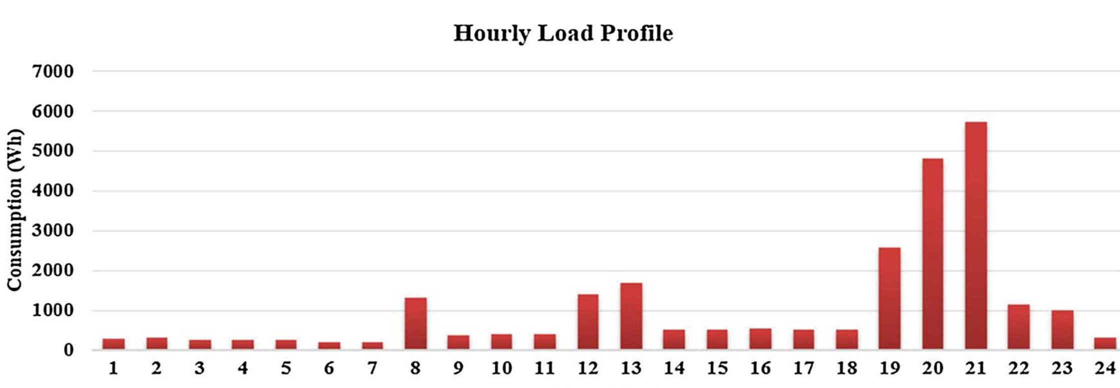

Fig. 3. Hourly load-profile in the normal scenario, summer.

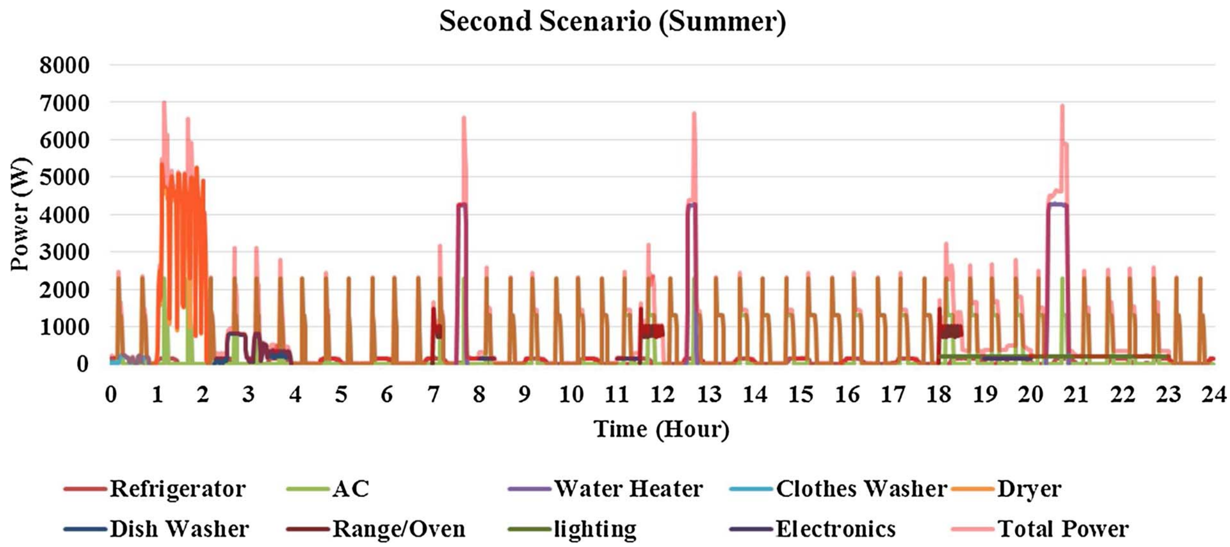

Fig. 4. Appliances characteristics and total power in the emergency scenario, summer.

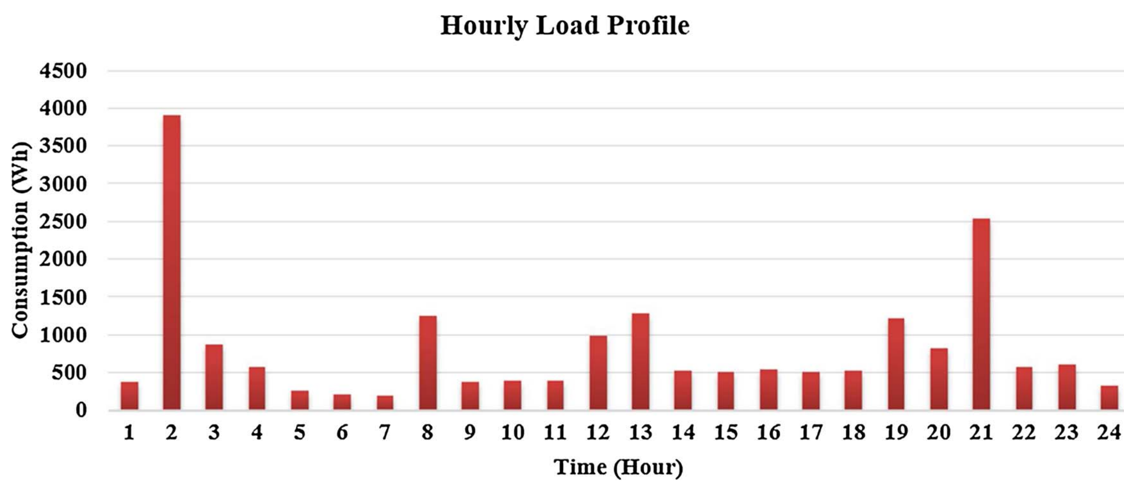

Fig. 5. Hourly load-profile in the emergency scenario, summer.

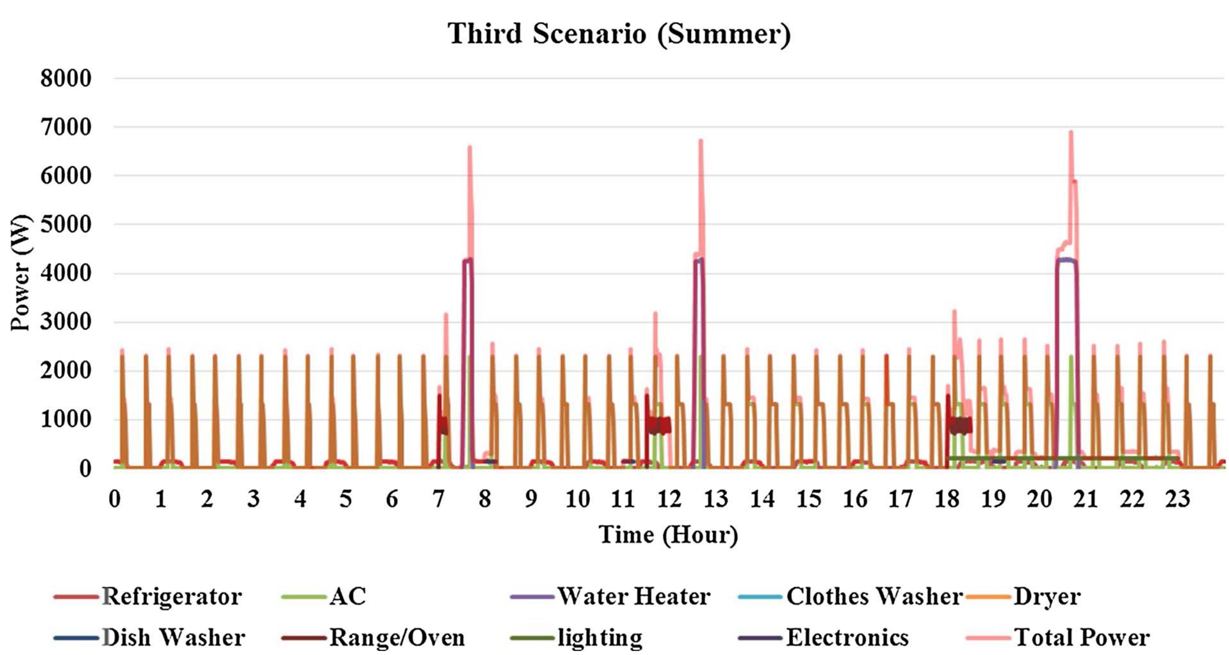

Fig. 6. Appliances characteristics and total power in the extreme emergency scenario, summer.

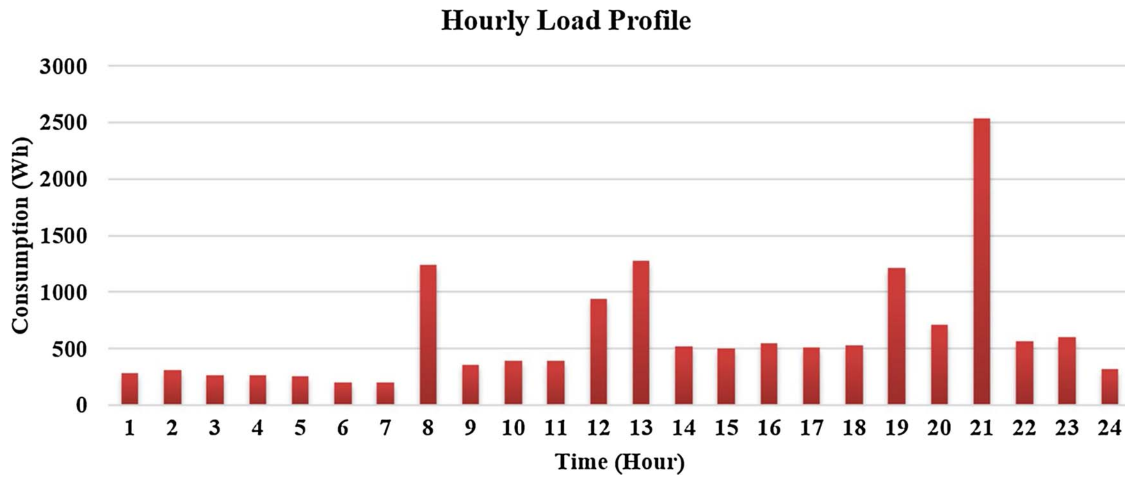

Fig. 7. Hourly load-profile in the extreme emergency scenario, summer.

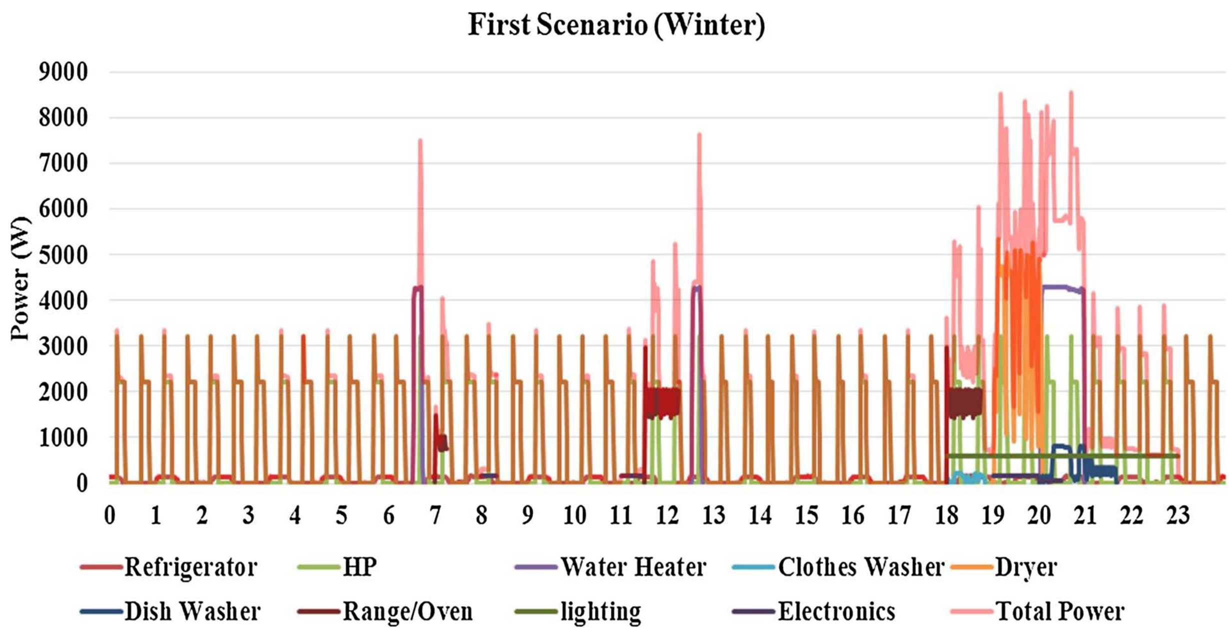

Fig. 8. Appliances characteristics and total power in the normal scenario, winter.

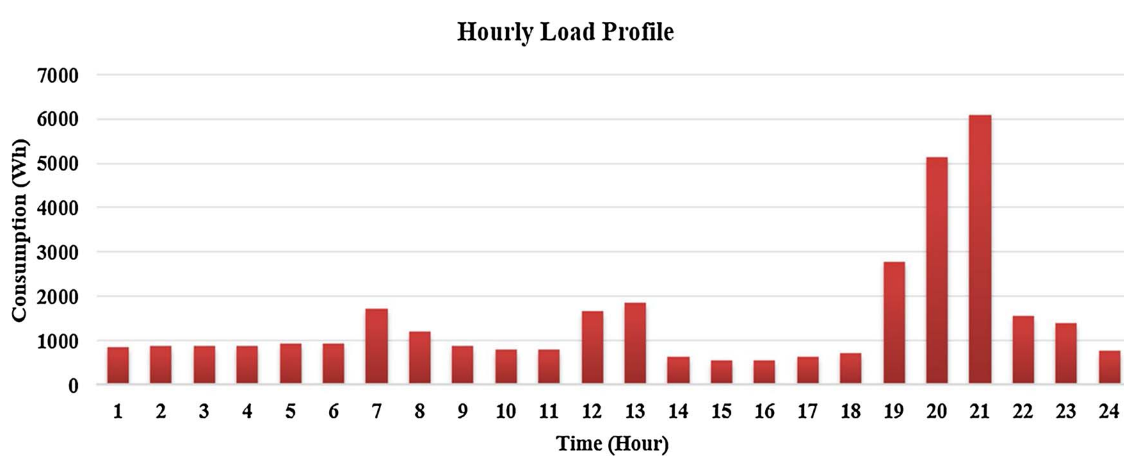

Fig. 9. Hourly load-profile in the normal scenario, winter.

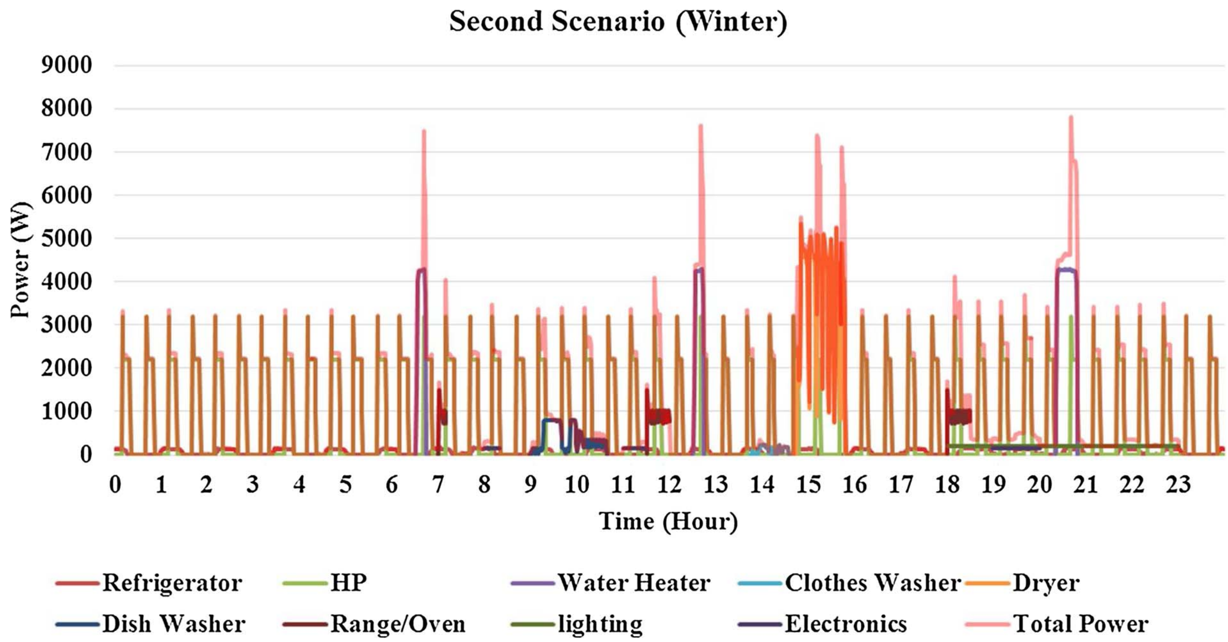

Fig. 10. Appliances characteristics and total power in the emergency scenario, winter.

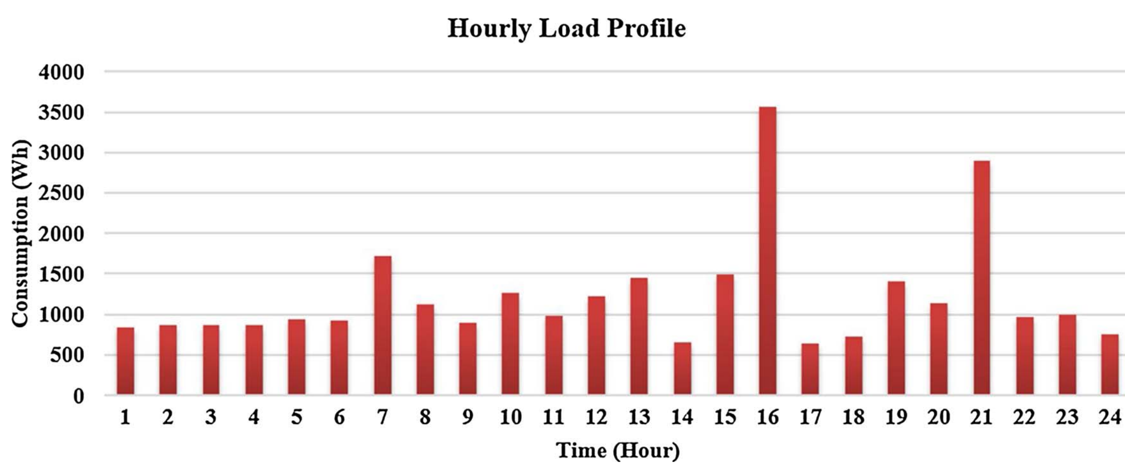

Fig. 11. Hourly load-profile in the emergency scenario, winter.

to be more than the summer. Although this assumption depends on the geographical location and the climate of the location, it is generally considered in this work in the proposed approach for the use of EVs.

In winter condition, total consumption in normal scenario, Fig. 8, is equal to 40.2 kWh. This is also close to the average summer daily consumption of a residential customer in the state of Maryland (Spink and Saathoff, 2013), i.e. 42 kWh. The emergency and extreme emergency load scenarios in winter condition have a total consumption of 33.5 kWh and 28 kWh, respectively.

5.3. Calculating the duration of availability of HEV

In this section, the amount of energy which can be obtained from an EV is considered. For an HEV, the stored gasoline in its tank as well as the charge in its battery, and for a BEV, only the available charge in its battery is considered as the main source of energy for a residential customer. Since most weather related power outages may be forecasted to some extent and some early preparations may be feasible, the amount of energy obtained by a full capacity of the vehicle is also considered. Knowing the amount of energy obtained from the EVs as well as the energy consumption in each scenario, the amount of time the vehicles can be utilized as an emergency power supply can be calculated.

The total energy (kWh) that can be provided by each EV studied in this paper can be calculated as follows. In case of an HEV, first the energy available form gas tank needs to be calculated. The kWh equivalent of full tank capacity of an HEV, E_{tank}, is calculated considering the thermal efficiency of each HEV(η_{tank}):

$$E_g = \eta_{tank} \times Cap_{\text{tank}} \times 34 \tag{3}$$

Considering that energy of one gallon of gas is 34 kWh (Alternative fuels data center, 2016), and Cap_{tank}denotes the capacity of gas tank in gallons. Then, the total available energy is calculated by taking into account the capacity of the battery (Cap_{battery}). Considering a maximum discharge limit for the battery ($Max_{discharge}$) based on its characteristics, the available DC energy from the battery can be calculated as follows:

$$E_b = Max_{disch\arg e} \times Cap_{battery} \tag{4}$$

Finally, the energy stored in battery (E_b) should be converted to AC current to be available to a typical residential customer. This is also true for the energy available from the gas tank, since it will be first converted to the electricity, stored in the battery, and then be available to the customer. Therefore, both sources of energy are exposed to the inverter efficiency (ss$\eta_{inverter}$). The total available AC energy for the

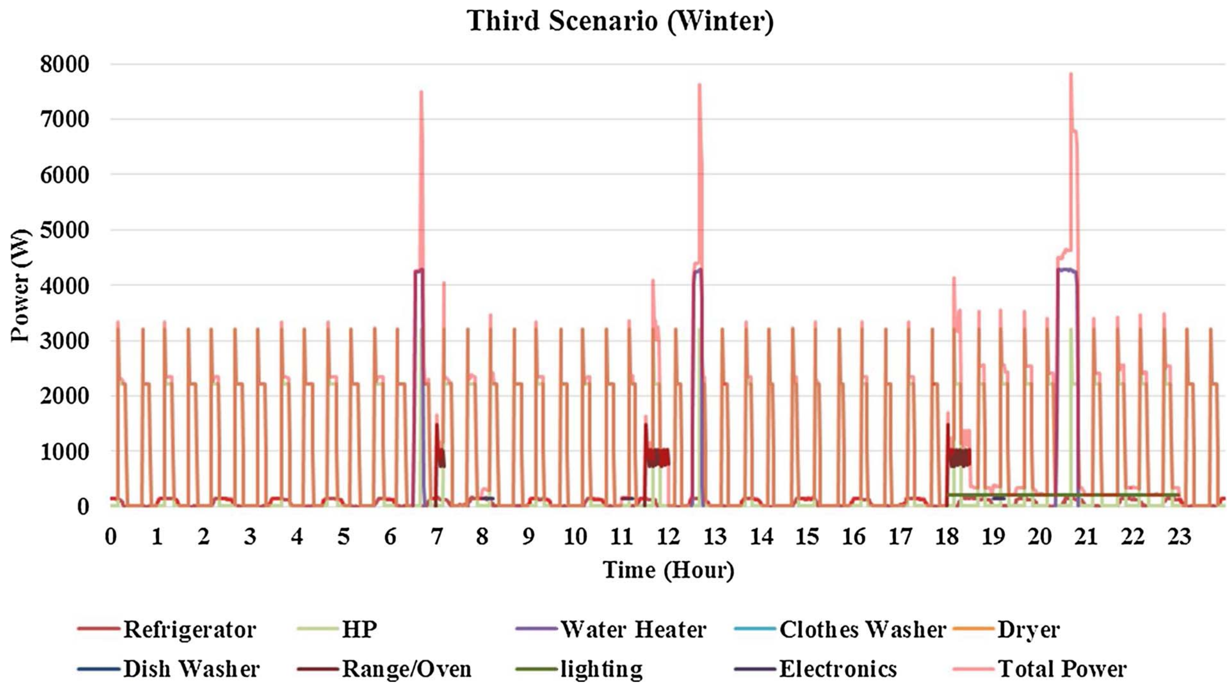

Fig. 12. Appliances characteristics and total power in the extreme emergency scenario, winter.

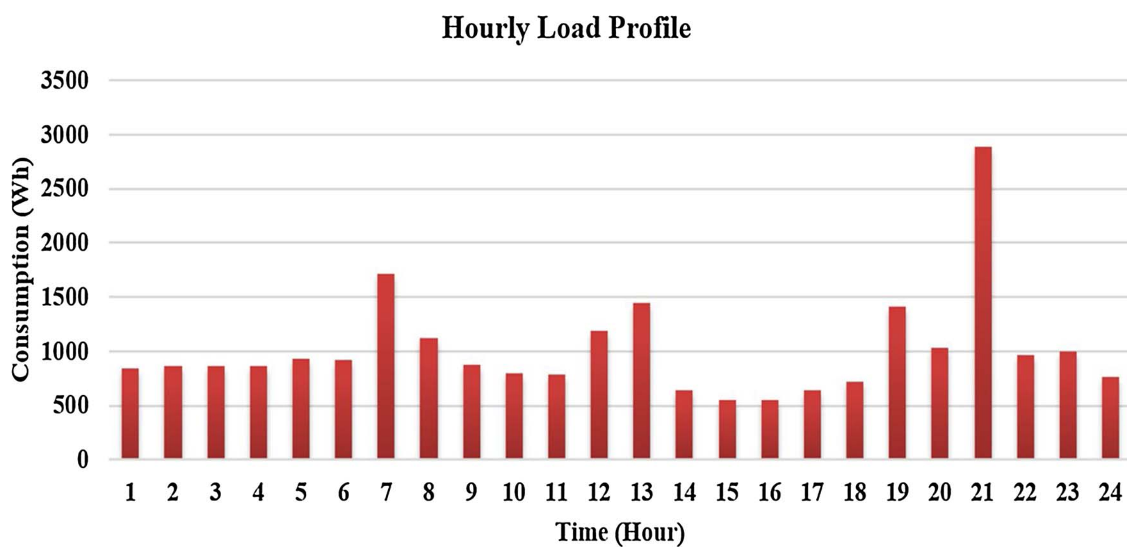

Fig. 13. Hourly load-profile in the extreme emergency scenario, winter.

Table 4
Total energy available to ac loads in full and half capacity of EVS under study.

Vehicle (2016 model)	Tank			Battery		Available DC energy (kWh)		Energy available to AC loads (kWh)	
	Capacity (gal.)	Equivalent in kWh	Thermal Efficiency	Capacity (kWh)	Max. discharge	Case 1, full capacity	Case 2, half capacity	Case 1, full capacity	Case 2, half capacity
Prius	11.3	384.4	0.4	4.4	90%	157.7	78.9	142.0	71.0
Camry Hybrid	17	578.3	0.4	1.6	90%	232.8	116.4	209.5	104.7
Chevrolet Volt	8.9	302.8	0.37	18.4	90%	128.6	64.3	115.7	57.9
Nissan Leaf	NA	NA	NA	24	83%	20.0	10.0	18.4	9.2
Tesla model S	NA	NA	NA	85	83%	70.8	35.4	63.8	31.9

residential customer in case of a full capacity HEV would be:

$$E_{AC} = (E_g + E_b) \times \eta_{inverter} \tag{5}$$

In case of a BEV, the term Eg would be zero.

Calculating the aforementioned steps for each EV, the energy available to AC loads in two cases and both seasonal conditions are achieved, as shown in Table 4. First case is considering that enough time was available for early preparations; i.e. before the outage, battery

Table 5
Serving time of each EV in emergency and extreme emergency scenarios.

Vehicle	Available Capacity	Serving time (days) based on load scenario			
		Emergency		Ext. Emergency	
		Summer	Winter	Summer	Winter
Prius 2017	Full	4.9	4.0	6.5	4.8
	Half	2.5	2.0	3.3	2.4
Camry Hybrid	Full	7.3	6.0	9.6	7.1
	Half	3.6	3.0	4.8	3.6
Chevrolet Volt	Full	4.0	3.3	5.3	3.9
	Half	2.0	1.6	2.7	2.0
Nissan Leaf	Full	0.6	0.5	0.8	0.6
	Half	0.3	0.3	0.4	0.3
Tesla S	Full	2.2	1.8	2.9	2.2
	Half	1.1	0.9	1.5	1.1

is fully charged and in case of HEVs, the tank is full. The second case considers the half capacity conditions, where battery is half charged and the tank is half empty. The data regarding the characteristics of each EV shown in Table 5 can be found in the following references: inverter efficiency equal to 90% (Burress, Campbell, Coomer, Ayers, & Wereszczak, 2011) and (Burress, 2015), Toyota Prius (Toyota official website, 2017a), Toyota Camry (Toyota official website, 2017b), Chevrolet Volt (Chevrolet official website, 2017), Nissan Leaf (Nissan official website, 2017), Tesla model S (Tesla official website, 2017).

Calculating the amount of energy available to the AC loads in Table 4 and using the total consumption of each consumption scenario, the amount of time in which the vehicle can serve as an emergency power supply can be calculated. A 5% security margin is considered for the calculated energy consumption to consider miscellaneous loads and make the results more realistic and reliable. Table 5 shows the amount of energy computed in each scenario and the amount of time which each vehicle can serve as a backup power supply.

The simulation results show that even if preparations are not performed and a half capacity Prius (half tank, half battery) is considered, a residential customer can be supplied for more than 2 days in emergency conditions in both summer and winter scenarios. The serving time for a HEV with a larger tank such as Camry Hybrid is more than 3 days in emergency conditions.

However, by considering preventive measures and charging the battery before an emergency as well as having a full tank Prius (full capacity), the minimum available serving time of the car can be doubled, i.e. reaching 4 days. Similarly, Camry Hybrid can supply a typical residential customer for more than 6 days. This duration is enough for the customer to pass the emergency condition it is facing, until the grid is available again. Note that considering more conservative consumption, as in extreme emergency scenario, the minimum duration of availability of EVs as a backup supply can even be increased. For instance, in extreme emergency scenario, Prius can provide minimum of 2.4 days with a half capacity, and for a minimum of 4.8 days with a full capacity. In the same manner, Camry Hybrid can supply a customer for more than 3 days in half capacity condition and more than 7 days is full capacity condition.

Duration of available serving time for other vehicles are also provided in Table 5. For Camry, due to its bigger gas tank and higher capacity battery, the minimum serving time is higher than Prius; while Chevrolet Volt has a serving time less than but close to Prius. Note that, as expected, Nissan Leaf is not a viable option with respect to the scope studied in this paper, due to its limited battery capacity and being a BEV. Tesla model S can supply the studied load profiles for a reasonable amount of time, although this duration is significantly lower than the least duration of HEVs studied here. Another fact to be considered for Tesla model S is its expensive price, which makes it less popular for the average residential customer. Results shown in Table 5 show that HEVs are the best options in terms of providing the most serving time.

It should be noted that the results will be different for other geographical locations due to different climate conditions. Moreover, the number of residents in each household will also be another factor which may alter the consumption, and hence increase or decrease the duration of available time for HEV to act as a backup supply.

6. Discussion and conclusion

Employing existing infrastructures and facilities can change an expensive solution to a cost-effective and economical one. This paper investigates the feasibility of providing power to residential consumers during power outages to improve the resilience of a distribution system. A cost-effective solution which increases survivability of distribution systems during extended power outages is introduced and validated. With the proposed approach, thousands of consumers without power can conceivably survive during power outages for a reasonable amount of time. Different scenarios in different seasonal conditions were developed and simulated to validate the proposed approach by studying different consumption patterns. Simulation results showed that hybrid vehicles can be the best option in term of providing the most serving time among the studied electric vehicles due to the fact that their gasoline energy can be used and hence they can be utilized as economical emergency power supplies to serve residential consumers during power outages. For example, one of the assessed HEVs could serve a residential customer for more than 7 and 9 days in summer and winter, respectively, in full capacity condition. Although there might be other solutions to the issue of supplying power to residential consumers during outages, the proposed approach is an affordable solution for individual residences to survive a potentially deadly power outage.

Appendix A

Table A1
Employed GA parameters.

Population size	500
Selection Method	Roulette Wheel
Crossover Method	Single Point (Random Point)
Crossover Rate	0.8
Mutation Method	Single Point (Random Point)
Mutation Rate	0.05
Termination	200 iterations, or improvement of less than 0.01% over last 10 generations

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