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Extreme typhoon events trigger long-lasting power outages and require demand-side solutions to enhance energy resiliency

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As climate change intensifies, the adverse impacts of extreme weather events on energy supply systems will increase. Here, we collected energy grid utility datasets to illustrate causes and recovery processes of extended power outages induced by typhoon events in Japan. We also assessed the performance of demand-side solutions to enhance home energy resilience using household load profiles. We show that power outages present similar recovery curves, with full restoration times highly dependent on maximum wind velocities and affected regions. Ensuring a 24-hour self-energy supply is essential to mitigate outage impacts. Further, our results highlight the importance of off-grid energy storage or production in sustaining critical household energy loads under extended outage conditions. Building electrification scenarios challenges meeting increased demand under power outages. Building electrification and resiliency should be designed in tandem to improve energy security. Findings shed light on the effectiveness of demand-side solutions in enhancing Japan's home energy resilience.

Climate change has increased the intensity of extreme weather events, such as typhoons, snowstorms, and heatwaves[1–3]. Although they have a low probability of occurring, extreme weather events undermine the reliability and resilience of energy systems[4,5]. Moreover, the severity of climate-induced extreme events is projected to continue to increase[6–8]. The growing integration of weather-dependent renewable energy sources, coupled with the increasing electrification of various energy sectors, exacerbating challenges related to the security and resilience of modern energy supply[9–11].

Adverse effects of extreme weather events on centralized power grids, include widespread damage to power generation, transmission, and distribution components, causing widespread power outages[12,13]. From an overall structural perspective, power systems are designed to meet energy demand by deploying long-duration energy storage systems[14], resilience upgrades, and enhancement of transmission networks[15,16]. Those common approaches often require high investment costs. In the absence of a comprehensive understanding of mitigation preparation for outage risks associated with extreme events, utility regulators or policymakers can only hope that the next occurrence will not lead to sudden and severe impacts on the power supply. As society transitions ever more toward widespread electrification, long-duration power outages will have further-reaching consequences, including substantial economic losses[17,18] and threats to human safety and health[19,20]. Assessing and planning for energy resilience in the face of extreme events is receiving increasing attention from researchers and policy makers[11,21]. Outages must be understood accurately and deeply to combat their effects. Yet accurate characterization of the dynamic of outages during extreme events is scarce partly because datasets of real-world outages are difficult to obtain.

The integration of distributed energy resources and rapid electrification is transforming the conventional power transmission architecture[22]. To mitigate the extended power outage, previous works verify that collaborations between policymakers, power utilities, and distributed energy prosumers are alternative approaches to cope with the impacts of power outages under extreme weather conditions[23,24]. Active distribution energy network offers increased opportunities to reduce the impact of widespread power

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outages and enhance energy resilience by transitioning from a centralized to a decentralized energy supply paradigm[25,26]. For example, deploying distributed energy generators is widely regarded as one of the effective approaches to reduce the need for costly upgrades and helps alleviate peak load[15,27]. Adoptions of distributed electricity generation and storage systems can provide localized power supply during public grid disruptions, and enable an opportunity to secure critical energy demand[28–30]. Rapid building electrification drives the evolution of residential energy systems, accelerating investments in electrical heat pump and battery systems[31,32]. It is worth noting that building electrification with distributed energy resources can also change the amount and pattern of time-series electricity demand[33], consequently impacting energy resilience. The increasing adoption of plug-in electric vehicles (EVs) and the construction of charging infrastructures are closely interconnected with the power and building sectors, providing an opportunity for bio-directional power exchange[34]. Previous studies and surveys have confirmed that residential customers demonstrate a willingness to pay additional costs to enhance their energy[35–37]. This knowledge gap still exists, although many studies have explored the energy resilience of building energy systems, they primarily rely on simulation work that focuses on either the supply or demand side. This is partly due to the scarcity of high-resolution data on real-world grid operations and consumer demand patterns. The implications of growing building electrification on energy resilience, as well as the ability and effectiveness of various demand-side solutions to enhance this resilience, are not well understood. Furthermore, the power generation ability of distributed generation is constrained, necessitating the prioritization of critical electricity-dependent demands over regular operational management during prolonged outage events. However, limited research has been conducted to effectively ensure the provision of critical demand energy services during the recovery process following extreme event outages. Results can inform strategies for enhancing infrastructure resilience and provide valuable insights into the effectiveness of demand-side solutions.

Part I of this work, we investigate public grid power outages caused by typhoon events from 2018 to 2022. In Part II examines how to manage distributed energy resources to minimize the impacts of severe power outages have on residential consumers.

Results

Characterization of supply-side power outage conditions

Part I of this study investigated the effects of typhoon events on four regional electrical systems in Japan from 2018 to 2022. The disruption conditions in public power grids were reported by the affected electrical companies. Figure 1a shows the geographical regions of the power grid studies and the typhoon occurrences from 2018 to 2022. Figure 1b illustrates common physical damages observed in distribution and transmission networks resulting from typhoon events, including electric pole toppling, circuit disconnection, and power tower failures.

This study selected six typhoon events based on their wind velocities exceeding 40 m/s and the widespread power outages they caused, supported by reported recovery data. Table 1 provides detailed information on these typhoon events and induced power outage events affecting four electrical companies. Typhoons are numbered according to the order in which they occur each year. According to the Japanese Meteorological Agency, there was a high frequency of landed typhoons in September and October[38] reported severe power outages concentrated in this period. Table 2 provides a summary of component failures caused by typhoon events based on company reports. A large portion of the damage are in power distribution infrastructures, similar to previous works[8,39,40].

Gaining insights from past outage events is crucial for improving energy resilience when faced with extreme weather events. Here, we characterize utility-scale power outages using publicly available data, Fig. 2 illustrates 2-week grid electricity loads (blue lines) and regional solar PV generation (yellow lines) at 60-min interval before, during and after typhoon events. The red dot denotes the specific grid load at the time the greatest number of customers lost power. The effect of widespread power outages on the grid load during typhoon events is particularly evident for the Chubu (Typhoon Nos. 24 and 19) and Kyushu (Typhoon Nos. 10 and 14) grids, where there was a substantial reduction in grid power supply. While typhoons are typically accompanied by heavy rainfall, which can lead to a decline in solar PV generation, it is important to note that the extent of this decline can vary depending on the specific location and timing of the typhoon. In the Tokyo grid, solar PV systems may still generate power during certain periods of the typhoon, resulting in less impact on generation profiles.

Figure 3 depicts the initiation and restoration of power disruptions caused by typhoon events, *y*-axis presents the number of customers experiencing outages. The dataset used for this analysis was sourced from regional Power Companies' websites and reports. The *x*-axis begins at the moment the typhoon starts affecting the power grid. Initially, the number of customers experiencing outages rises sharply, reaching a peak that represents the maximum impact of the typhoon. After this peak, the number of affected customers gradually decreases as power restoration efforts proceed, eventually returning to normal levels once all services are fully reinstated. The scenarios analyzed for the Chubu (Typhoon Nos. 24 and 19) and Kyushu (Typhoon Nos. 10 and 14) grids indicate that higher maximum wind velocities are associated with longer recovery durations. However, the increased number of affected customers does not appear to impact recovery

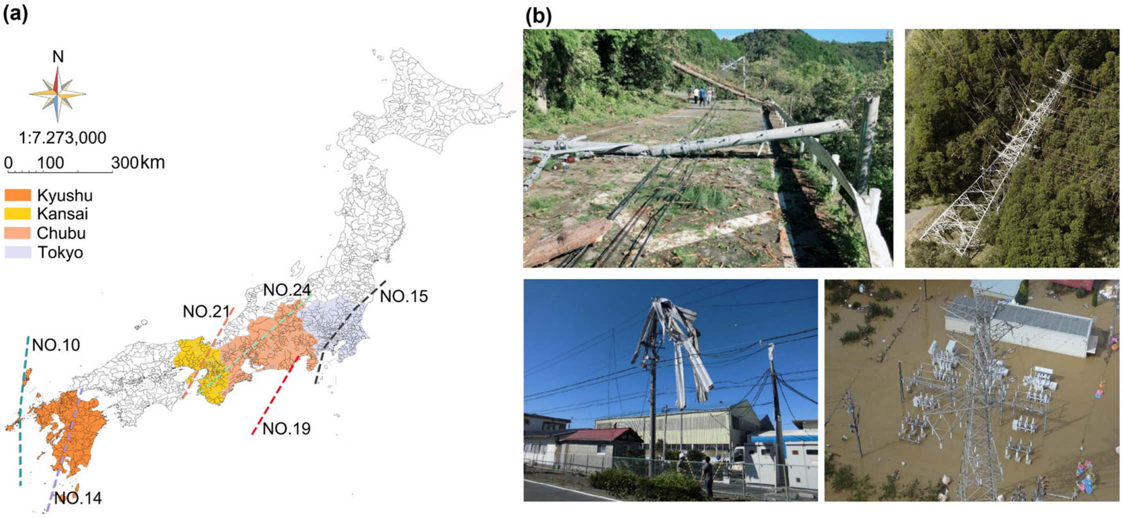


Fig. 1 | Examined typhoon events that trigger widespread power outages. Map of the typhoon path (**a**) and physically damages caused by severe typhoon events (**b**).

Table 1 | Information summary of surveyed regional outages triggered by typhoons

Name of extreme event (Number)	Date landed	Maximum wind velocity (m/s)	Regional power grid	Integrated PV capacity (MWp)	Maximum number of customers without power	Time of peak power outage
Typhoon Jebi (No. 21)	September 4, 2018	48.2	Kansai	4900	1,684,300	21:00, September 4
Typhoon Paeng (No. 24)	September 30, 2018	40.0	Chubu	7600	1,022,710	1:00, October 1
Typhoon Faxai (No. 15)	September 9, 2019	45.0	Tokyo	13,080	931,800	8:00, September 9
Typhoon Hagibis (No. 19)	October 12, 2019	43.9	Chubu	8500	65,230	1:00, October 13
Typhoon Kristine (No. 10)	September 6, 2020	44.2	Kyushu	10,000	475,910	6:00, September 6
Typhoon Josie (No. 14)	September 18, 2022	45.0	Kyushu	11,000	353,480	1:00, September 19

durations, in consist with previous work[41]. A comprehensive comparison of those scenarios shows that the severity and recovery duration of outage events present regional variations, which could come from regional intrinsic resilience characteristics and the varying number of customers at the grid edge. As shown in Table 2, the main cause of power outages is distribution network disruption. The service areas of the Kansai and Tokyo grids are 28,704 and 39,575 km^2, respectively. The population densities in these regions are approximately 700 people per km^2 and 1100 people per km^2. The Tokyo grid's recovery process exhibits a long tail characteristic, likely due to its larger service area and higher population density, which can complicate logistics and resource allocation during recovery efforts. Figure 4 shows the restoration pattern of each power outage for the maximum number of customers affected. The dots present the normalized raw data (reported number of customers affected by peak power outage number), and the yellow curves illustrate the recovery process. The widespread power outages affect customers across a wide geographical area, the primary cause of these outages, as demonstrated in Table 2, is attributed to infrastructure failures in distribution lines. Therefore, identifying failures is time-consuming, repairing damage to the transmission network over long distances typically takes longer time compared to shorter distances[42].

The recovery processes among regional power grids follow exponential decay dynamics. The regression results indicate that, on average, percentages of affected customers after peak power outages decrease to 38.5% and 16.3% after 24 and 48 h, respectively.

Harding measures, such as undergrounding distribution lines and upgrading poles can make centralized grids less susceptible to extreme weather events[8]. However, hardening the system is usually costly. The decentralized energy system, characterized by high spatiotemporal flexibility and rapid response capability, offers an opportunity for reliable power flow implementation and management. This, in turn, enhances the security of energy supply[11].

Securing long-duration home energy self-energy supply

People tend to spend more time at home during extreme weather periods, and losing power for extended periods can create potential safety risks. As the penetration of distributed energy generators, EV cars, and smart meters increases, managing on-site energy generators and integrating electric vehicles (EV) in Vehicle-to-Building mode presents an opportunity to mitigate home power outages[43,44]. Figure 5 depicts representative distributed power resources (home battery storage, bidirectional EV, and fuel cell) in Japan's house. The micro combined heat and power (CHP) systems can deliver power and hot water even given power failures in the centralized power network, thereby guaranteeing critical energy services at minimal levels. Installation of a battery storage system gives homeowners independent control over their energy usage.

Rapid building electrification is accelerating investments in electrical heat pump and battery systems. We assess the performances of demand-side resources to meet home electricity demand given the increase in building electrification in Japan. In Japan's current market, the storage capacity of home battery systems generally ranges from 4.0 to 15.0 kWh[45,46]. The power generating capacity of fuel cells, which are used widely as cogeneration systems in Japanese residential houses, is 0.70 kW[47], power consumption of electrical heat pump water heater is about 1.0 kW at nominal generating capacity[48,49]. If local backup generators are installed to ensure uninterrupted energy services during prolonged power outages, a substantial capacity of on-site generators or power storage units would be necessary. Although EV storage capacities range from 20 to 80 kWh, the actual electricity available depends on the state of charge of the battery storage system. Therefore, it needs to consider power availability constraints and priorities of the critical electricity demands under extended power outage events.

At present, the average annual household electricity consumption shares roughly 50% of the total energy demand within the Japanese residential sector[50]. The intensity and pattern of household energy load profile depend on the number of appliances in use[51] and occupants' energy

Table 2 | Summary of component failures causing the power outage

Typhoon events	Distribution network					Transmission network	
	Support pole	Overhead lines	Transformer	Underground equipment	Communication network	Steel tower	Line
No. 21	1343	4914	362	38	544	0	10
No. 24	209	2974	53	0	0	0	2
No. 15	1996	5529	431	1	0	4	3
No. 19	242	1502	2	0	0	0	0
No. 10	163	4705	0	0	5	1	2
No. 14	481	7467	0	0	13	0	1

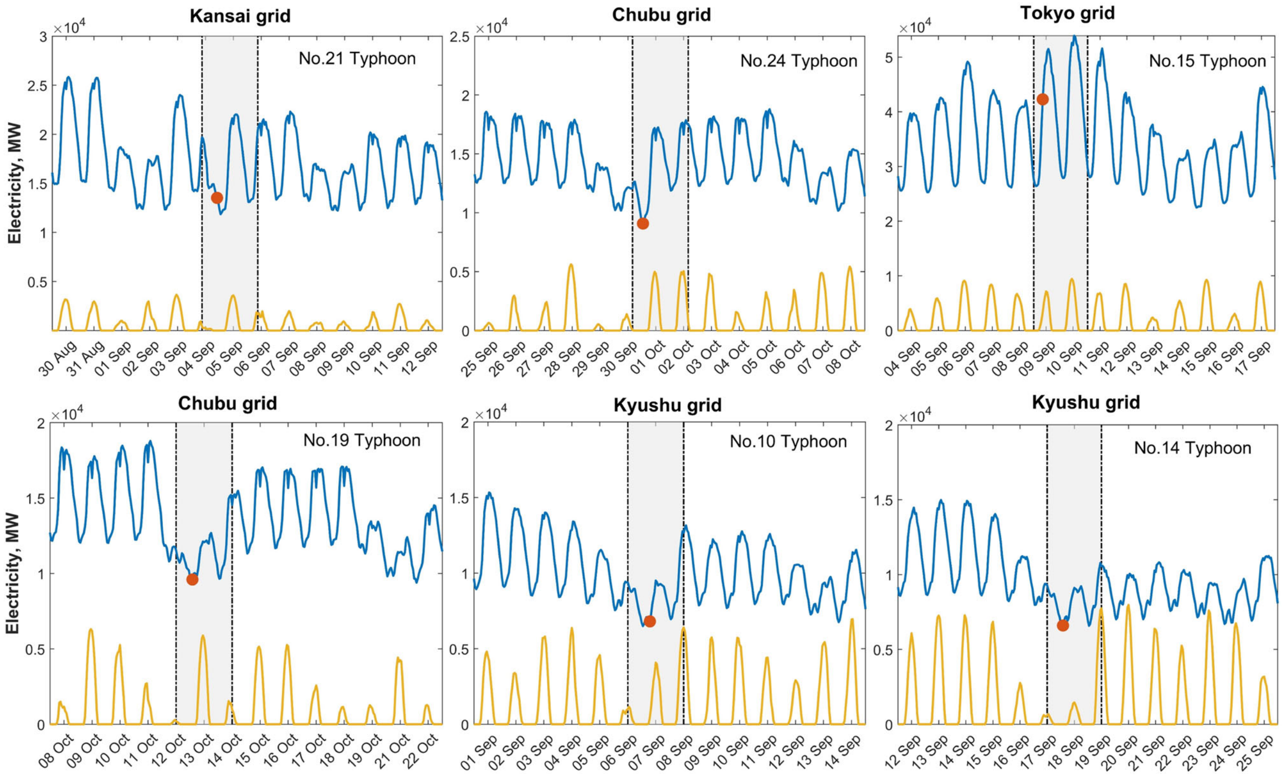


Fig. 2 | Hourly grid load and solar PV generation profiles before and after typhoon events. Blue line refers to grid load, yellow line is PV generation, color band presents 48 h period that experiences typhoon events (from reported typhoon increased outage).

consumption behavior[52]. Moreover, hot water shares a large proportion of home energy usage, electrifying hot water would increase home electricity demand. This work distinguishes home energy loads by hot water resources, including electrical heat pumps and fuel cell systems. To ensure the representativeness of the examined households, a careful selection process was employed. We randomly collected half-hourly measurements of single-family electricity loads of two groups characterized by different hot water resources (electrical heat pump and micro fuel cell system) throughout September. Figure 6a shows the daily electricity load profiles of the two groups; both exhibit similar normal distributions. The average daily electricity loads of Group 1 and Group 2 are 17.0 and 14.6 kWh, respectively. As described in Fig. 6b and c, electrifying domestic hot water increases daily electricity consumption and results in an obvious peak load during early morning. Additionally, we specifically measured the load profiles of critical lighting and refrigeration appliances at 30-min intervals. We chose those end uses because power disruptions that interfere with the functioning of refrigerators can result in food or medication insecurity[20]. While room lighting systems play a crucial role in ensuring residents' safety (national survey results show that lighting is the top function residents want during natural disasters)[53]. As shown in Fig. 6e, the power consumption of the refrigerator exhibits relative stability, while the lighting power consumption profile displays variability with prominent peak periods during the early morning and night as shown in Fig. 6d. The average daily power consumption for home lighting and refrigeration is 2.95 and 2.17 kWh, respectively, which closely aligns with the reported dataset[54].

This study assesses energy resilience through the self-load cover ratio index, defined as the ratio of on-site generation to energy demand during power outages. By analyzing measured daily electricity loads from representative households, we constructed distributions of these ratios for various on-site technologies across outage durations of 24 and 48 h (see Fig. 7). On-site available energy can fully sustain energy demand when the self-generated energy to load ratio is over 1.0. As electrification increases, there are greater challenges in sustaining the home electricity load solely through an on-site battery storage system, it even becomes difficult to fully cover critical loads under prolonged outage events. In high-electrified homes, we investigate the energy self-sustaining scenario with power from bidirectional EV and home storage systems, Fig. 7a and c depict the self-load covering scenarios under different available electricity from bidirectional EV and home battery systems during 24 and 48 h home outages, respectively. It is important to recognize that battery storage systems may not be capable of providing or

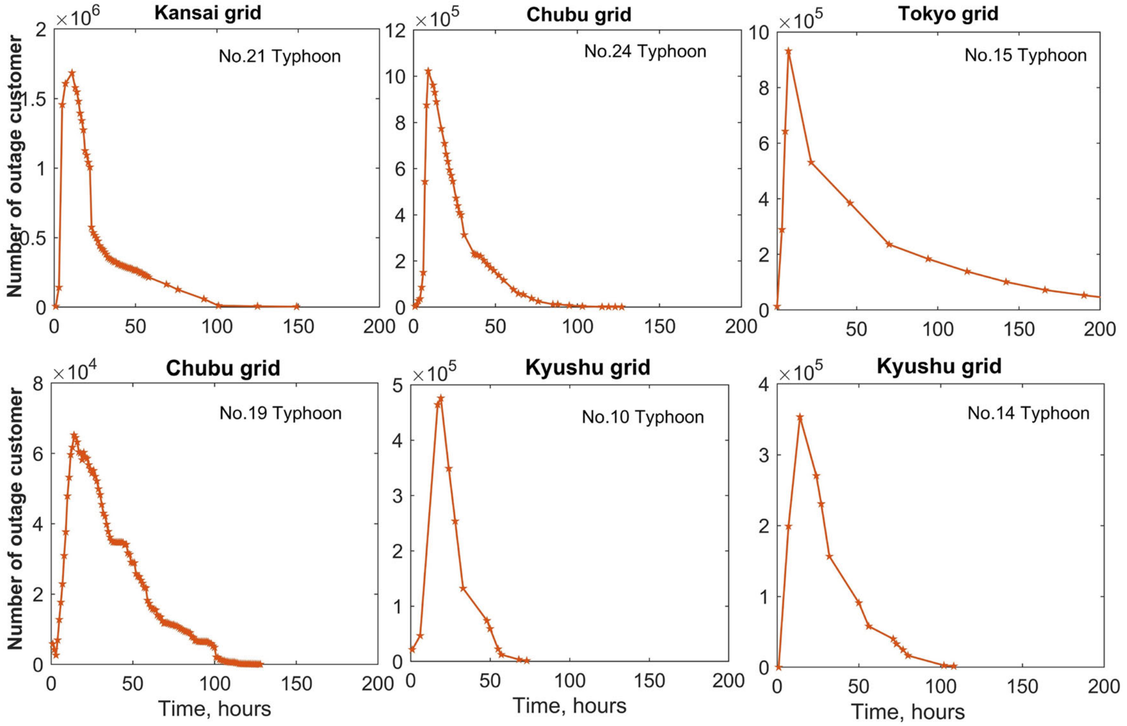


Fig. 3 | Changes in the number of customers lacking electricity, beginning with the initial outage increase triggered by the typhoon.

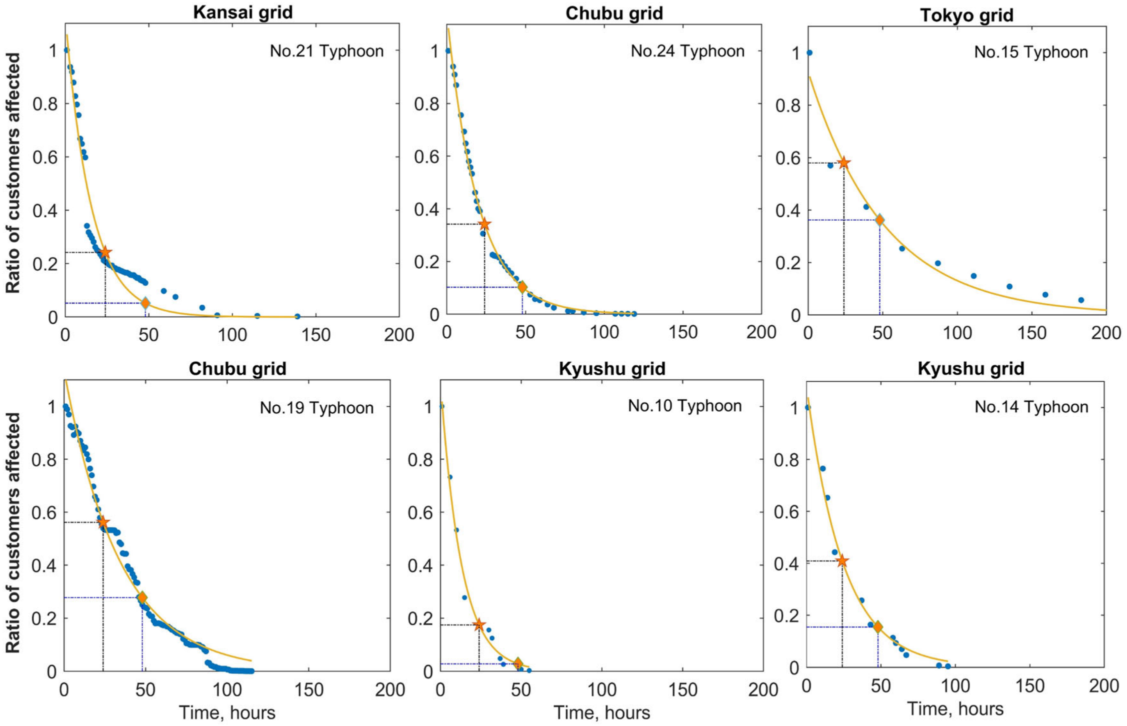


Fig. 4 | **Recovery process for regional power outages.** Circle dots present normalized raw data; yellow lines show regression results; pentagram dots present 24 h; and diamond dots show results after 48 h.

sustaining power for all private energy needs due to limited energy capacity, 10.0 kWh electricity from on-site storage systems can only sustain critical loads when experiencing a prolonged power blackout. Therefore, priority selection of home appliances is important to sustain critical loads.

Figure 7b and d display the self-generating scenarios using on-site fuel cells and different home battery systems. Uptake of distributed fuel cell system effectively increases self-energy sufficiency, the combination of home battery and fuel cell systems offers a reliable ability to sustain critical electricity demands under prolonged outage conditions. According to measured results, implementations of fuel cell cogeneration systems smooth the electricity load. A fuel cell operating at nominal power capacity can meet critical lighting and refrigerator load, while also meeting hot water demand. However, it may fail to meet the entire peak electricity load, however, requiring a battery storage system or load restoration.

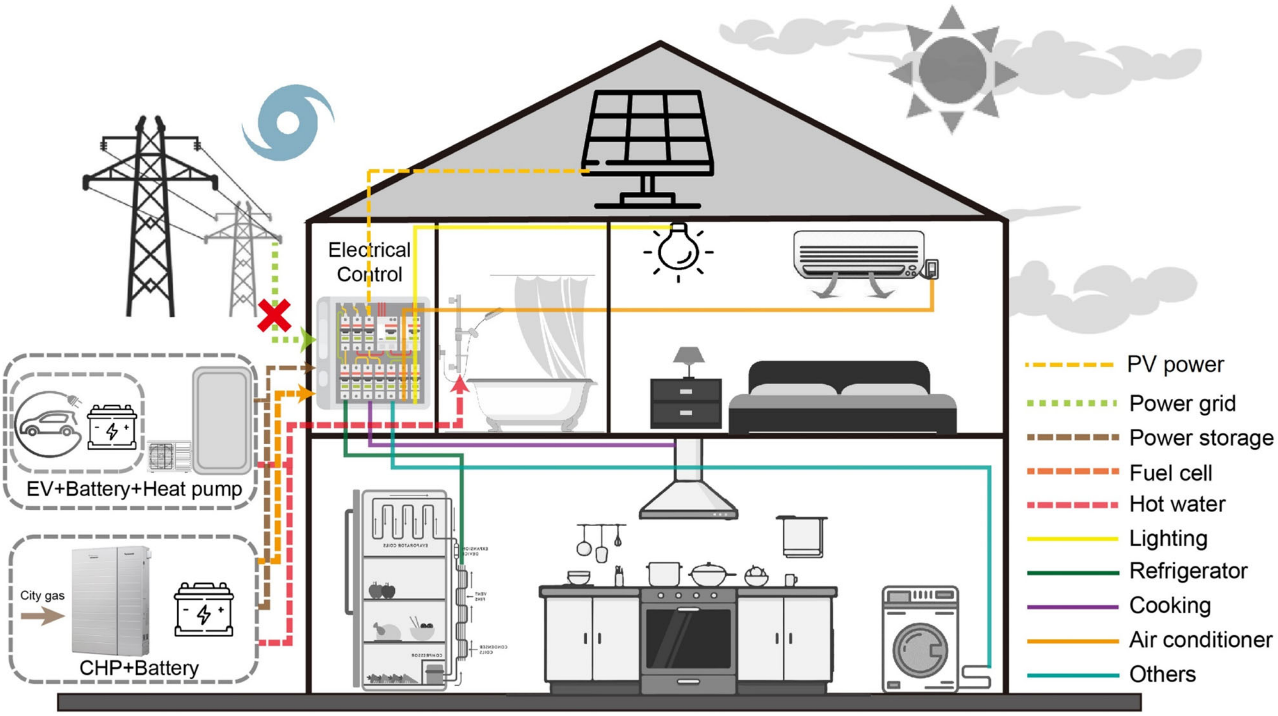


Fig. 5 | Representative distributed energy resources. EV electric vehicle, home battery, rooftop PV, micro fuel cell (combined heating and power CHP), and heat pump systems, and detailed electricity loads in residential houses.

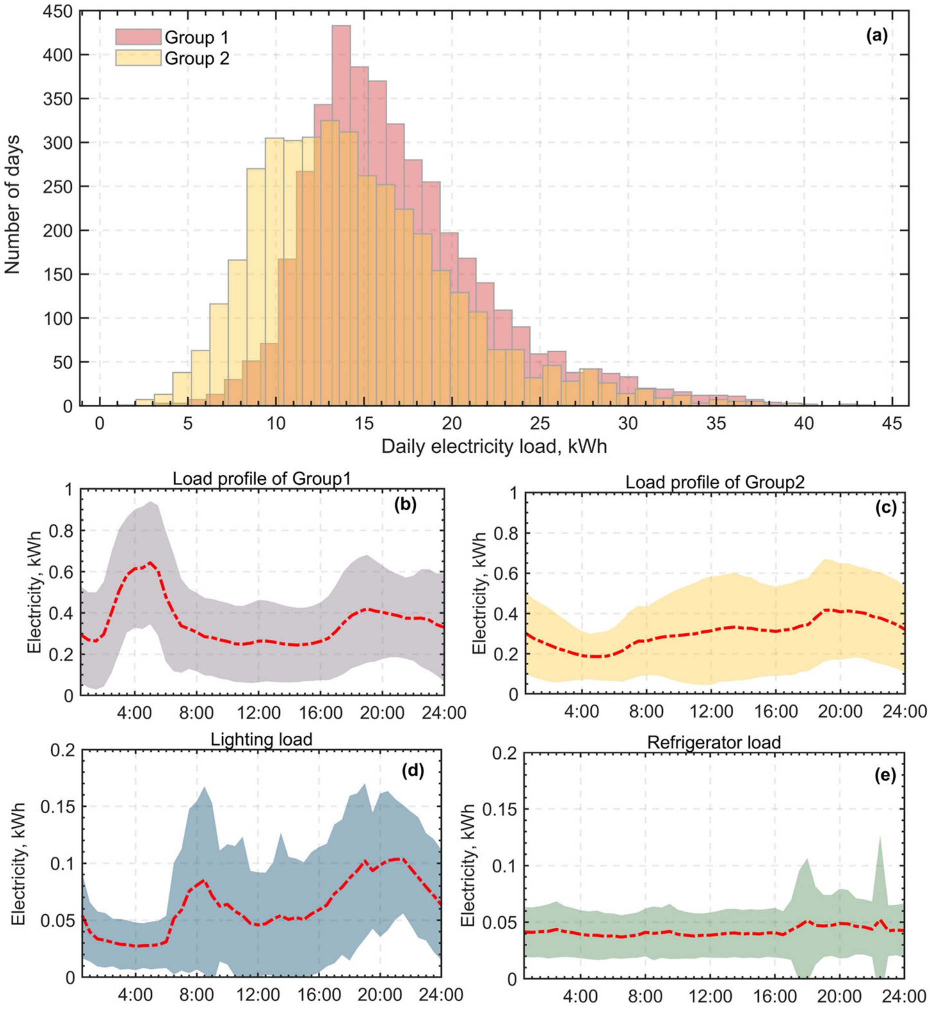
Although integrating rooftop solar panels can promote energy self-sufficiency, the heavy rainfall that accompanies typhoons leads to intermittent PV generation, which is insufficient to reliably cover daily energy demand. Consequently, a standalone PV system cannot meet critical household energy loads throughout the day. Therefore, energy cover ratios of PV standalone and hybrid PV and battery systems are also examined. Two types of residential loads, as described in Fig. 6b and c, are examined. The energy load cover ratios of standalone PV and hybrid PV-battery systems in maximum power outage days are presented in Table 3. The hourly generation profiles of a 5.0 kWp rooftop PV system over two days (the day before and the day of the typhoon event) were computed by scaling the monitored PV load profiles (illustrated in Fig. 2) according to solar PV capacity connected to the power grid (reported in Table 1). PV capacity is determined based on limited rooftop areas and previous survey work[55]. Detail simulation process is described in the "Methods" section, results indicate that standalone PV systems are unreliable for meeting home energy demand during typhoon events. Incorporating battery storage effectively increases the load cover ratio, providing increased opportunity to meet critical energy demand. Case studies have shown that 5.0 kWp battery storage systems can increase the load coverage ratio by 25–50% in certain disruption scenarios. This improvement enhances the reliability of the lighting and refrigeration energy supply (as illustrated in Fig. 6), ~30% of daily electricity consumption. However, fully meeting the total electricity demand remains challenging when PV generation significantly decreases.

Discussion

Typhoons although infrequent, damage centralized energy supply systems, often resulting in widespread power outages. Prolonged power disruption may expose many residents to darkness, leading to economic loss[37] and even threatening occupants' health[56]. It is the increase in the intensity of extreme events more than the frequency that causes increasing severe disruption in systems[11,57]. Using data collected from four power companies, this study characterizes widespread power outage events. The analysis results also reveal that the utility grid load is greatly impacted during power outages, and the restoration of service follows a consistent exponential pattern. The extended recovery process is primarily attributed to the extensive damage sustained by the distribution infrastructure across a wide geographical area. Given this, it is crucial to implement demand-side solutions to mitigate the impacts of extended power outages.

The increasing integration of environment-dependent renewable energy sources, as well as rapid electrification, highlights the need for strengthening the energy resiliency of power supply[21]. Grid utilities must prioritize boosting electric system resilience at a reasonable cost, it should be noted that solely focusing on improving energy resilience from a top-down perspective can create a financial burden[58]. Demand-side solutions have the potential to enhance the flexibility and resilience of the overall energy system at a relatively low cost[59,60]. To address this challenge, the present study explored the effectiveness of demand-side solutions in mitigating the risk of power outages in residential settings. By analyzing actual household energy consumption data, it became evident that relying solely on batteries may be insufficient to achieve high levels of energy self-sufficiency during prolonged outage events. Moreover, increasing battery storage capacity poses a financial burden on customers, and the issue of low annual utilization rates needs to be addressed, prioritizing critical energy services is crucial for occupant safety and health under prolonged outages. Demand options, such as deploying microgrids and energy electrification, emerge as promising approaches to mitigate carbon emission[61]. The electrification of households contributes to increased electricity demand, which in turn impacts the resilience of home energy systems. Therefore, striking a balance between electrification and resiliency is crucial. This balance can be achieved by adopting a diversified mix of distributed energy resources, ensuring a reliable and sustainable energy supply while reducing carbon emissions[22]. Energy resilience can be enhanced by investing in distributed energy resources, levelized costs of electricity for solar PV, home battery storage, and electric vehicles vary by region and electricity market. Their estimated values are as follows: electric vehicles at 0.30 $/kWh[62,63], solar PV systems at 0.05 $/kWh[64], and home battery storage at 0.25$/kWh[65]. The levelized costs for rooftop PV systems are lower than market electricity prices. The

Fig. 6 | Distributions of measured daily electricity loads for representative single-family homes.
a Group 1: Electrical heat pump supplies hot water (136 families), Group 2: Fuel cell meets hot water needs (131 families). **b** load profile for Group 1, **c** load profile for Group 2, **d** critical home lighting, and **e** refrigerator electricity demand, red dashed lines, and shaded band indicate standard deviations of average load at various times, respectively.



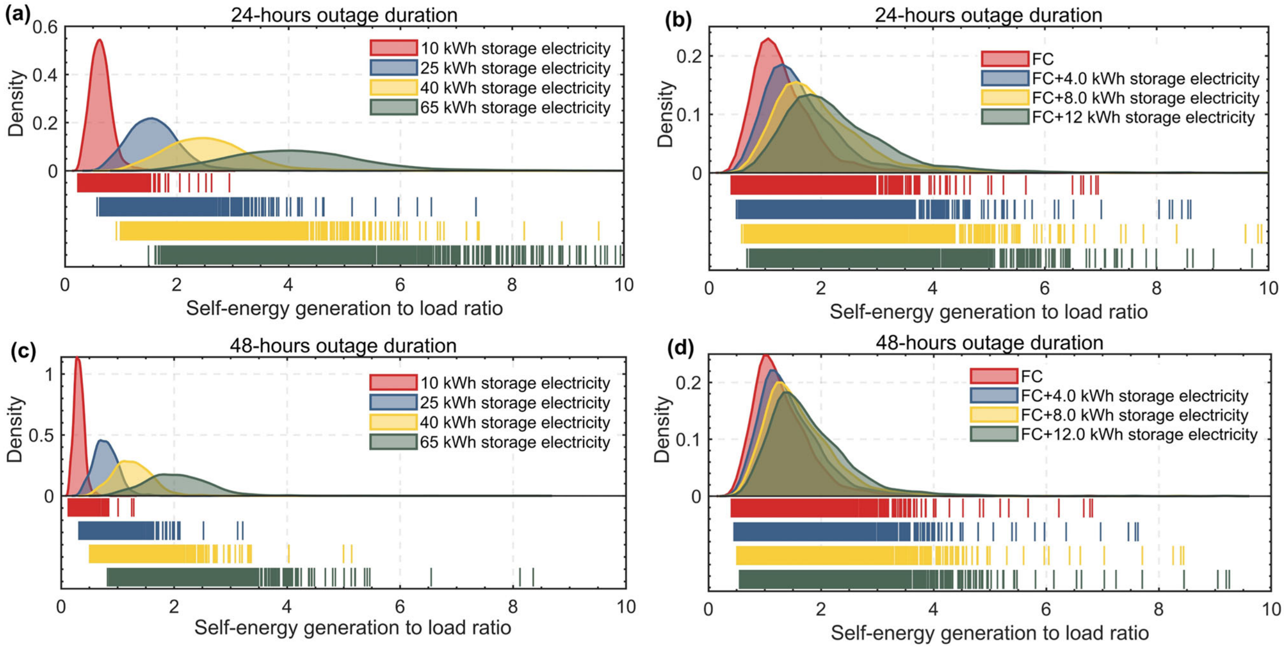


Fig. 7 | Distributions of ratios of on-site electricity generation to demand using various technologies. (**a**) and (**b**) are under 24-h outage duration, (**c**) and (**d**) are under 48-h outage duration.

Table 3 | Comparison of energy cover ratios of different energy systems

Typhoon event	Load Type 1			Load Type 2		
	PV alone	PV + 5.0 kWh battery	PV + 10.0 kWh battery	PV alone	PV + 5.0 kWh battery	PV + 10.0 kWh battery
No. 21	0.209	0.477	0.715	0.236	0.556	0.834
No. 24	0.314	0.817	1.00	0.415	0.931	1.00
No. 15	0.309	0.812	1.00	0.416	0.943	1.00
No. 19	0.318	0.821	1.00	0.420	0.927	1.00
No. 10	0.238	0.482	0.720	0.286	0.564	0.843
No. 14	0.240	0.496	0.734	0.305	0.584	0.863

levelized costs for micro-CHP units are based on several factors, including generator lifespan, efficiency, installed capacity, and fuel cost. The estimated levelized costs for home fuel cell and diesel generators are 0.25 $/kWh[66] and 0.40 $/kWh[67], respectively. Electrical vehicles can serve dual purposes but involve higher costs due to vehicle prices and battery capacities. While micro-CHP technologies are commonly used for backup power, they have higher operating costs and environmental impacts, fuel availability may be constrained during extreme events. Integrating PV systems with home battery storage enhances reliability in meeting critical household energy demands during prolonged outage periods. Customers need to consider techno-economic performances of these solutions carefully to make informed investment decisions that increase home energy security.

There are indeed regional differences in household electricity use per day, and these differences are influenced by factors such as the number of electrical appliances, the electrification rate, and home income. According to IEA reported data[68], daily household electricity consumption in the United States is 28 kWh, Japan is 13 kWh, Germany is 8.6 kWh, China is 6.0 kWh, and India is 2.8 kWh. The difference would substantially affect the ability of demand-side solutions to sustain self-energy supply under extended power outage conditions. In rich countries, the role of demand resources in reducing the risks associated with extended outages can be enhanced by identifying and prioritizing energy loads. In developing regions, affordability can be a barrier for households to access on-site power generation technologies, and the implementation of subsidy programs can enhance their economic viability and social energy equality[69]. In terms of the varying energy consumption levels among residential consumers, promoting shared energy solutions in microgrids can help overcome affordability barriers of on-site power generation and storage technologies[70,71].

This study can serve as a valuable reference for enhancing home energy security during extended power outages in the Japanese public grid. However, it is important to acknowledge the limitations associated with the selection of a specific regional grid and residential customers in Japan. Daily household electricity demand may vary significantly driven by seasonal space heating and cooling loads. Future research endeavors should focus on investigating the energy resilience of home energy systems in light of the rising occurrence of heat waves and cold snap events.

Methods

Grid utility and customer dataset

Detailed information regarding each power outage includes the number of customers affected at specific times and the identified component failures, which were sourced from publicly available websites published by four electricity companies in Japan. The hourly grid supply load and PV generation data from publicly available websites published by the Japanese Renewable Institute. Detailed demand-side electricity loads were collected from behind-meter via smart home energy management systems.

Characterization of power outage recovery process

This work employs the exponential decay model to fit normalized outage data for each outage event. This model is widely adopted to analyze the recovery process of extreme weather events[72,73], described in the following equation.

$$y = p1 \cdot e^{p2 \cdot x} \tag{1}$$

In the above equation, $p1$ is positive and $p2$ is negative, x denotes duration in hours and y is the ratio of customer affected to peak value depicted in Fig. 4. The nonlinear exponential decay function can be modeled as linear ones by a log transform, resulting in the following equation:

$$\log(y) = \log(p1) + p2 \cdot x \tag{2}$$

This transformed linear model presented in Eq. (2) can be fitted using ordinary linear least squares.

To analyze energy resilience performances of demand-side mitigation solutions, the self-power cover ratio is electricity demand divided by total available electricity.

Load cover ratio of hybrid home PV and battery systems

To simulate the load cover ratio, this work modeled the interaction among PV generation, residential electricity demand, and battery storage capacity under specific constraints. PV generation was prioritized to meet immediate electricity demand. We assumed that the home battery started at 90% of its total storage capacity, charging, and discharging efficiency were 90%, respectively. When PV output was insufficient, the battery discharged energy up to the lesser of the remaining demand or the maximum allowable discharge rate. Any excess PV generation, after fulfilling the demand, was used to charge the battery, ensuring that charging did not exceed predefined safety limits. The energy cover ratio was calculated as the total electricity demand met during the outage period divided by the total electricity demand during that period. The energy cover ratio was calculated using the following equation:

$$Ratio = \frac{\sum_{i=1}^{N} \mathrm{Cover\_load}_i}{\sum_{i=1}^{N} \mathrm{Demand\_load}_i} \tag{3}$$

where, $\mathrm{Cover\_load}_i$ represents the electricity demand met by on-site PV generation and home battery discharging flows at hour i, $\mathrm{Demand\_load}_i$ is the hourly residential electricity load at hour i, N denotes the length of the simulation period in hours.

Data availability

The raw data profiles of hourly grid load and solar PV generation before and after typhoon events are available at https://www.renewable-ei.org/en/statistics/electricity/#demand. Data of each power outage event: Power outage event induced by Typhoon 21 in the Kansai grid. (2018) at https://www.kepco.co.jp/corporate/pr/souhaiden/2018/pdf/1213_1j_02.pdf. Power outage event induced by Typhoon 24 in Chubu grid. (2019) at https://www.meti.go.jp/shingikai/sankoshin/hoan_shohi/denryoku_anzen/tettou/pdf/001_03_03.pdf. Power outage event induced by Typhoon 15 in Tokyo grid. (2019) at https://www.tepco.co.jp/press/release/2019/pdf4/191031j0201.pdf.

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Conceptualization, Y.L. and F.X.; methodology, Y.L. and F.X.; investigation, X.Z. and W.G.; formal analysis, Y.L.; visualization, F.X., N.Z., and Y.R.; writing–original draft, Y.L.; writing–review & editing, Y.L., X.Z.; supervision, F.X., W.G., and D.M.K.

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The authors declare no competing interests.

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