

Article

Improving the Power Outage Resilience of Buildings with Solar PV through the Use of Battery Systems and EV Energy Storage

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Abstract: Buildings with solar photovoltaic (PV) generation and a stationary battery energy storage system (BESS) may self-sustain uninterrupted full-level electricity supply during power outages. The duration of off-grid operation is dependent on the time of the power fault and the capabilities of the home energy management system (HEMS). In this paper, building resilience is quantified by analyzing the self-sustainment duration for all possible power outages throughout an entire year. An evaluation method is proposed and exercised on a reference house in California Climate Zone 9 for which the detailed electricity usage is simulated using the EnergyPlus software. The influence of factors such as energy use behavioral patterns, energy storage capacity from the BESS, and an electric vehicle (EV) battery on the building resilience is evaluated. Varying combinations of energy storage and controllable loads are studied for optimally improved resilience based on user preferences. It is shown that for the target home and region with a solar PV system of 7.2kW, a BESS with a capacity of 11kWh, and an EV with a battery of 80kWh permanently connected to the home, off-grid self-sustained full operation is guaranteed for at least 72 hours.

Keywords: Distributed Energy Resource (DER), Solar PV System, Battery Energy Storage System (BESS), Vehicle-to-Home (V2H), Electric Vehicle (EV), Resilience, Home Energy Management (HEM), Power Outage, Blackout

1. Introduction

In the rapidly evolving electric power system, wherein new renewable and distributed energy resources are being connected and fossil fuel based generators are being retired at a growing rate, it is increasingly more important to ensure a continued and reliable supply of electricity. For example, approximately 8,000 MW may need to be imported to avoid blackouts in California by filling in gaps caused by renewable energy generation variability and increased power demand. Another major threat to energy supply reliability are large natural disasters, such as, in recent years, wide-spread wild fires [1]. In 2020, there were more than 8 thousand fires in California alone resulting in almost 1.5 million burnt out acres and significant power system damage [2]. In a winter storm in 2021, approximately 2 million homes suffered power outages in Texas which substantially increased electricity demand due to record-breaking low temperatures [3]. Worse still, about 34,000 MW of renewable wind generation capability within Texas was lost during this storm as freezing temperatures forced power plants offline in quick succession [4]. It is very important to ensure power system reliability through whatever means possible under such conditions to protect residents from environmental health risks.

Residences equipped with rooftop solar photovoltaic (PV) panels and battery energy storage systems (BESS) turn into prosumers with generation capability to supply their own on-site demand [5]. The increasing trend of independent PV producers is representative of the possibility of decentralized

34 power generation and distribution [6]. Solar PV panels can achieve the best performance when its
35 material is suitable for the external condition as measured by matrices including energy payback time
36 (EPBT), energy production factor (EPF) and life cycle conversion efficiency (LCCE) [7]. The thermal
37 and chemical treatment based end-of-life (EOL) method reduces the cost for recycling PV system
38 waste material making PV generation even greener [8]. Solar PV systems may be considered a reliable
39 distributed energy resource (DER) only when it is coordinated with BESS [9]. In-home BESS can
40 store variable renewable generated energy allowing it to be used whenever needed by the user but
41 often have a limited energy capacity due to its hefty initial investment [10]. When advanced thermal
42 management is implemented, BESS can charge and discharge with large power while maintaining
43 operational safety [11].

44 The growing trend of electric vehicles (EV) provides the potential to boost the energy capacity
45 of residential energy storage systems (ESS) [12]. Hence, research towards the development of smart
46 energy management in residential houses using home ESS and EV battery systems is in progress
47 [13,14]. Residences with EV can help to improve the load factor in communities, reducing costs related
48 to the maintenance of transformers, feeders, etc. [15] A previous study using data from the national
49 household travel survey (NHTS) found that most cars commute around 20 miles daily, resulting in
50 90% of SOC remaining on average for EVs when they return home [16].

51 Recent research shows that EV batteries can operate as a voltage source or offline uninterruptible
52 power supply (UPS) for a home in an outage [17,18]. A well managed energy storage system with BESS
53 and EV support could provide good performance during both transient and steady-state operation,
54 considering the voltage waveform and current harmonics distortion [19]. Different operation modes
55 of EV in smart homes have been proposed and explored, and it was shown that depending on the
56 usage preferences of the user, EV batteries can act as a power source to feed residential appliances
57 during a power outage [17]. When energy not supplied (ENS) or system average interruption duration
58 index (SAIDI) is taken into consideration, the participation of a EV connected to the home improved
59 resilience the most [20].

60 The vehicle-to-home (V2H) capability of EV realizes the outage management and cost reduction
61 for a smart home [21,22]. EV systems can potentially adopt the same method introduced in [23]
62 allowing the battery system to switch between input PV energy harvesting mode and output V2H
63 mode for emergency situations. V2H functionality also improves power system resilience factors
64 including load restoration, reactive power supply, and peak reduction, etc. [24–28]. Bidirectional
65 wireless power transfer will further facilitate V2H applications by enabling higher power transfer and
66 easing the barrier to entry for the consumer [29].

67 Depending on the user preferences and applications of the EV, the additional energy storage
68 can expand the residential ESS, but may not be available at the residence when the outage occurs.
69 For example, according to recent reports, the very large 90kWh battery installed on the most recent
70 EV model of the Ford F-150 truck can be controlled to supply up to 10 days of electricity for a
71 connected home [30]. Other factors including user behavior regarding residential load, the capacity
72 of the residential ESS, renewable energy generation, etc., should all be taken into consideration for
73 systematically quantifying building resilience.

74 Research gaps remain as the prediction of building resilience duration should consider different
75 time occurrences for power outages. Residences with solar PV generation would be less dependent on
76 electricity from the grid during the daytime and could self-sustain longer if outages occur at times
77 when electricity usage is low. The building resilience for residences with varying electricity usage, PV
78 generation capability, and BESS capacities need to be analyzed in order to provide a reference for all
79 types of house owners. This paper focuses on minute-based simulations of power flow and energy use
80 with building resilience studied by monitoring the energy balance on the demand and supply sides.
81 The quantification of building residence provides utilities with a basis for better planning of rolling
82 blackouts and power restoration, and guide house owners when sizing their localized residential
83 power system.

Table 1. Main specifications for the electricity usage model of the reference house

Parameters	Value
Conditioned area	223 m ² (2,401 ft ²)
House type	4-bedroom, 3.5-bathroom
Location	Burbank, CA, Zone 9
PV rating/annual generation	7.2kW/11,316kWh
Annual electricity usage w/o EWH	13,628kWh
Annual electricity usage of EWH	4,233kWh
EWH rated electric power	5kW
BESS energy capacity/maximum power	11kWh/5kW
Initial BESS SOC	100%
Minimum BESS SOC	20%
EV battery energy capacity/maximum power	90kWh/10kW
EV battery SOC when EV arrives home	90%
Minimum EV battery SOC	20%

84 The major contributions of the paper include:

- 85 • quantification of building resilience considering all possible power outage occurrence times,
- 86 • analysis of building resilience for different factors including user behavior, the impact of
- 87 renewable energy generation, and the energy capacity of the residential ESS,
- 88 • exploration of the possibility of EV battery incorporation into the residential ESS,
- 89 • evaluation of the impact of EV battery capacity on building resilience.

90 The typical electricity usage for the reference house is calculated and the main parameters of this
 91 model are presented in Section 2. Section 3 focuses on the definition and quantification of the reference
 92 house's building resilience. In Section 4, the impact of the varying home load percentages and the
 93 sizing of the BESS energy capacity on building resilience is studied. The possibility of incorporating
 94 the EV battery into the residential ESS is explored in Sections 5. Finally, Sections 6 and 7 provide
 95 concluding remarks and a summary of this study's results.

96 2. Energy Model for the Reference House

97 The main parameters for the reference house considered in the study are summarized in Table
 98 1. The use of batteries for power flow and energy studies are based on results from the EnergyPlus
 99 software and the INSPIRE+D co-simulation framework [31]. The framework realizes the dynamic
 100 communication between the power system simulator and the building model, based on a prototype
 101 EnergyPlus model released originally by the Pacific Northwest National Laboratory (PNNL) [32]. The
 102 weather data for the studied Burbank area in California Climate Zone 9 was publicly available on the
 103 EnergyPlus website as a typical meteorological year (TMY) [33]. The outputs of the EnergyPlus model
 104 include energy usage and generation with a 5-minute resolution and detailed usage for appliances
 105 including HVAC, water heater, etc.

106 In the schematic representation and graphs from Fig. 1, the dark blue area in the middle of the
 107 annual electricity usage graph corresponds to power flow from the house to the grid caused by surplus
 108 PV generation. Variations in the blue area was caused by the pool pump, which operates during
 109 9:00–15:00. The yellow strip at around 21:30 stands for evening demand peaks of power flow into the
 110 house.

111 The electric water heater (EWH) was modeled and its typical high and relatively short power
 112 draw corresponds to the red dots in Fig. 1. The electricity usage and power profile of the EWH
 113 are determined by the water draws, quantified according to the California Building Energy Code
 114 Compliance for Residence (CBECC-Res) [34]. The rated electric power of EWH is 5kW, and the
 115 calculated annual electricity usage of the EWH is 4,233kWh.

116 The stationary BESS introduced to the home is a Li-ion battery rated as 11kWh/5kW in the
 117 following studies, and is assumed to have 100% SOC when the power outage occurs. The EV battery

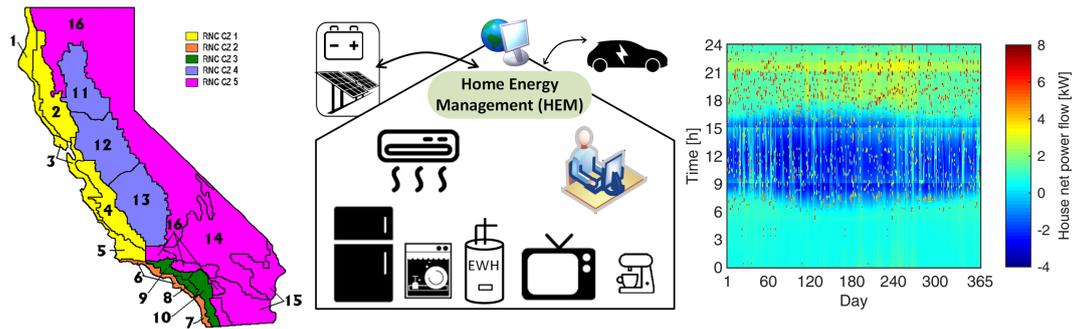


Figure 1. Illustrations for the example reference home: location in California zone climate 9 (left); home energy management, PV, battery, EV, and appliances diagram including major energy users HVAC system and EWH (center); and power flow during a year (right). The negative power flow during daytime is due to surplus solar PV generation. The very high power draw marked with red dots and occurring mostly in the evening and at night is due to the EWH.

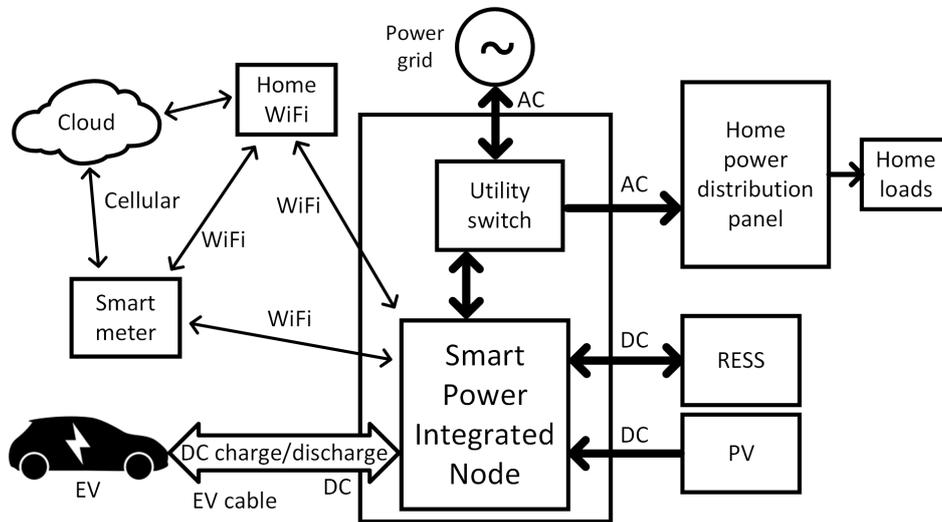


Figure 2. Example of a residential power and energy management system, based on the concept described in a US patent [36]. Such a multifunctional system can ensure V2H operation, providing support during grid power outages and increased resilience.

118 is rated as 90kWh for the reference house. The most recent level 2 charger allows the EV to be
 119 charged/discharged at a maximum power of 10kW with a lower limit of 20% for the EV battery [35].
 120 The EV is scheduled to leave home at 6 am and return at 6 pm every day with an SOC of 90%, given
 121 the fact that most daily driving mileages are less than 20 [16].

122 The example topology published in patent [36] includes inverters for connections to EV and
 123 other components (Fig. 2). Such a multifunctional system can ensure V2H operation, providing
 124 support during grid power outages and increased resilience. Residential power system components
 125 are represented as nodes or individual elements that interact with a central power management
 126 system connected to the cloud for long-distance control and capable of multi-function operation. The
 127 central system includes a smart power integrated connected to power grid, BESS, PV cell and EV.
 128 Communication can be realized via Ethernet, WiFi, cellular connection, or any available communication
 129 protocol. The smart power integrated node (SPIN) provides DC charge and discharge capability to EV
 130 via an EV cable in this embodiment. The SPIN may incorporate functionalities such as service setup,
 131 display & control, and is capable of receiving transit information from remote server or user interfaces.
 132 The operating procedure defined by the user is employed by its many DC/DC, DC/AC switching
 133 components.

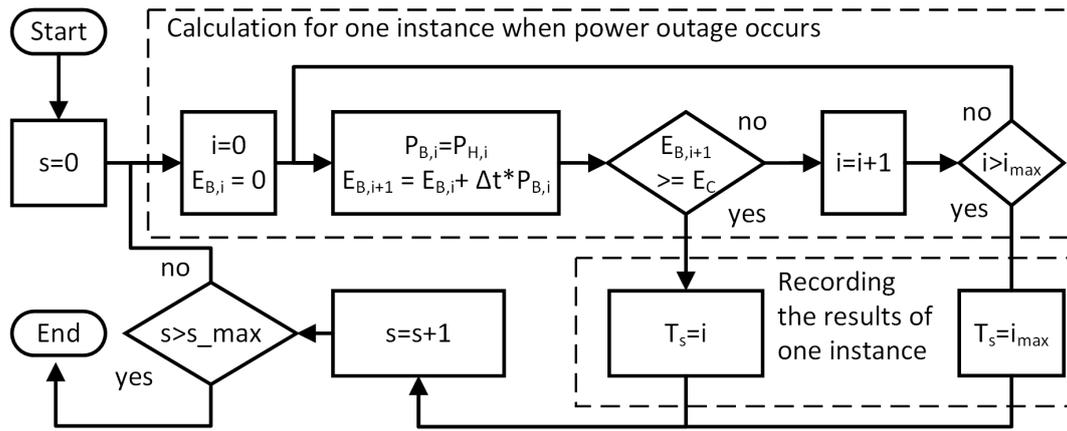


Figure 3. Systematic procedure for the evaluation of building resilience. Simulation is performed for each time step, corresponding to instances for which power outage occurs. The self-sustainment duration is calculated for each instance.

134 3. Method for Calculating the Self-sustainment Duration for a Reference House

Power outages or blackouts may occur at any time throughout the entire year, and in such conditions, the house loses electricity supply from the grid. In the following studies, residential loads are supplied by the BESS and PV generation when the blackout occurs, and the resulting performance is analyzed for the following 24 hours. The total electricity provided by the BESS after the power outage occurs is defined as:

$$E_{B,t} = \sum_{i=0}^t P_{B,i} \cdot \Delta t, \quad (1)$$

where i is the simulated time step, with $i = 0$ indicating the time origin when the power outage occurs; and $P_{B,i}$ represents the power of BESS. During a power outage, the BESS supplies the total house demand to provide full building resilience. Therefore,

$$P_{B,i} = P_{H,i}, \quad (2)$$

135 where $P_{H,i}$ is the net power flow of the residence. When $P_{H,i}$ is larger than the maximum power rating
136 of the BESS, the residential load has to be curtailed.

The self-sustainment performance is measured as the duration when the BESS can supply the residential loads. At one instance, e.g., time step s , when the power outage occurs, the BESS was discharged down to the minimum acceptable SOC. The self-sustainment operation duration T_s for this instance is defined as:

$$\exists i = T_s : E_{B,i} \leq E_C \wedge E_{B,i+1} \geq E_C, \quad (3)$$

where E_C , the maximum available energy of the residential ESS:

$$E_C = \eta_B \cdot E_{C,B}, \quad (4)$$

137 where η_B is 80% in the study, as the maximum SOC for BESS is 100% and minimum is 20%; $E_{C,B}$, the
138 rated energy capacity of BESS. When the SOC is 100%, the surplus PV generation is curtailed. After
139 calculating the following 24 hours for step s , the same procedure is applied to step $s + 1$, and up to the
140 last time step s_{max} . Every time step has its own corresponding self-sustainment operation duration T_s .
141 The procedure for calculating the self-sustainment operation duration is illustrated in Fig. 3.

The constraints are the maximum BESS power:

$$|P_{B,i}| \leq P_{max}. \quad (5)$$

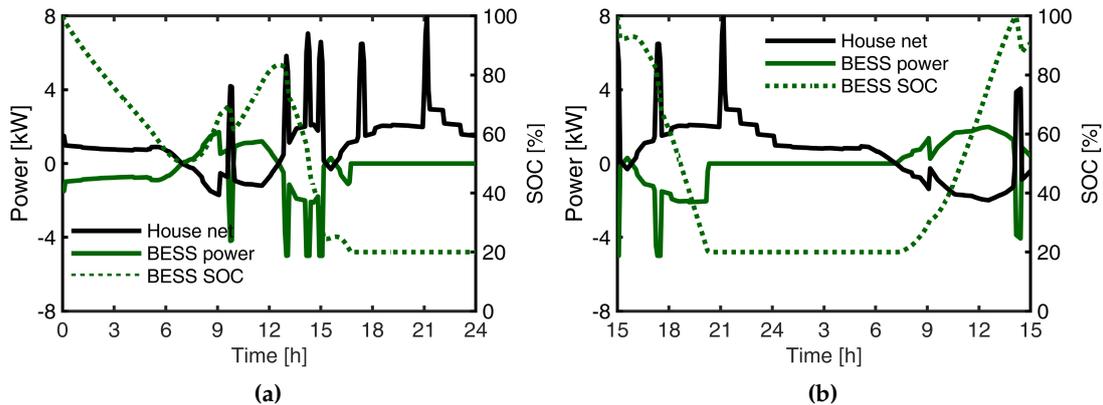


Figure 4. An example of the daily self-sustain case for the reference house when the power outage occurs at (a) midnight and (b) 3 pm. The BESS covers the residential load in the morning and was charged by surplus solar PV generation throughout the day. As PV power rapidly declined and no longer met the residential load, the BESS discharged until falling to the minimum SOC of 20%. The reference house tends to self-sustain longer when the power outage occurs in the early morning because the BESS could be charged by PV generation during the daytime hours.

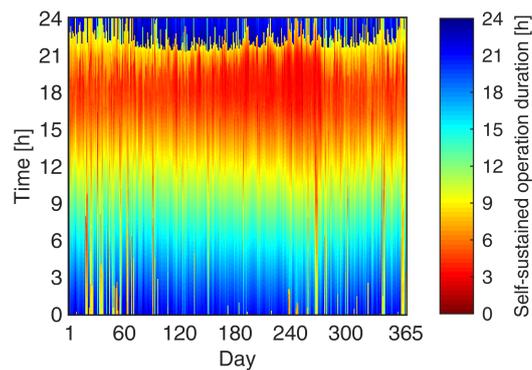


Figure 5. Self-sustained operation duration of the reference house for power outages occurring at different times. All 105,120 instances of varying days and times for power outages were calculated throughout the year. The self-sustained operation duration is longer if the power outage occurs in the morning because the BESS could be charged during the day with surplus solar PV generation.

142 Residential power must be curtailed if it is too high during a outage. On the other hand, the PV
 143 generation input needs to be curtailed if the negative net power flow is too high.

144 Simulation results in Fig. 4 show that the time of the power outage has a great impact on the
 145 self-sustainment duration from the reference house. When the power outage occurred at the midnight
 146 as shown on the left, the reference house self-sustained approximately 17 hours (Fig. 4 (a)). The BESS
 147 SOC in this case dropped in the early morning, increased in the midday, and decreased in the evening
 148 until it was 20%. This happened because the BESS was charged by the surplus PV generation in the
 149 midday and discharged to power the loads for the rest of the time. On the same example day, however,
 150 when the power outage occurred at 3 pm, the house self-sustained for approximately 5 hours, as
 151 shown in Fig. 4 (b). The house self-sustained a significantly shorter amount of time because the BESS
 152 was not charged for that day when PV generation faded away in the evening.

153 With the simulation time step of 5-minutes, there are $12 \times 24 \times 365 = 105,120$ instances throughout
 154 the entire year when the power outage could occur. Correspondingly, there are 105,120 calculated
 155 self-sustained operation durations which are represented as different colors in Fig. 5, with each cell
 156 indicating a 5-minute increment. The two instances in Fig. 4 result in the colors for the 17 and 5

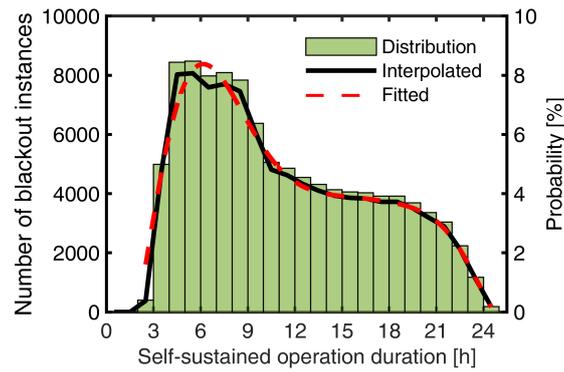


Figure 6. The distribution of residence self-sustained operation duration for all 105,120 instances. All instances were binned into duration categories with a time interval of 1-hour.

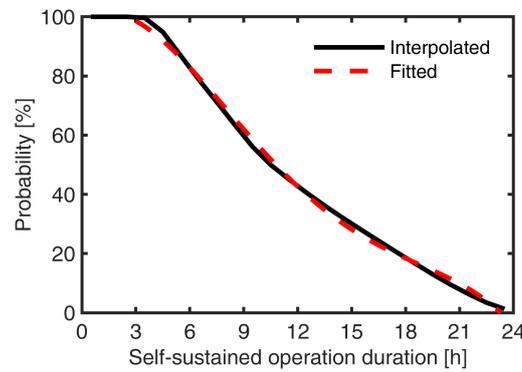


Figure 7. The cumulative probability curve for self-sustained operation duration of the reference house. Regardless of when a power outage occurs, the reference house is highly likely to completely self-sustain at 100% load for up to 3 hours. If the power outage occurs at any point in time there is a 50% likelihood the residence will self-sustain for up to 10 hours.

157 hours for their two cells. Self-sustained operation duration trended towards being longer if the power
 158 outage occurred in the early morning because the BESS was charged in the midday by surplus solar PV
 159 generation. The self-sustained operation duration around 6 pm was short because of both the evening
 160 residential load peak and lower solar PV generation.

The simulation results of self-sustained operation duration for the entire year were summarized with an interval of 1-hour in Fig. 6. If the self-sustained operation duration of the house falls into the interval of $(t_1, t_1 + 1]$, it can self-sustain any hours within $[0, t_1]$. The cumulative probability curve presented in Fig. 7 indicates that after a power outage occurrence, the reference house is almost 100% likely to self-sustain for up to 3 hours, and 50% likely to self-sustain up to approximately 10 hours. The cumulative curve, which stands for the building resilience, was fitted and represented explicitly with a 4th order polynomial equation, as follows:

$$f(t) = \begin{cases} 100, & t \in [0, 3) \\ p_1 t^4 + p_2 t^3 + p_3 t^2 + p_4 t + p_5, & t \in [3, 24] \end{cases} \quad (6)$$

161 where the coefficients for the reference example are $p=[-0.0017, 0.0934, -1.5743, 3.7379, 99.1833]$.

162 4. Study for Different Home Load and BESS Energy Capacities

163 Curtailing the load can reduce the electricity usage and prolong the self-sustained operation in a
 164 power outage. The load in Fig. 8 was reduced to 50% after the power outage occurred at the midnight.

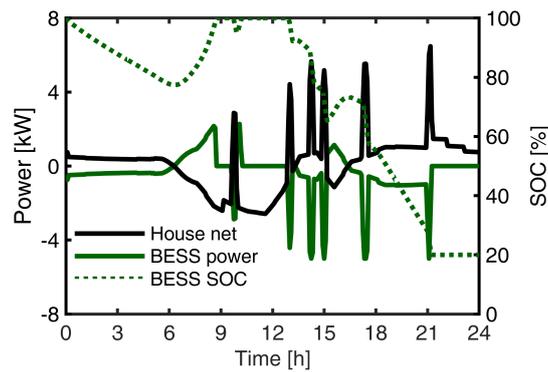


Figure 8. An example of a self-sustained case with residential load, except for the electric water heater, curtailed to 50% of the reference value. The self-sustainment duration was 21 hours, 4 hours longer than the reference house because of the lower electricity usage.

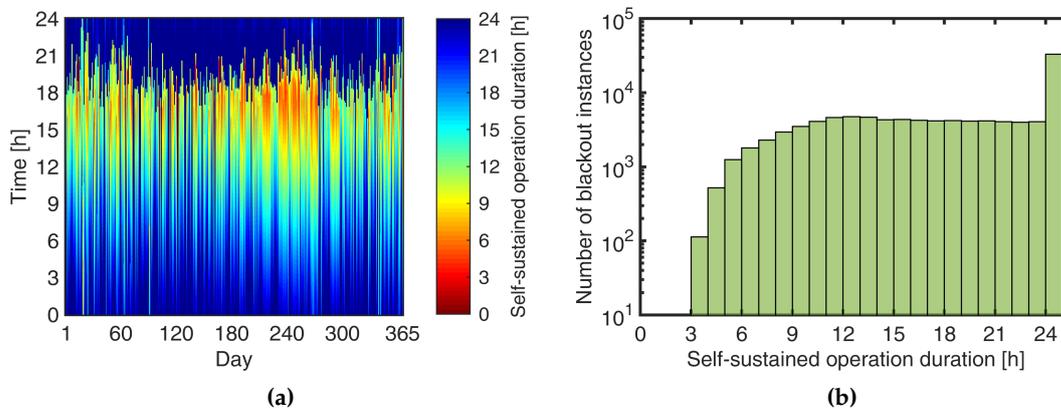


Figure 9. Self-sustained operation duration of the house with 50% of the reference residential load presented as a (a) heat map and (b) distribution. The likelihood of the house self-sustaining for more than 24 hours is approximately 31%.

165 Reducing the load in this scenario enabled the house to self-sustain for approximately 21 hours, 4
 166 hours more than the reference house at the same instance, as shown in Fig. 4 (a).

167 Curtailing the residential load increased the self-sustained hours for all 105,120 instances
 168 throughout the entire year (Fig. 9 (a)). The house load, except for EWH power, was curtailed to
 169 50% while other parameters had the same values from Table 1. The distribution with 1-hour interval
 170 bins in Fig. 9 (b) shows that the probability to self-sustain more than 24 hours was increased to
 171 approximately 31% when the residential load was curtailed to 50%. Meanwhile, the reference house
 172 without load curtailment has a near 0% chance to self-sustain for more than 24 hours (Fig. 7).

173 A BESS with larger capacity could store more surplus energy from solar PV generation and sustain
 174 the house for a longer time when a power outage occurs. When the house was connected to a BESS
 175 with a capacity of 27kWh, the self-sustained operation duration was prolonged to 22 hours, as shown
 176 in Fig. 10, 5 hours more than the reference house case in Fig. 4 (a).

177 Larger BESS capacity increased the self-sustained operation duration for all 105,120 instances
 178 throughout the entire year (Fig. 11 (a)). When the reference house was equipped with a BESS rated at
 179 27kWh, it could self-sustain at least 24 hours for approximately 72% of all instances (Fig. 11 (b)). The
 180 self-sustained operation duration was extended in general with larger BESS capacity, as cases with
 181 longer time intervals increased compared to the reference house case shown in Fig. 6.

182 The effect of combining partial load and BESS capacity modifications on self-sustained operation
 183 duration were studied and for each combination, only the probability of self-sustaining for at least 24

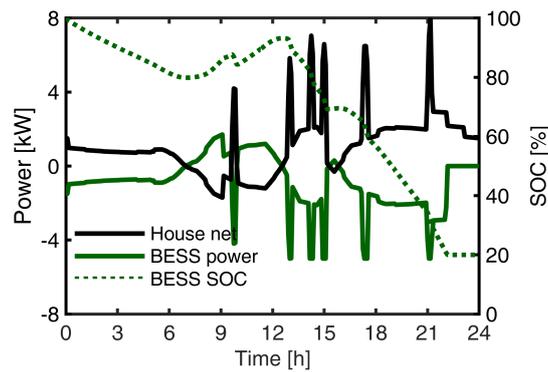


Figure 10. An example of self-sustained operation for a house with an increased BESS rating of 27kWh. In this case, the self-sustained operation of approximately 22 hours was 5 hours longer than the reference case.

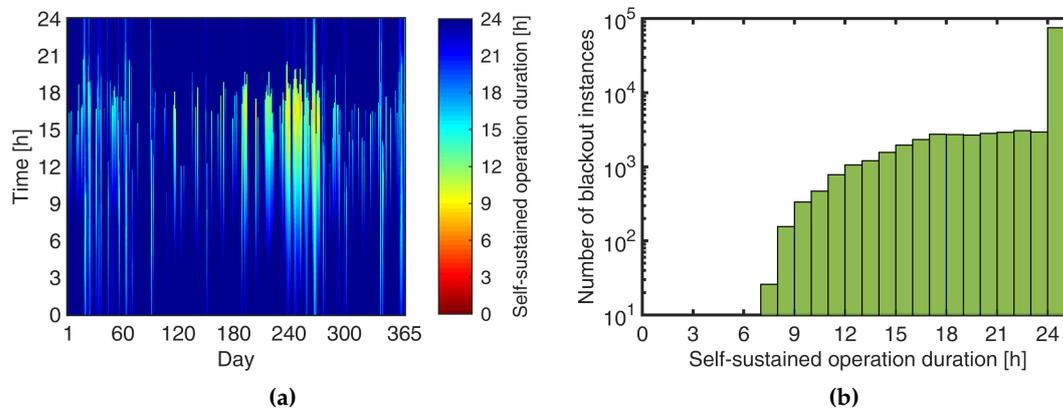


Figure 11. Self-sustained operation duration of the house with a BESS rating of 27kWh is presented as a (a) heatmap, and (b) distribution. The probability that the house can self-sustain for more than 24 hours is approximately 72%.

184 hours was recorded. For example, the combination of 50% load percentage and 11kWh BESS resulted
 185 in a 31% likelihood of self-sustaining for at least 24 hours, as shown in Fig. 9. The simulation results
 186 for other combinations were summarized in Fig. 12. The load percentages from 50% to 300% covered
 187 are representative of the power profiles of residences with different user behaviors and house types.
 188 BESS capacities studied were between the range of 10 to 60kWh. The colors represent the probabilities
 189 for residences with combinations of different load percentages and BESS capacities to self-sustain for
 190 more than 24 hours.

191 In Fig. 12, the horizontal trend indicates the case for different residential loads with a fixed BESS.
 192 The case studies for curtailing the reference house from Fig. 9 can be referred as the BESS=11kWh
 193 horizontally. When the residential load of the reference house curtailed from 100% to 50%, the
 194 probability to self-sustain more than 24 hours was increased from virtually 0% to 31%, as shown in Fig.
 195 9. For a BESS capacity larger than 40kWh, the probability for a house with 100% residential load to
 196 self-sustain more than 24 hours is almost 95%. With a larger BESS of 60kWh, the probability for the
 197 house to self-sustain at least 24 hours is more than 90% even when the load is 150%.

198 In Fig. 12, the vertical trend indicates that for a fixed load percentage, the probability of the
 199 residence self-sustaining for more than 24 hours increased, in line with the expectations, as the BESS
 200 capacity increased. The case study for increasing the BESS capacity to 27kWh from Fig. 11 can be
 201 referred to as the Load = 100% case vertically. When the BESS capacity was increased from 11kWh to
 202 27kWh, the probability for the house to self-sustain for more than 24 hours increases from virtually

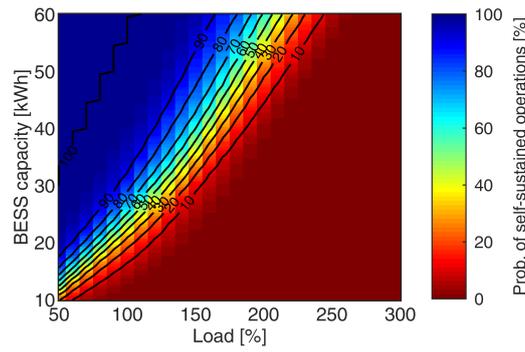


Figure 12. Results of a case study examining varying combinations of BESS capacities and home load percentages in self-sustainment duration of 24 hours or greater.

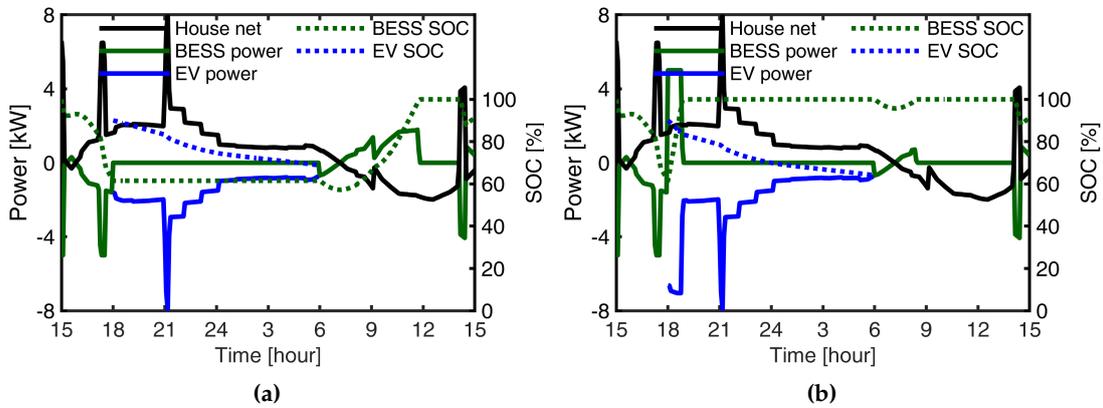


Figure 13. An example of a self-sustained case for the reference house with EV contributing to (a) supply the residential load only, (b) supply the residential load and charge the BESS. Assuming that the EV arrived home every day at 6 pm with a SOC of 90% and left home at 6 am the next day.

203 0% to 72%. For a house load percentage of less than 250%, increasing the BESS capacity significantly
 204 increases the residence self-sustainment duration.

205 5. EV Participation

The reference EV battery considered in the study is rated 90kWh/10kW with the returning SOC of 90%, as summarized in Table 1. Within this study, the EV is scheduled to leave and return home at 6 am and 6 pm, respectively. The EV can interface with the HEMS and supply residential loads when the EV is at home. When supplying power to the home, the total capacity of the residential ESS is expanded and the total energy capacity defined in (3) becomes:

$$E_C = \eta_B \cdot E_{C,B} + \eta_E \cdot E_{C,E} \cdot B_E, \quad (7)$$

206 where η_E is 80%. the maximum range of the EV battery SOC; $E_{C,E}$, the energy capacity of the EV
 207 battery; B_E , Boolean results for 1 represent EV at home, 0 otherwise.

208 Two types of EV discharging scenarios considering whether or not the BESS was charged by the
 209 EV battery were explored in this study. In the first scenario, the EV was discharged to supply the
 210 residential load when it arrived home and the BESS stopped discharging, as shown in Fig. 13 (a).
 211 As a result, the BESS SOC remained the same until the EV left home at 6 am the next morning. In
 212 the second scenario, the EV supplied the residential load and charged the BESS (Fig. 13 (b)). In this
 213 case, the BESS was left with 100% SOC when EV left home. The residence can self-sustain for more

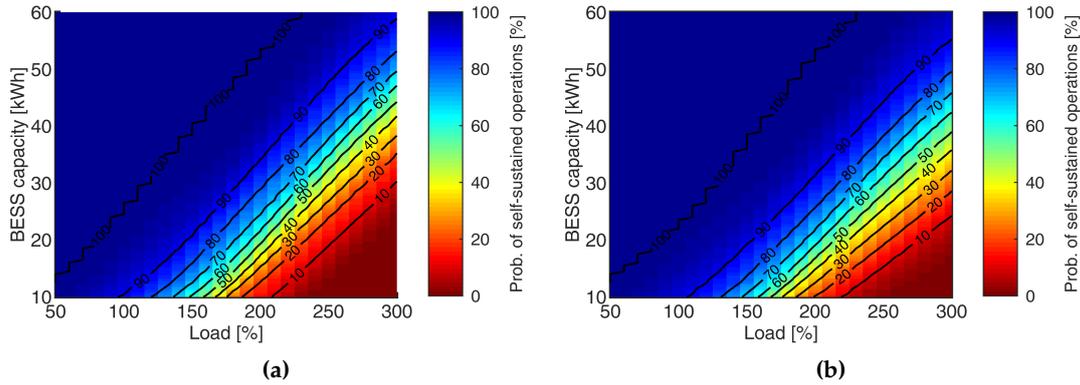


Figure 14. Case study for combinations of different load percentage and BESS capacities with an EV participating to (a) supply the residential load only, (b) supply the residential load and charge the BESS.

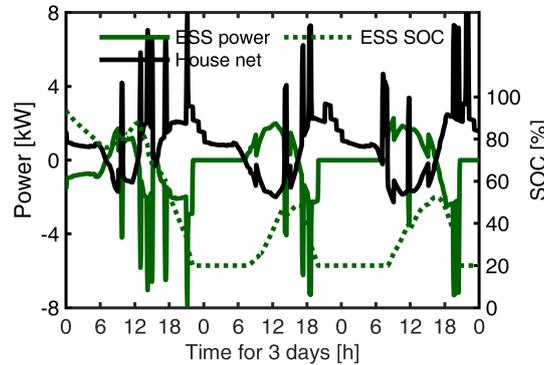


Figure 15. An example self-sustain case for the house with the EV staying at home. Shown is the case with an EV battery rated at 20kWh. The capacity of the energy storage system (ESS) was expanded dramatically by incorporating the EV battery.

214 than 24 hours under both EV discharging scenarios compared to self-sustaining approximately 5 hours
 215 in the reference case without EV discharging, as shown in Fig. 4 (b).

216 Load percentage and BESS capacity effects on self-sustainment were studied and results are
 217 shown in Fig. 14. For both EV discharging scenarios, the probability to self-sustain more than 24
 218 hours was increased to more than 90% for the reference house, which can be located as (Load=100%, BESS
 219 capacity=11kWh) in the heatmap shown in Fig. 14. Enabling EV to interface with HEMS increases
 220 house resilience significantly compared with the case shown in Fig. 12. Furthermore, self-sustainment
 221 duration increased when the BESS was able to be charged directly by the EV battery, especially when
 222 the load percentage is high. For example, when the BESS capacity is 11kWh and load percentage
 223 is 150%, the results for the two EV discharge scenarios are between [50%, 60%] and [60%, 70%],
 224 respectively.

In some extreme power outages, such as those caused by extended wildfire, the power supply may only be restored after a few days. In such cases, the EV is expected to stay home and its battery can be incorporated to expand the residential ESS capacity, which is defined as:

$$E_C = \eta_B E_{C,B} + \eta_E E_{C,E}. \quad (8)$$

225 The simulation results from Fig. 15 show that when the EV battery rated 20kWh was incorporated
 226 in the ESS, self-sustained operation duration was increased to approximately 20 hours. Introduction
 227 of the EV battery increased the total residential ESS capacity significantly, and since the duration of

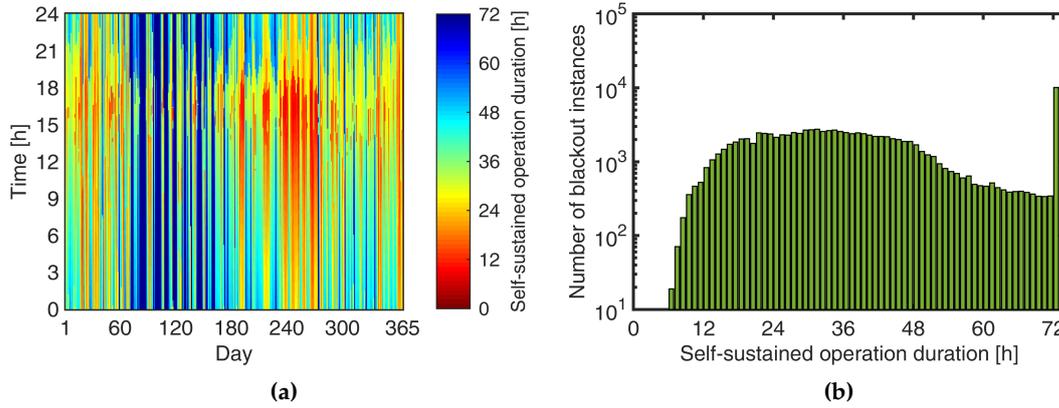


Figure 16. The self-sustained operation duration of the house with an EV at home for the duration of 72 hours presented as a (a) heatmap, and (b) distribution. The EV battery was rated 20kWh in this case. The probability that house can self-sustain for at least 72 hours is approximately 10%.

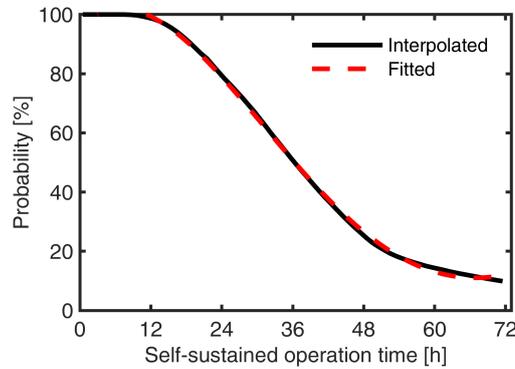


Figure 17. The cumulative distribution for the self-sustained operation duration of the house with an EV at home rated for 20kWh. Building resilience was analyzed over a duration of 72 hours.

self-sustainment drastically increased, all instances with an interconnected EV were analyzed for 72 hours following an outage.

The results for all 105,120 instances are shown in Fig. 16. When the EV with a battery of 20kWh stayed at home, the house could self-sustain longer in general and at least 72 hours for approximately 10% of the instances (Fig. 16 (b)).

With a 20kWh EV battery staying at home during the outage, building resilience of the residence improves significantly. The probability of the residence self-sustaining for at least 12 hours is almost 100%, as shown in the cumulative probability curve in Fig. 17. In this example, the probability that the house could self-sustain at least 24, 48, and 72 hours are approximately 80%, 26%, and 10%, respectively. The cumulative distribution of building resilience for varying scenarios was fitted and represented explicitly with a 4th order polynomial equation, as follows:

$$f(t) = \begin{cases} 100, & t \in [0, 12) \\ p_1 t^4 + p_2 t^3 + p_3 t^2 + p_4 t + p_5, & t \in [12, 72], \end{cases} \quad (9)$$

where the coefficients are $p = [-0.0000097, 0.0022765, -0.1557, 1.8578, 95.7078]$. It is essential to keep the resolution of the first two coefficients 7-decimal to maintain the accuracy.

The effect of different EV battery ratings were studied and results are shown in Fig. 18. All parameters apart from the EV energy capacity are kept the same as the reference house (Table 1). The probability shown in Fig. 17 is represented by the case of fixing the x-axis at 20kWh. At this value,

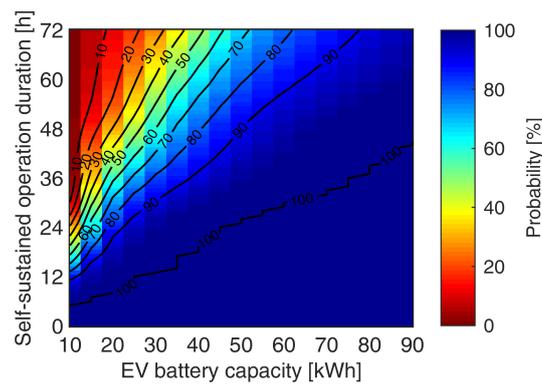


Figure 18. Building resilience heatmap for the house with an EV staying at home and providing additional energy storage. The effect of different EV capacities on building resilience was evaluated.

238 the colors show that there exists approximately 80%, 26%, and 10% probability for self-sustainment
 239 duration of 24, 48, and 72 hours, respectively. EV battery capacities of 30kWh, 60kWh, and 90kWh give
 240 the residence a 100% probability to self-sustain approximately 12, 30, and 45 hours, respectively. The
 241 probabilities for residence with EV battery capacities of 30kWh, 60kWh, and 90kWh to meet a given
 242 duration target, e.g., 48 hours, are approximately 60%, 92%, and 98%, respectively.

243 6. Discussion

244 In this paper, the resilience of a building was quantified as the probability to self-sustain for a
 245 specified duration of time following a power outage, which can occur at any time throughout an entire
 246 year. Factors including the electricity usage of the house, renewable generation, the capacity of the
 247 residential energy storage system (ESS), and the availability of a electric vehicle (EV) with its associated
 248 battery have been studied. The results show that the reference house considered could self-sustain up
 249 to 3 hours in almost all instances.

250 The probabilities for a house to self-sustain for at least 24 hours were summarized for combinations
 251 of different home loads, which range from 50% to 300%, and BESS capacities, which range from 10kWh
 252 to 60kWh. For a residence with a fixed BESS capacity, of 40kWh, the quantified results, which are the
 253 probabilities for the house to self-sustain for at least 24 hours are 100%, 95%, and 60%, for home load
 254 percentages of 50%, 100%, and 150%, respectively. For the example residence with 100% full load, the
 255 quantified results, which are the probabilities for the house to self-sustain for at least 24 hours are 0%,
 256 25%, and 95%, for BESS capacity of 11kWh, 20kWh, and 40kWh, respectively. The quantified results
 257 provides the utility and house owners with the basis for planning rolling blackout, power restoration,
 258 and for sizing the residential ESS.

259 This paper explored the possibility of utilizing an EV during a power outage by incorporating its
 260 charged battery into the residential ESS. Considering fixed times for the EV departure from and return
 261 to the residence, building resilience increased for all cases even when the EV is away and not available
 262 in the daytime. The probability of a reference house with a BESS of 11kWh, home load percentage of
 263 100%, and a EV battery of 90kWh to self-sustain for at least 24 hours is approximately 90% in such
 264 cases. When the house owner opts to keep the EV at home all the time during an extreme power
 265 outage, building resilience increased significantly even without load curtailment. The results show
 266 that incorporating the EV battery into residential ESS substantially increases self-sustainment duration.
 267 With EV battery capacities of 20kWh, 50kWh, and 90kWh, the probability for the house to self-sustain
 268 24 hours is, 85%, 100%, and 100%, respectively. With the same capacities, the probability to self-sustain
 269 for 48 hours is, 30%, 90%, and 98%, respectively.

270 The effect of different PV ratings was studied with PV rating being changed from 5kW to 10kW
 271 with increments of 0.1kW. Results show that, with the ratings considered and all other parameters
 272 fixed, this has a negligible impact on building resilience as minor changes in self-sustained duration

273 were noted. This indicates that the capacity of the BESS and that of an additional EV battery system
274 provided have some of the largest impact on improving building resilience.

275 7. Conclusion

276 A procedure was developed to estimate the building resilience considering the load percentage,
277 capacity of BESS and EV battery. A reference house from California, with an annual electricity usage of
278 13,628kWh and a BESS with capacity of 11kWh, was used as the baseline for developing the building
279 resilience model. The probability for the reference house to self-sustain for more than 3, 10, and 24
280 hours was found to be 100%, 50% and 0%, respectively. For the reference house, when the BESS
281 capacity was increased, for example, to 40kWh, the probability for the house to self-sustain for at least
282 24 hours increased to 95%. When the load of the reference house was reduced, for example, to 50%,
283 while other parameters were kept the same, the probability of self-sustaining for 24 hours increased to
284 31%. When an EV with a battery capacity of 90kWh was incorporated in the home energy management
285 system, the probability for the reference house to self-sustain at least 24 hours increased to 90%. If this
286 same EV was parked at home all the time, the probability to self-sustain 24 hours was 100%, and the
287 likelihood of self-sustaining for 48 hours increased to 98%. When the EV battery capacity was 20kWh,
288 the results for 24 and 48 hours were 85% and 30%, respectively.

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