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Enhancing Adequacy of Isolated Systems with Electric Vehicle-based Emergency Strategy

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***Abstract*—Extreme events can extensively damage power systems, causing customers to experience long-lasting outages. During such events, an electric vehicle (EV) can be used to directly power a house, i.e. vehicle-to-home (V2H). Specifically, the EV serves as a mobile energy storage system—running errands to "transport" energy from other places. Vehicle-to-grid (V2G) further allows cooperation among houses. It enables EV fleets to take turns running the errands so that sustained power supply is possible. Moreover, autonomous driving technology can also benefit system adequacy because the charging errands of EVs can be scheduled flexibly without being bonded to human activities.**

An emergency power supply strategy featuring scheduled EV charging errands as introduced above is proposed. It answers the questions whether and to what extent a system can survive an extended period of outage with the use of EVs only. An optimization problem is formulated with the purpose of maximizing the supply adequacy of the isolated system during the outage period. Both V2H and V2G scenarios are considered in the problem formulation, as well as self-driving capability. The complex optimization problems are solved with genetic algorithm. It is significant to find from the case study that the proposed strategy is able of fully restoring an islanded system when V2G and self-driving EVs are implemented.

***Index Terms*—Adequacy assessment, autonomous driving, electric vehicle (EV), isolated system, vehicle-to-grid (V2G), vehicle-to-home (V2H).**

NOMENCLATURE

i	Index of EV.
j	Index of time.
k	Index of charging errand.
n_{D}	Index of day.
S_{H}	Set of time periods when EVs are house-connected.
N_{EV}	Total number of EVs.
$P_{\mathrm{H},ij}$	Electricity load of household i at time j.
$P_{\mathrm{EV},ij}$	Power output of EV i at time j.
Δt	Duration of each time slot.
$t_{\mathrm{I},ik}$	Time when EV i starts its kth charging errand.
$t_{\mathrm{II},ik}$	Time when EV i arrives at the charging station during its kth errand.
$t_{\mathrm{III},ik}$	Time when EV i leaves the charging station during its kth errand.
$t_{\mathrm{IV},ik}$	Time when EV i arrives home during its kth errand.
N_{D}	Number of days the outage lasts for.
M_i	Distance between the isolated system and the charging station for EV i.
$v_{\mathrm{avg},i}$	Average driving speed of EV i.
$e_{\mathrm{EV},ij}$	Available energy capacity of EV i at time j.
$e_{\mathrm{F},ij}$	Energy capacity of EV i.
$R_{\mathrm{avg},i}$	Average energy consumption rate of EV i.
$P_{\mathrm{O},ij}$	Maximal power through outlets for EV i at time j.

I. INTRODUCTION

EXTREME events, especially extreme weather events, have been assailing the electricity grid in recent years with unprecedented frequency and intensity [1]. These events have caused power loss for millions of households and businesses and long outage periods [2]. The power industry is urged to make strides toward building a resilient power sector. On the other hand, vehicle technologies especial those of electrical vehicles (EVs) are advancing rapidly [3], [4]. With technologies such as bidirectional charger, EVs can serve as distributed generators (DG) when upstream power supply (generation and transmission) fails [3], [5].

In terms of extreme events that result in prolonged period of outage, prevailing assessment methods for system adequacy including analytical and simulation methods [6] struggle to hold these accountable. The impact of extreme events varies drastically from case to case. Samples of such diversity and sparsity cannot feasibly be included in stochastic approaches. Consequently, emergency power supply plans for the isolated system are desired.

A. Adequacy of Isolated Systems

The notion of adequacy of systems islanded/isolated from the main grid arises with the rise of DG technologies, which make power supply of systems possible during "stand-alone" periods. Karki and Billinton [7], [8] study the adequacy of small isolated power system (SIPS) containing photovoltaic (PV) and wind energy sources. Atwa *et al.* [9] point out that a distribution system during the islanding period is effectively a small autonomous system. Hegazy *et al.* [10] define adequacy assessment as the determination of system power capacity and

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the ability of this capacity to meet the total system demand.

During islanding mode of operation, the common setup in existing studies is wind/solar-powered DG units being the energy sources. However, extreme weather conditions may prohibit those DG units from functioning. Weather conditions may remain unsettled even after an event, making renewable energy sources (RES) unreliable. For this reason, the adequacy of islanded/isolated systems is no longer guaranteed with the existing paradigm.

B. *Involvement of Electric Vehicles*

One of the advantages of EV is its flexibility for charging and trip-scheduling. Optimal charging schemes are approached from various perspectives, [11], [12]. Optimal routing problems with different charging requirements for EV fleets are studied in [13] and [14]. Further, EV also has the ability to improve system adequacy by ejecting power back to the grid when in need. It is useful when upstream power supply is down. V2H is considered the first step towards the diffusion of vehicle-to-grid (V2G). In [5], Shin *et al.* optimize vehicle-to-home (V2H) to provide maximum "backup duration" during islanded mode. Using EVs for reliability improvement are discussed in [15]–[17]. During outages, EVs directly power the house (V2H) or pour extra electricity back into the grid (V2G). Charging can resume as soon as the power supply is restored. In [15], an isolated system with 500, 1000 and 2500 households are assumed for different lateral feeders. Normally, repair time for a typical feeder failure lasts one to several hours. It is found in the previous studies that V2H and V2G are able to pick up most of the load during the outage period of such extent.

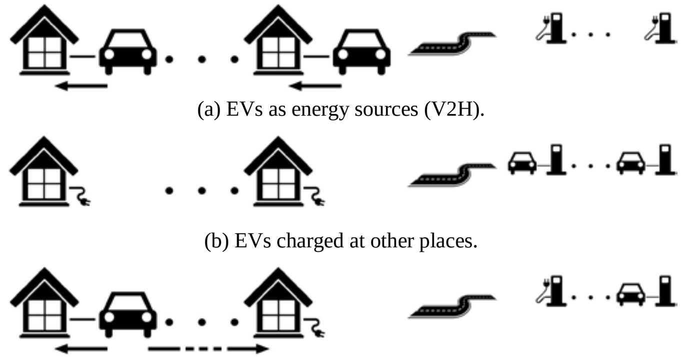
In the aftermath of extreme events, however, the restoration may extend to days or even weeks [18]. For such prolonged outage period without local power generation, the amount of energy EVs or a stationary storage system can contribute with limited energy stored is a mere drop in the bucket. In these situations, the mobility of EVs comes into use.

This paper proposes an EV-based emergency power supply strategy for isolated system. The strategy makes use of EVs as mobile energy storage systems. By regularly driving to unaffected areas and replenishing batteries with secured energy sources, EVs can "transport" electricity to the islanded system. This strategy remains effective regardless of the duration of the outage period. The notion of the proposed strategy is detailed in Section II, where an optimization problem is formulized aiming at minimizing total loss of load. Both scenarios of V2H and V2G are considered as well as non-self-driving and self-driving EVs. Given the extent of the problem, the optimization problem is solved using genetic algorithm (GA). A numerical study is carried out and various scenarios are investigated in Section III. Section IV concludes the paper.

II. Problem Formulation

A. *EV-based Emergency Power Supply Strategy*

The ideas of the proposed strategy are illustrated in Fig. 1. When an outage takes place and the affected system is isolated, EVs turn into emergency generators. With V2H, each household is backed up by its EV (Fig. 1(a)). EVs can run errands to other places where functioning power supplies exist to get charged (Fig. 1(b)) and return to power the house again (Fig. 1(a)). Further improvement in system adequacy can be gained via V2G, which allows energy to flow back to the system and be shared between households, i.e., Fig. 1(c). Moreover, autonomous driving technology is able to entitle flexible charging errands since vehicles' trip schedules no longer bond to human activities. In this paper, it is assumed that in the isolated system each household possesses an EV, which is able to execute the emergency strategy during outages.



(a) EVs as energy sources (V2H).

(b) EVs charged at other places.

(c) EVs as energy sources (V2G).

Fig. 1. Illustration of EV-based emergency power supply strategy.

B. *Objectives*

The adequacy of a typical distribution system can be evaluated through several indices [6]. One of the major consideration is energy not supplied (ENS) [6], [10]. It is defined as the summation of loss of load over the study period. The less the ENS the higher the adequacy. In this paper, the goal of EV-based power supply strategy is to minimize ENS during the outage period. The objective for V2H is given by

$$\textit{Minimize:}\quad \sum_{j\in S_{\mathrm{H}}}\sum_{i=1}^{N_{\mathrm{EV}}}\left(P_{\mathrm{H},ij}-P_{\mathrm{EV},ij}\right)\Delta t \tag{1}$$

where S_{H} is a set indicating the time periods during which EVs are connected to the house, as given in (5); and positive values of $P_{\mathrm{EV},ij}$ denote discharging while negative indicates charging. When only V2H is allowed, every household in the system is isolated from others. Thus, power output of EV i is capped by consumption level of household i, i.e.,

$$P_{\mathrm{H},ij}\geq P_{\mathrm{EV},ij}\quad \text{for}\quad j\in S_{\mathrm{H}}. \tag{2}$$

With V2H only, the situation is literally "every household for itself". In contrast, with V2G the output of EVs can be shared among households; the power/energy surplus of one household can be used to cover shortage of another. The objectives for V2G is given by

$$\textit{Minimize:}\quad \sum_{j\in S_{\mathrm{H}}}\left(\sum_{i=1}^{N_{\mathrm{EV}}}P_{\mathrm{H},ij}-\sum_{i=1}^{N_{\mathrm{EV}}}P_{\mathrm{EV},ij}\right)\Delta t \tag{3}$$

where,

$$\sum_{i=1}^{N_{\mathrm{EV}}}P_{\mathrm{H},ij}-\sum_{i=1}^{N_{\mathrm{EV}}}P_{\mathrm{EV},ij}\geq 0\quad \text{for}\quad j\in S_{\mathrm{H}}. \tag{4}$$

C. *The Optimization Problem*

As an EV traverses back and forth to deliver power, schedule of its activities determines how much energy can be used to power the house, i.e. the second term in objective functions (1) and (3). Given the power consumption level of household (the first term in (1) and (3)), the objective is directly affected by the schedule of EV's activities.

The islanded period can be broken down into cycles consisting of four events. In each cycle, the EV is either (1) home-connected, (2) on the way to the charging station, (3) plugged in, or (4) on the way back to be home-connected again. Fig. 2 illustrates an EV's activities and their timing, along with power and SOC curves. As shown in Fig. 2, the EV's available energy rises and falls within the cycle as it charges or discharges over the course of the four events, which are segmented by $t_{\mathrm{I},ik}$, $t_{\mathrm{II},ik}$, $t_{\mathrm{III},ik}$, and $t_{\mathrm{IV},ik}$, where k is the number of the errands. The kth errand takes place between $t_{\mathrm{I},ik}$ and $t_{\mathrm{IV},ik}$.

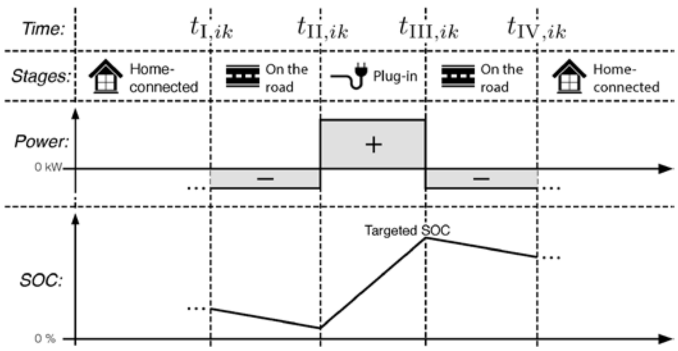


Fig. 2. Timeline of the kth errand of EV i and its conceptual power and SOC curves.

Provided EVs are the only energy sources in the system, ENS during the outage period depends on how much energy EVs can actually deliver. Given the system and EV fleet, each EV can be assumed to take fixed routes back and forth, and the time and energy spent on the way remain the same throughout the whole period. As a result, $t_{\mathrm{II},ik}$ and $t_{\mathrm{IV},ik}$ are known once $t_{\mathrm{I},ik}$ and $t_{\mathrm{III},ik}$ are known, respectively.

The decision variables in this problem are the time when EVs start the trips, $t_{\mathrm{I},ik}$, and the time when EVs stop charging and head back, $t_{\mathrm{III},ik}$. EV i cannot be in service when it is not at home. The general idea is to schedule daily errands during off-peak periods; however, coordination between each charge-discharge cycle must be considered. For instance, EV i is home-connected after it last returned ($t_{\mathrm{IV},i(k-1)}$) and before it takes a new trip ($t_{\mathrm{I},ik}$), so $t_{\mathrm{I},ik}$ should not be too close to $t_{\mathrm{IV},i(k-1)}$, otherwise it could increase the loss of load due to the short home-stay period. On the other hand, the period between $t_{\mathrm{II},ik}$ and $t_{\mathrm{III},ik}$ determines the amount of energy EV i receives. Ideally, the more energy the EVs receive, the less the loss of load can be. However, charging takes time. Longer charging time also means less time EVs serve the houses; this is especially true when only V2H is enabled.

D. Constraints

S_{H} can be defined as

$$S_{\mathrm{H}} = [1, t_{\mathrm{I},i1}) \cup \cdots \cup [t_{\mathrm{IV},i(k-1)}, t_{\mathrm{I},ik}) \cup \cdots \cup [t_{\mathrm{IV},i(\mathrm{K}-1)}, t_{\mathrm{I},i\mathrm{K}}) \cup [t_{\mathrm{IV},i\mathrm{K}}, N_{\mathrm{D}} \cdot res], \quad 2 \le k \le \mathrm{K} \tag{5}$$

where K denotes the last errand, and res is the temporal resolution, i.e., the number of intervals per day. So $N_{\mathrm{D}} \cdot res$ is the end of the outage period with 1 being the beginning.

The four events must be in sequence:

$$t_{\mathrm{I},ik} < t_{\mathrm{II},ik} < t_{\mathrm{III},ik} < t_{\mathrm{IV},ik}. \tag{6}$$

Across cycles, home arrival should precede the following departure:

$$t_{\mathrm{IV},i(k-1)} < t_{\mathrm{I},ik}, \quad k \ge 2 \tag{7}$$

Provided with the mileage between the two places and an average speed, $t_{\mathrm{II},ik}$ and $t_{\mathrm{IV},ik}$ can be calculated from $t_{\mathrm{I},ik}$ and $t_{\mathrm{III},ik}$, respectively:

$$\begin{cases} t_{\mathrm{II},ik} = t_{\mathrm{I},ik} + \frac{M_i}{v_{\mathrm{avg}} \cdot \Delta t} \\ t_{\mathrm{IV},ik} = t_{\mathrm{III},ik} + \frac{M_i}{v_{\mathrm{avg}} \cdot \Delta t}. \end{cases} \tag{8}$$

Available energy of EV i at each time step can be obtained using the recurrent relationship:

$$e_{\mathrm{EV},i(j+1)} = \begin{cases} e_{\mathrm{EV},ij} - \eta \cdot P_{\mathrm{EV},ij} \cdot \Delta t & \text{for charging} \\ e_{\mathrm{EV},ij} - P_{\mathrm{EV},ij} \cdot \Delta t / \eta & \text{for discharging.} \end{cases} \tag{9}$$

where efficiency η is also considered. Note that positive values of $P_{\mathrm{EV},ij}$ denote discharging while negative indicates charging, thus the minus signs in (9).

The upper and lower limits of available energy are given by

$$0 \le e_{\mathrm{EV},ij} \le e_{\mathrm{F},i}. \tag{10}$$

In addition,

$$e_{\mathrm{EV},ij} \ge M_i \cdot R_{\mathrm{avg}} \quad \text{for } j = t_{\mathrm{I},ik} \text{ and } t_{\mathrm{III},ik} \tag{11}$$

is used to guarantee EVs do not run out of electricity midway, where $M_i \cdot R_{\mathrm{avg}}$ is the amount of energy EV i requires to make a complete trip. Available energy should not be lower than that at the onset of each trip.

The charging/discharging power is capped by the power level of the charging outlets:

$$0 \le |P_{\mathrm{EV},ij}| \le P_{\mathrm{O},ij}. \tag{12}$$

E. Non-Self-Driving EVs

Normally, EV users (i.e., house owners in this case) are not able to be on call 24 h a day. A time window may be specified, within which the user is able to do the daily errands. The number of trips per day is also limited, as per

$$[t_{\mathrm{I},ik}, t_{\mathrm{IV},ik}] \subseteq [\underline{t_{\mathrm{I},i}}, \overline{t_{\mathrm{IV},i}}] \subset [(n_{\mathrm{D}} - 1) \cdot res + 1, n_{\mathrm{D}} \cdot res] \tag{13}$$

where $\underline{t_{\mathrm{I},i}}$ to $\overline{t_{\mathrm{IV},i}}$ is the time window and $[(n_{\mathrm{D}} - 1) \cdot res + 1, n_{\mathrm{D}} \cdot res]$ is the time period of the n_{D}th day following the outage. It is assumed in this paper that the trip number for non-self-driving EVs is limited to one per day. Consequently, the number of errands k is equal to the day count n_{D}, (14).

$$k = n_{\mathrm{D}}. \tag{14}$$

F. Self-Driving EVs

In the case of EVs equipped with self-driving technology, on the contrary, both constraints (13) and (14) can be relaxed. With the vehicle unoccupied, daily trips no longer bond to human activities and multiple errands can be done per day.

(15) and (16) are used to replace (13) and (14), respectively:

$$[t_{\mathrm{I},ik_1}, t_{\mathrm{IV},ik_2}] \subseteq [(n_{\mathrm{D}} - 1) \cdot res + 1, n_{\mathrm{D}} \cdot res] \tag{15}$$

where k_1 and k_2 are the indices of the first and the last errands taken in day n_{D}. Time window $\left[\underline{t_{\mathrm{I},i}}, \overline{t_{\mathrm{IV},i}}\right]$ in (13) is no longer required.

As mentioned above, EVs with self-driving capability are able to do more than one errand each day. The daily errand number can be represented by

$$\frac{k_2}{n_{\mathrm{D}}} = k_2 - k_1 + 1 \geq 1. \qquad (16)$$

When $k_1 = k_2$, the daily errand number is one and (16) is equivalent to (14).

To sum up, with non-self-driving EVs, number of errands is limited to 1 per day and time window $\left[\underline{t_{\mathrm{I},i}}, \overline{t_{\mathrm{IV},i}}\right]$ is applied. Self-driving EVs are able to take multiple daily errands without the time window.

G. *Solution*

From Section II-C, it can be found that some of the constraints are variables themselves, such as time constraints cross errand cycles (5)–(7). The other challenge is the number of variables. An isolated system may contain hundreds of EVs. There are two variables ($t_{\mathrm{I},ik}$ and $t_{\mathrm{III},ik}$, Section II-B) for each errand cycle per EVs. This number increases as number of errands increases. A genetic algorithm toolbox [19] is employed to solve this scheduling problem in a Matlab environment. Solving the problem yields an optimized schedule for charging errands. While the objectives directly give the value of ENS, other reliability indices [6] can be evaluated once the schedule is obtained. Scenarios are designed in order to give an insight into the effectiveness of utilizing different car types and numbers of errands.

III. Numerical Study

A system containing 500 households is considered. Optimization and evaluation is per-minute based. Each household owns an EV. The system is assumed to remain isolated for 5 days. Daily load profiles for the households are randomly chosen from the dataset given in [20]. The load demand adds up to 64.78 MWh (i.e. system ENS) and there are 7200 minutes in 5 days. The peak load of each house during that period varies between 1.56 and 10.67 kW.

The charging station is 20 miles away. Given an average speed of 40 mph, it takes 30 minutes to travel between the two places. The energy consumption rate is 0.25 kWh/mile. The energy capacity of each EV is 25 kWh. Their available energy at the beginning of the outage is sampled in a range from 10 to 25 kWh, following a uniform distribution. Power for both charging and V2H/V2G is capped at 5 kW ($P_{0,ij}$). Non-self-driving cars are not allowed to run the errands before 7:00 AM or after 6:00 PM each day.

A. *V2H with Non-Self-Driving EVs*

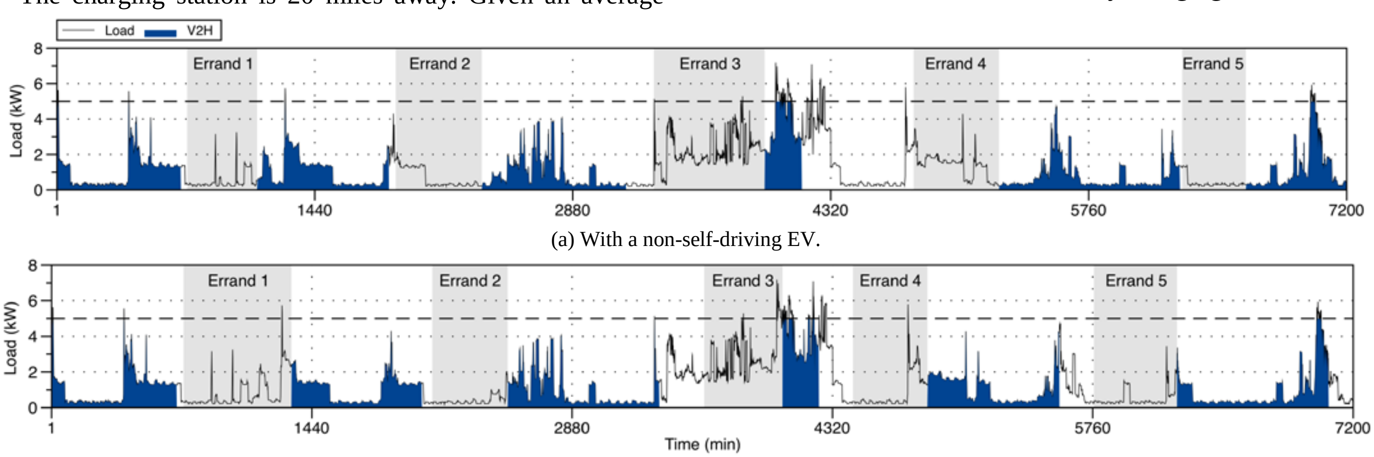
For V2H with non-self-driving EVs, where the objective is (1), the time windows for the daily activity of the EVs (13) are applied, and the number of charging errands is limited to one per day (14). With the emergency strategy applied, ENS of the isolated system is reduced to 31.49 MWh and system average interruption duration index (SAIDI) is shortened to 3207 min per house. Both energy-oriented (ENS) and customer-oriented (SAIDI) indices for distribution system reliability [6] show that, with V2H, the EV fleet is able to pick up more than half of the load demand. Table II in Section III-D summarizes the results.

The V2H coverage of a single EV during the outage period is detailed in Fig. 3(a). The dashed line represents the upper limit for charging/discharging power ($P_{0,ij}$), which is set to be 5 kW. Load supplied is in dark blue. Otherwise, the load is either curtailed or totally interrupted. The daily charging errands are confined to within the defined time window: 7:00 AM–6:00 PM. In most cases, the EV ceases powering the house some time before it goes on a subsequent charging errand. On average, the EV offers 13.63 kWh for V2H following a charging errand. Considering the full capacity is 25 kWh, and 10 kWh of which is reserved for the trips back and forth (0.25 kWh/mile × 20 miles = 5 kWh for each trip), the EV uses up almost all the SOC it can get with the given number of errands.

B. *V2H with Self-Driving EVs*

When EVs are considered self-driving capable, constraints (15) and (16) are used to replace (13) and (14). To facilitate comparison with non-self-driving EVs, the daily charging errand is set to once every day, i.e., $k_1 = k_2 = n_{\mathrm{D}}$ in (15) and (16). The V2H coverage for the same customer is given in Fig. 3(b). The system ENS is 30.39 MWh and SAIDI is 3088 min.

Without the time window, the daily charging activities can



(a) With a non-self-driving EV.

(b) With a self-driving EV.

Fig. 3. Load of a typical household supplied through V2H during the outage period.

be scheduled freely. However, the subsequent reliability improvement is limited. ENS and SAIDI only see a reduction of 1.10 MWh and 119 minutes, respectively. In retrospect, the reason is obvious; as mentioned in the previous subsection, the EVs already contribute almost all of the energy available despite the confined charging activities and there is little room for further V2H coverage. This is also reflected in Fig. 3(a) and (b): the EV always ceases discharging and remains idle for a while before taking the next trip.

This observation leads to the speculation that more charging errands could help supply more load. It is because the other advantage of self-driving cars is that they are able to take any number of errands without human's intervention.

C. V2H with Self-driving EVs and Multiple Errands Daily

Increasing the number of errands to two per day results in the arrangement of V2H and charging errands for the same customer illustrated in Fig. 4(a). Compared to Fig. 3, the EV tends to have shorter charging periods with frequent errands. The duration during which the EV remains idle with its battery drained (neither discharging nor on the road) is also shortened. In Fig. 3, the idle periods totaled 864 and 724 minutes for non-self-driving and self-driving EVs, respectively. In Fig. 4(a), the idle period add up to 32 minutes only. The EV is also able to supply more load. With two errands per day, ENS of the household is reduced to 41.20 kWh from 62.28 kWh for self-driving EVs.

Table I gives a comparison of system adequacy against varying numbers of daily charging errands. The system ENS reaches the lowest value (21.71 MWh) when the daily errand number is set to two. As shown in the figure, increasing the number further does not interpret into improvement in system adequacy. More errands could mean longer charging periods and thus more energy stored into the EVs. On the other hand, it could also mean less time spent on powering the house. Too many daily trips actually negate the benefit of extra energy gained from additional charging periods.

From the perspective of interruption time, however, it is interesting to find that SAIDI is the lowest when EVs run one errand per day instead of two. To understand this phenomenon requires investigation of details at the individual level. As exemplified in Fig. 4(a), daily errands are generally scheduled during off-peak periods. By doing so, periods with higher demand can be covered. However, due to the charging/discharging limits, a single EV is not able to fully support the household once the consumption level exceeds 5 kW. In such instances, some of the load has to be curtailed. These occasions with partially curtailed load are considered as interruptions. As a result, when the daily errand number increases from one to two, the interruption duration is extended slightly although ENS shrinks significantly (Table I).

TABLE I
SYSTEM ADEQUACY VERSUS NUMBER OF ERRANDS PER DAY (V2H)

No. of errands	1	2	3	4	5
ENS (MWh)	30.39	21.71	27.17	34.68	43.47
SAIDI (min per customer)	3088	3275	4066	4787	5415

D. V2G Performance

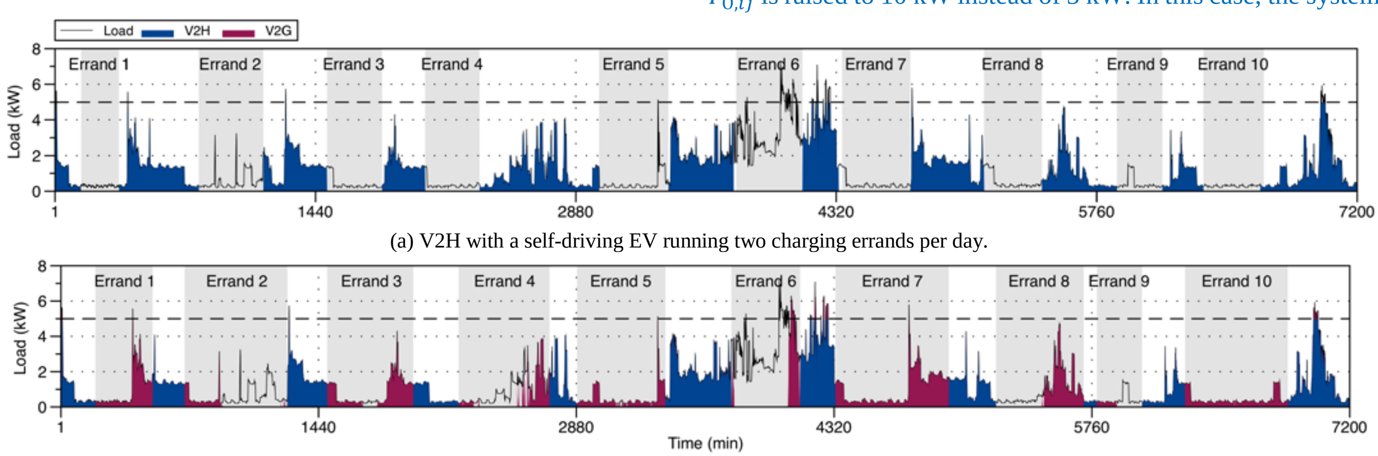
The most significant adequacy improvement comes when V2G is applied with self-driving EVs. During the period when an EV is taking the trip, the house can be powered by EVs from other households, as long as excess energy and power capacity are available. The schedule for charging errands is optimized with objective (3) and the system adequacy is re-evaluated. Fig. 4(b) shows the power supply on an individual level, where the load covered by V2G is in dark red. System reliability indices are summarized in Table II.

TABLE II
EVALUATION RESULTS FOR V2H AND V2G SCENARIOS

	V2H, Non-self-driving	V2H, Self-driving (2 errands/day)	V2G, Self-driving (2 errands/day)
ENS (MWh)	31.49	21.71	8.89
% of total demand	48.61%	33.51%	13.72%
SAIDI (min per customer)	3207	3275	1340
% of total duration	44.54%	45.49%	18.61%

Further implementation of V2G significantly reduces load interruption. With two errands per day, the ENS reaches its lowest value and accounts for 13.72% of total demand and SAIDI is 18.61% of the total outage duration.

A significant result can be obtained when the power limit $P_{0,ij}$ is raised to 10 kW instead of 5 kW. In this case, the system



(a) V2H with a self-driving EV running two charging errands per day.

(b) V2H + V2G with a self-driving EV running two charging errands per day.

Fig. 4. Load of a typical household supplied through V2H and V2G during the outage period.

ENS is reduced to 0 MWh. This means that V2G with self-driving EVs is able of fully restoring the islanded system.

IV. Conclusion

This paper proposes an EV-based emergency power supply strategy for isolated power systems. Despite the long outage duration, sustainable energy provision is possible with EVs regularly running charging errands. The balance between time spent on running the errands and the energy delivered must be achieved in order to maximize system adequacy.

The numerical results shows that EVs are already able to pick up more than half of the load with V2H alone. Self-driving EVs provides the flexibility in scheduling charging errands, which further brings adequacy amelioration. The most significant observation from the case study is that the proposed pure EV-based strategy is capable of fully restoring the islanded system when V2G and self-driving EVs are implemented.

Moving forward, one direction for future research is taking into account unpredictability such as uncertainties in household load demand, size of available EV fleets, and EV charging/discharging behavior [17]. The additional consideration may call for advanced algorithms other than GA proposed in this paper. In that case, convergence performance is also of importance in order to achieve quick yet reliable solutions. Some relevant studies can be found in [11]–[14].

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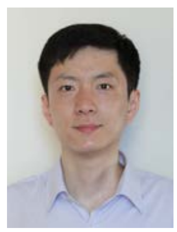

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