INVITED PAPER

Demand-Side Resiliency and Electricity Continuity: Experiences and Lessons Learned in Japan

This paper discusses the experiences and lessons learned from Japan using demand-side resources to improve electricity continuity.

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ABSTRACT | In March 2011, Japan suffered devastating damage from the Great East Japan Earthquake (GEJE) and accompanying tsunami, which caused massive blackouts affecting 8.5 million customers. Damage to power stations, including Fukushima Daiichi Nuclear Power Station, caused a long-term, nationwide power shortage. Other infrastructure and customer facilities were damaged as well. Demand-side resiliency means the availability of electricity to consumers, which is an important factor that affects business continuity. Onsite generation and microgrids have been recognized as important measures that improve resiliency; successful real-life applications of these technologies, such as the Sendai Microgrid and Roppongi Hills, have increased after the GEJE. Metrics on the importance of loads or facilities and resiliency are needed to encourage investment by supporting business operators' decision making and enabling quantitative analyses of the tradeoff between cost and resiliency improvement. This paper presents a comprehensive outline of experiences and lessons learned from the GEJE from the viewpoint of demand-side resiliency—or the availability of electricity to consumers. Damage to power systems and power supply capability through power source loss, best practices (including microgrids), and post-disaster responses and lessons learned are all examined.

KEYWORDS | Demand side; disaster; distributed generation; earthquake; Great East Japan Earthquake (GEJE); microgrid; resiliency; tsunami

Manuscript received August 24, 2016; revised November 14, 2016; accepted November 25, 2016. Date of publication January 16, 2017; date of current version June 16, 2017.
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Digital Object Identifier: 10.1109/JPROC.2016.2633780

I. INTRODUCTION

The threats of natural disasters have been increasing around the world [1], and there have been extensive efforts to reduce the impacts of these disasters. Resiliency has thus become an important value in recent years, and the improvement of communities' resiliency, including that of their infrastructures, has been recognized as an important measure for improving preparedness and mitigating the impacts of natural disasters [2], [3].

The main focus in preparing for natural disasters has been making utilities' facilities, such as transmission towers for distribution cables, as strong as possible. The adoption of resiliency gives other options, including fast restoration of services and demand-side measurements. Another important measure of the preparedness of a power system is its "demand-side resiliency," or customers' ability to continue using electricity in a disaster (i.e., the assurance of electricity continuity for customers). The increase in onsite generation has made it possible for customers to become self-sufficient in electricity. Distributed energy resources—including onsite generators, batteries, and microgrids—enable customers to continue electricity use during power outages, thus improving their demand-side resiliency [4], [5], [6].

After the Great East Japan Earthquake (GEJE), which hit Japan in March 2011, it became important to build a more resilient power system. The country suffered devastating damage from the earthquake and subsequent tsunami, and massive blackouts occurred, affecting 8.5 million customers. Damage to power stations, including Fukushima Daiichi Nuclear Power Station, caused a lengthy, nationwide power shortage; rolling blackouts lasted for two weeks and electricity saving campaigns, designed to maintain the supply–demand balance in summer and winter, influenced not only daily life, but also businesses and the nation's economy. This experience proved that onsite generation and microgrids could be effective ways of maintaining power [7], though critics also pointed out several problematic issues.

Electrical engineers, civil engineers, architects, medical professionals, social scientists, and other experts reported their own experiences and analyses during the GEJE. Compiling and systemizing these fragmented stories is a necessary step to improving the resiliency of our society.

This paper presents a comprehensive outline of experiences of and lessons learned from the GEJE from the viewpoint of demand-side resiliency. Damage to power systems and power supply capability through power source loss, best practices (including microgrids), and post-disaster responses and lessons learned are all covered. The experiences of the rolling blackouts and electricity saving campaign showed that the influence of a natural disaster can last for a long time. This led to a greater focus on demand-side resiliency, including such measures as backup systems, microgrids, and demand responses for peak reduction. The lasting influence of the GEJE is apparent not only in current energy policies, but also in the research that is being done by power engineers.

II. RECAP OF THE GREAT EAST JAPAN EARTHQUAKE

A. The Great East Japan Earthquake

The GEJE, also known as "the 2011 Earthquake off the Pacific Coast of Tohoku," occurred at 14:46 JST (05:46 UTC) on Friday, March 11, 2011 [8]. The magnitude of 9.0 was extremely large. It triggered a tsunami with a catastrophic impact. The epicenter was located approximately 70 km from the coastline, and the hypocenter depth was shallow at 24 km. The Japan Meteorological Agency (JMA) measured a maximum seismic intensity scale of 7, indicating that the earthquake had a much greater impact than expected. The intense shake continued for 120–190 s [9]. The measured maximum height of the tsunami was at least 9.3 m along the coastline of Fukushima Prefecture [10].

The affected area was familiar with large earthquakes and tsunamis, as earthquakes with a magnitude of 7.0–7.5 strike around every 30–40 years. However, the GEJE was much larger than normal. There were a number of aftershocks, which made rescue and recovery efforts more challenging. In total, 13 000 aftershocks, including six with a magnitude of 7.0 and 102 with a magnitude of 6.0, had been counted by the JMA as of July 2016 [8].

More than a million residential dwellings and 56 000 other buildings were damaged; the number of confirmed deaths was 15 894, and 2558 are still missing [11]. The total area flooded was 561 km^2 [12] [13] [14]. More than 100 000 dwellings were swept away by the tsunami. Debris smashed into buildings, destroyed oil tanks, and started fires. Electricity services for 8.7 million customers [15], city gas for 0.46 million [16], [17], and city water for 2.3 million [18] were interrupted.

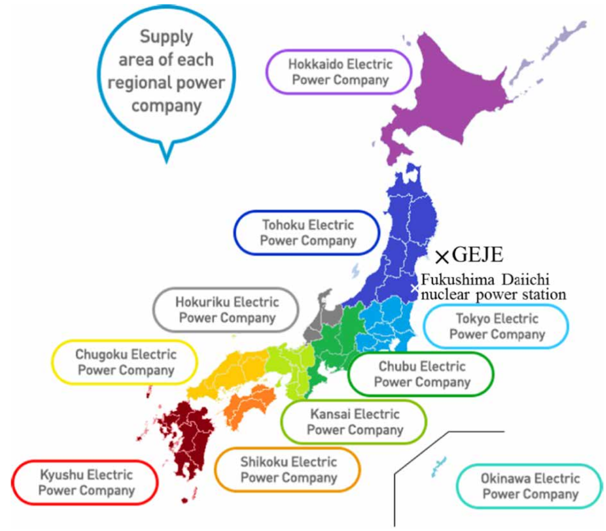

Fig. 1. *Service areas of power companies (adapted from [21] with modifications).*

B. Damage to Power Systems

There are ten major electric utilities (Hokkaido, Tohoku, Tokyo, Hokuriku, Chubu, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa) in Japan, as shown in Fig. 1. Each utility is fairly dominant in its own geographic area and is responsible for all power generation, transmission, and distribution; they have constructed secure and independent power systems in their own service areas. Their power systems are interconnected using limited-capacity lines [(alternating current (ac) or direct current (dc)]. It should be noted that the power systems of eastern and western Japan operate at 50 and 60 Hz, respectively [19]. These two grids are interconnected via frequency conversion stations with a total capacity of 1035 MW (as of March 2011; this increased to 1200 MW in February 2013). Peak demand was approximately 178 GW in 2010 [20]. In the 2010 fiscal year, the total generation capacity of the ten utilities was 207 GW, including 35 GW of hydropower, 124 GW of thermal, 46 GW of nuclear, and 2 GW from other types of generation; they supplied 906 PWh that year.

Most of the damage caused by the GEJE occurred in the Tohoku region and the northern part of the Kanto region. Tohoku is a service area of the Tohoku Electric Power Company (ToPo), whose peak demand was 15.6 GW before the GEJE. The Tokyo Electric Power Company (TEPCO), which supplies electricity to the Kanto region, is the largest utility in Japan. Its pre-quake peak demand was 60.0 GW [20]. Profiles of ToPo and TEPCO can be found in Table 1.

When the GEJE hit Japan, 60% of ToPo's power demand (7.9 GW) and one-third (12.8 GW) of TEPCO's disappeared [22]. In ToPo's service area, substations near the coastline were destroyed by debris from the tsunami, and there was seismic damage to the inland substations. Short circuits and ground faults affected a substation and

Table 1 Profiles of ToPo and TEPCO (Based on [20]) As of the Fiscal Year 2010 (April 2010-March 2011)

Item	ToPo	TEPCO
Service area (1000 km^2)	79.5	39.5
Generation capacity (GW)		
Total	17.2	65.0
Hydro	2.4	9.0
Thermal	11.3	38.7
Nuclear	3.3	17.3
Supplied electricity		
Total (TWh)	82.7	293.4
Peak (GW)	15.6	60.0
No. of customers (million)		
Total	7.4	28.7
Residential	4.6	20.0
Revenue (trillion JPY)[1]	1.33	4.80

[1] Only income from electricity sales to general customers is listed. A small portion of electricity was sold to other utilities, but this is excluded here.

a 270-kV transmission cable in the Miyagi Prefecture. The isolation of the facilities divided ToPo's grid between the northern and southern areas. The supply–demand balance became unstable and frequency and voltage decreased, causing service interruptions in the northern area [23].

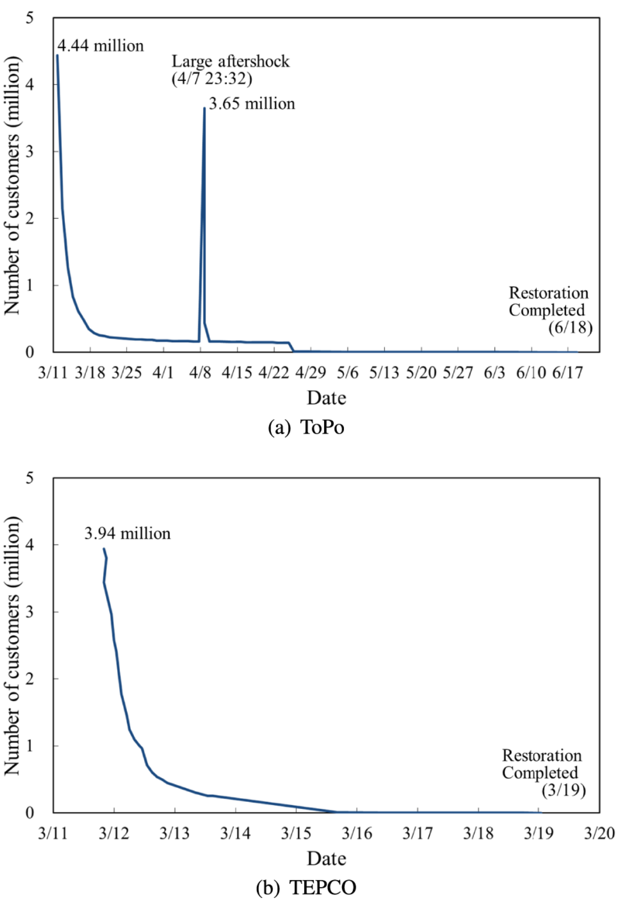

Fig. 2. ***Service interruption and restoration (source: [24], [25]).***

In total, 4.5 and 4 million residential customers, respectively, who relied on ToPo and TEPCO lost power. Recovery efforts began immediately, as shown in Fig. 2. TEPCO restored the power supply to most customers within 24 h. Although the damage to ToPo's power system was significant, they resumed service to approximately 90% of customers within a week. Note that some of ToPo's customers disappeared because the area was devastated by the tsunami. Another large earthquake hit the Tohoku region on April 7 and caused another service interruption.

Table 2 summarizes the damage the GEJE caused to the power systems of ToPo and TEPCO. Entire power systems suffered damage. Quite a number of distribution poles were destroyed (underground distribution cables are not common in Japan, except in urban centers). The effects of the tsunami were much more severe than those of the earthquake, and they lasted longer.

The damage to some thermal power stations was significant. A quarter of ToPo's plants were destroyed. Three thermal power stations—located on the coastlines of Haramachi, Sendai, and Shin-Sendai, with a total generation capacity of 3.4 GW—were flooded by the tsunami, leaving equipment submerged in seawater. Recovery of these plants took one to two years. Haramachi Plant was hit by the tsunami at a maximum height of 18 m [26], [27]. An emergency operation panel on the second floor was submerged, making it impossible to start the emergency generator on the third floor. Auxiliary equipment, such as coal handling facilities and bug filters, was destroyed [28], either by the seismic impact [29] or debris.

The greatest damage to the Japanese power system took place at Fukushima Daiichi Nuclear Power Station. The plant consists of six reactors, with a total generation capacity of 4.7 GW. When it was rocked by the earthquake, the emergency shutdown process was conducted automatically on reactor units 1–3, which were in operation at the time. The plant lost its external power supply due to the failure of the electrical facilities. Backup generators started, but failed (with the exception of unit no. 6) after they were flooded by the tsunami (at 14 m), and the plant completely lost power. Finally, the reactors lost their cooling systems and a meltdown and explosion occurred. Radioactive material scattered over a wide area [30], [31].

Table 2 Damage to Power Systems [15]

	ToPo		TEPCO	
	Damage cases (No. of facilities)	Percentage (damage / total)	Damage cases (No. of facilities)	Percentage (damage / total)
Thermal power plants	5 (20)	25%	14 (81)	17%
Substations	30 (1712)	1.8%	17 (2997)	0.57%
Overhead transmission systems	46 (28 205)	0.16%	15 (30 555)	0.05%
Underground transmission systems	20 (472)	4.2%	30 (3714)	0.81%
Distribution systems	36 048 (3 038 915)	1.2%	14 288 (5 818 237)	0.25%

Onagawa nuclear power station, which is located 120 km northeast of Fukushima Daiichi, was also hit by the tsunami (at 13 m) [32]. The station was 14.8 m above sea level, but was lowered 1 m by ground subsidence caused by the earthquake. However, it avoided catastrophic flooding. Only one of five power-receiving feeders remained functioning [33]. Most of the backup generators of units 1 and 2 failed.

There was considerable damage due to substations' circuit breakers and disconnectors, oil leakage from transformer bushings, and more. Other substations came through the disaster mostly intact. A substation in Hachinohe City was seen to be at risk of flood, and important equipment, such as gas-insulated switchgear, was elevated before the GEJE. The substation was not damaged by the tsunami with height of 1.6 m.

C. Damage to City Gas Supply Infrastructures

Electric utilities do not supply gas or water in Japan. Instead, critical lifelines such as electricity, gas, and water are supplied by various other utilities.

In contrast to electricity, the city gas supply is limited to urban areas and most gas utilities are small to medium scale. In total, 211 utilities supplied gas to 28.9 million customers as of 2010 [34]. The GEJE affected the service area of 16 gas utilities. Long-distance pipelines are not well developed in Japan, since the country does not produce natural gas and instead imports it as liquefied natural gas (LNG), which is stored in shore-side tanks. The largest utility, Tokyo Gas, used 10.1 Mton of LNG to supply cities in the 2010 fiscal year, while TEPCO used 19.5 Mton of LNG for power generation.

After the GEJE, the city gas supply for 0.46 million customers was interrupted [18] and took 54 days to be restored [16]. Gas utilities dispatched engineers to restore the supply. A maximum of 4100 engineers from other utilities were engaged per day, and around 100 000 engineers participated in restoration efforts in total [35].

In Sendai, the largest city in Tohoku, an LNG plant located near the coastline was severely damaged. LNG tanks were not damaged, but other facilities, such as the electrical system, instrumental system, and vaporizers were damaged by the tsunami's debris. The first floor was submerged by 1.8 or 2.0 m of water [16]. Since recovery was expected to take a long period of time, natural gas from another company in Niigata was supplied via a pipeline [36], [37]. Restoration of the natural gas supply in Sendai began 11 days after the GEJE. Natural gas from Niigata was also supplied to neighboring utilities. It ended up taking nine months to restore the city gas supply [36]. Vehicles with LNG tanks were dispatched to critical facilities, such as hospitals.

The natural gas distribution network was also damaged. Luckily, high-pressure pipes, which were securely installed, were not damaged at all over their total length of 948 km. However, medium-pressure pipes received minor damage at 22 points over 12 549 km, though operation was not interrupted. Low-pressure pipes, which supplied gas to residential or small customers, were damaged at approximately 670 points over a length of 82 936 km. Damage to distribution pipes inside customer buildings reached approximately 7000 cases [16].

D. Loss of Power Sources and Subsequent Power Shortages

Fig. 3 shows the daily maximum electricity supply by ToPo and TEPCO for 2010 and 2011. The power supply by both utilities has significantly decreased since the GEJE. The summer peak demands on TEPCO went from 60.0 GW in 2010 to 51.5 GW in 2011, a 14% drop. For ToPo, summer peak demand fell by 20%.

There are two major reasons for the reduction in the electricity supply: 1) the unavailability of power stations immediately after the GEJE; and 2) the shutdown of nuclear power stations. Both ToPo and TEPCO lost a significant portion of their electricity supply capability after the GEJE. The situation was more severe for TEPCO than ToPo in March. On March 11, 2011, the day before the GEJE, TEPCO's electricity supply capability was 52 GW, dropping to 35 GW the day after [38]. TEPCO's shortage

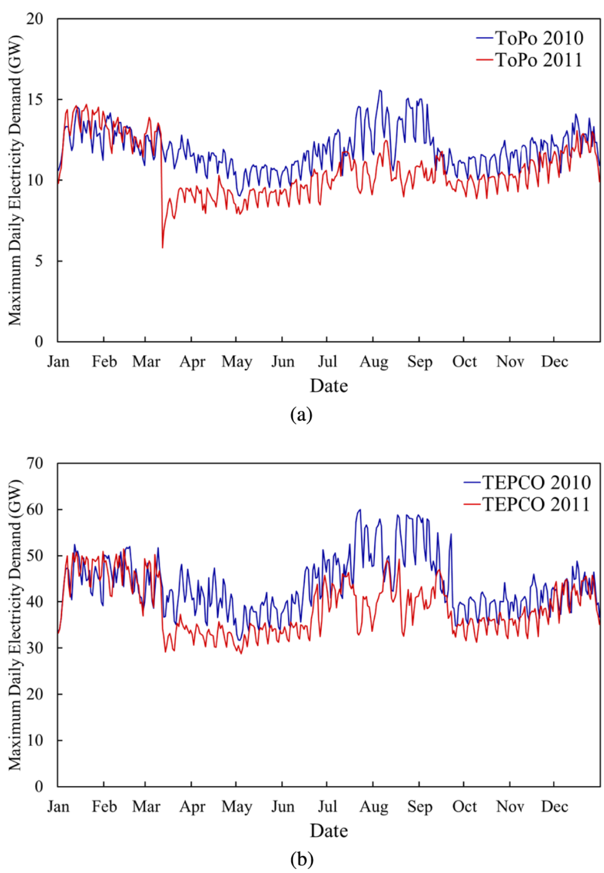

Fig. 3. ***Daily maximum electricity supply in 2010 and 2011. (a) ToPo. (b) TEPCO.***

was resolved by early April, as more than 40 GW of power became available.

TEPCO decided to carry out rolling blackouts for the first time in its history on Monday, March 14. It was obvious that TEPCO lacked the capability to meet all demand, and demand curtailment in any form was needed to avoid a large-scale blackout. Customers in its service area were divided into five groups of two to three million customers with a demand of 5 GW each, excluding the central part of Tokyo and areas affected by the GEJE, and each group was assigned a 3-h window from 6:20 to 22:00 [39], [40]. When supply and demand fell out of balance, service for the assigned group was interrupted. The first blackout was carried out for 1.5 h on the evening of Monday, March 14, when residential heating demands increased. Rolling blackouts were conducted during ten days between March 14 and 28 [38]. The influence of these rolling blackouts was significant: many workers and students could not reach their offices or schools because train services decreased by 30%–50% [41], traffic signals were turned off, etc.

The number of nuclear power stations in operation decreased gradually after the GEJE. They were not required to shut down immediately, but they could not restart once regular maintenance and inspection (which is mandatory every 13 months) began. Then, all nuclear power stations ceased operation in July 2012.

Fig. 4 shows the change in Japan's generation mix from fiscal years 2010 to 2012. Nuclear generation was replaced with thermal plants. Power companies restarted thermal plants and even restored some old ones. The power supply capability of TEPCO recovered to 56.7 GW in August, while expected peak demand was 55.0 GW [42], and actual peak demand was 51.5 GW. The supply–demand balance for ToPo was harder to maintain over the summer, as damaged power stations in Sendai could not be recovered. TEPCO sent a maximum of 1.7 GW of electricity via interconnection lines to ToPo, whose peak demand was expected to be 12.9 GW in August [23].

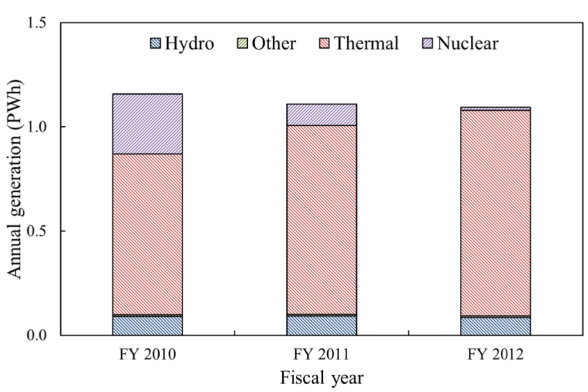

Fig. 4. ***Change in generation mix in fiscal years 2010–2012 (source: [43], [44]) . Note: A fiscal year runs from April through March.***

Power saving became an important topic nationwide [45]. The target for reductions in electricity demand was set at 15% in the service areas of TEPCO and ToPo [46] and 10% in western Japan [47]. The reduction target was achieved. According to a survey by Kimura and Nishio, large factories cooperated with the reduction demand by installing onsite generators or shifting operation to off-peak hours, which increased operating costs. The commercial sector reduced its use of lighting and air conditioning [48]. Households also adopted measures to reduce consumption, such as reducing lighting and air conditioning or unplugging unused devices, and achieved a 17% reduction [49]. However, because of the reduced use of air conditioners, the risk of heat stroke was a concern [50].

E. Damage to Customer Facilities

The resiliency of the electrical facilities of customer buildings is also important from a demand-side resiliency viewpoint. Customers cannot use electricity if their electrical facilities are impaired, even if the power supply from the utility is not interrupted. Damage to electrical facilities was the most common form of damage in customer buildings [51]. Lighting systems, power-receiving systems, electrical panels, and cables were all affected [52].

Semiconductor production facilities require reliable and high-quality electrical power. Since power interruption, including a voltage drop for a couple of cycles causes significant financial damage, many semiconductor production facilities are equipped with backup systems, such as an uninterruptible power supply (UPS) or generators [53]. However, the electrical facilities of one semiconductor production facility were destroyed by the GEJE [54]. In this case, the production facility could not use electricity even after the utility restored the power supply.

III. BEST PRACTICES LEARNED FROM THE GEJE EXPERIENCE

A. Data Centers

According to a survey by the Green Grid, only 1% of data centers were damaged by the GEJE, while 16% were influenced by rolling blackouts due to the power supply problems that followed [55]. Cases of falling PC server racks were reported as physical damage, but no service interruption occurred.

The data centers were designed and constructed to comply with the Data Center Facility Standard (DCFS) [56]. The DCFS was developed by the Japanese Data Center Council, based on the TIA-942 Standard [57], which is widely used around the world and classifies data centers from Tier 1 to 4 based on their required power supply reliability (Tier 4 ensures the highest reliability). Requirements for associated electrical equipment—such as transformer buildings, security, air conditioning, and communication systems—are also defined to ensure power availability.

One of the most important lessons from the data center case is that the DCFS provides multiple options to improve demand-side resiliency. These improvements carry a heavy monetary cost, but enacting them highly reduces the risk of business interruption. There is a tradeoff between investment cost and resiliency. By categorizing resiliency by Tier levels, business operators have a better understanding of their level of resiliency. They can consult tables that show Tier levels versus cost. Thus, categorization supports the decision making of business operators and encourages investment in improving resiliency.

B. Ishinomaki Red Cross Hospital

Ishinomaki Red Cross Hospital (IRCH) was one of the disaster response base hospitals in Miyagi Prefecture, and the only hospital in the affected service area that continued normal service at the time of the GEJE [58]. It is located in Ishinomaki City and provides medical services to 220 000 people in local and neighboring municipalities. Among the 86 medical facilities in the service area, IRCH is the only disaster response base hospital. The seven-story building is approximately 70 000 m^2 and has 402 beds. As of 2009, 80 medical doctors and 382 nurses and other staff were working there, and it accepted 371 inpatients and 893 outpatients per day. IRCH moved to its present location when the original building became too old to safely use. The new building, constructed in 2006, was designed and constructed with earthquakes in mind. The structure is seismically isolated with dampers. Oil-fired backup generators (625 kVA each) [59] with 20 kL of fuel storage (enough for three days' operation) were installed. Two types of water tanks were installed: clean water, which can be used for artificial dialysis (190 tons; enough for a half day), and general water (470 tons; enough for three days) [60]. A helipad is located on the ground, where there is no risk of losing access if the elevators fail [61].

When the GEJE hit IRCH, the power supply from ToPo was lost. The backup generators started, and the power supply to critical loads was quickly restored. The quakes continued for a couple of minutes. IRCH switched to a "level 3" formation, which interrupted all normal services and redirected all resources to disaster response [62]. As an alternative to high-tech medical equipment, which is fragile and needs electricity to operate, low-tech equipment was prepared in case of disaster. (Some high-tech equipment was broken during the quakes and subsequent power outages.)

Nobody at IRCH knew when the power supply from ToPo would resume, or when the fuel tanks of the backup generators would be refueled. What they did know was that they had enough fuel for three days and they would not have electricity after it ran out. The power supply resumed two days after the GEJE. A tank truck came to refuel the backup generator on the same day. While engineers from ToPo and the power industry worked hard to restore the power supply to support medical services, the oil industry worked to refuel the tank to keep the backup generator running.

After their power supply is restored, elevators cannot be used until a safety check is completed. At IRCH, the engineers conducting the safety check were also citizens, and would have been in a difficult situation if a disaster occurred. Almost all elevators in the affected areas required safety checks. The safety check at IRCH was completed two days after the GEJE.

As the electricity supply and other infrastructure elements remained limited, to continue operating it was also necessary to reduce the load. Patients who needed artificial dialysis were transported to another hospital in Yamagata Prefecture, where damage from the GEJE was relatively minor.

The operational continuity of hospitals depends on other infrastructure than electricity: gas, tap water, sewage, telecommunications, etc. IRCH's city gas supply—used for boilers, sterilizers, and cooking—was interrupted. Meals for patients are usually cooked in gas ovens, but electric cookware had to be used to prepare meals instead. The lack of sterilization equipment meant it was a challenge to maintain hygiene standards. There was an inadequate stock of disposable products such as paper towels. A mobile LNG supply facility, a vehicle with an attached LNG tank, arrived and supplied gas about two weeks later, until the city gas supply resumed.

C. Sendai Microgrid

The microgrid on the campus of the Tohoku Fukushi University in Sendai is already the subject of many articles and presentations [63], [64], [65]. It was developed by NTT Facilities as part of a demonstration project operated by the New Energy and Industrial Technology Development Organization, (NEDO), originally founded by the Ministry of Economy, Trade and Industry (METI). The main subject of the demonstration is multiple power quality services, including dc [7]. The installed distributed energy resources (DERs) include a photovoltaic generation system (50 kW), natural gas-fired engines (350 kW× 2), a molten carbonate fuel cell (250 kW), and battery energy storage (250 kWh). The microgrid is usually connected to the ToPo grid, and can be disconnected when there is a power outage while continuing to supply power to important loads through DER.

The power supply to critical loads was not interrupted at the time of the GEJE, thanks to photovoltaic generation and battery storage. However, battery storage was later discontinued due to safety concerns. Unfortunately, the gas engines ceased functioning when the utility grid failed, because abnormal voltage was detected. They were manually restarted the next day and continued to supply important loads until full service was restored three days later. The natural gas supply via medium-pressure pipelines, which are very secure, was not interrupted.

D. Roppongi Hills

Opened in 2003, Roppongi Hills is a complex consisting of offices, restaurants, residential space, and more located in central Tokyo. It occupies a geographical area of 84 800 m^2, with a total floor area of 724 500 m^2 [7]. Its energy system includes natural gas-fired turbine generators (6360 kW× 6), a steam turbine generator (500 kW), absorption chillers (73 340 kW), steam boilers (79.6 t/h), and exhaust heat boilers (77.76 t/h) [53], [66]. All of the energy demands (i.e., electricity and cooling and heating) of the complex and adjacent buildings are met by the complex's energy system.

The electrical system is usually operated in parallel mode, but can be switched to independent mode if the utility grid fails. While the system can be independent from the external grid, it is dependent on the natural gas supply. Natural gas is delivered via a medium-pressure pipeline that is configured in a loop to improve reliability. In addition to the natural gas-fired generators, a kerosene-fueled generation system was also installed in case of emergency.

The system proved its high reliability by meeting all energy demands after the GEJE, while surrounding buildings were suffering rolling blackouts. In fact, Roppongi Hills actually supplied its excess electricity to TEPCO [67], [68].

IV. LESSONS LEARNED FROM THE GREAT EAST JAPAN EARTHQUAKE

A. Review of Preparedness and Responses After the Great Earthquake in 1995

The METI reviewed the damage to the power system caused by the GEJE and tsunami and discussed countermeasures [15]. They also reviewed the damage caused by the Great Hanshin-Awaji Earthquake (Kobe Earthquake) that hit Kobe City and neighboring areas on January 17, 1995 and killed more than 6400 people [69]. The working group concluded that the policies implemented after the Kobe Earthquake were mostly appropriate and further revisions were not needed. However, there were no tsunamis after the Kobe Earthquake; therefore, measures against tsunami damage had never been discussed. Since complete protection against tsunamis is challenging, redundancy or fast restoration are emphasized. Preparation of cranes or bulldozers to clean up debris may also be effective. Technological innovations can help in the restoration efforts. After the GEJE, GPS navigation systems guided engineers to damaged distribution poles, as the locations of the poles were registered as GPS coordinates. Many engineers from other utilities joined the restoration effort to support ToPo. The use of helicopters to check transmission systems was effective; drones or unmanned aircrafts are expected be used in the future. Satellite pictures from the internet, including Google Maps, were also effective ways to investigate the damage.

B. Business Continuity Plans

The Japanese government, electric and gas utilities, and other stakeholders reviewed the damage to their own facilities and businesses. Although the power outages had critical impact, the lack of an electricity supply has not been seriously considered in the implementation of business continuity plans (BCPs). This is despite the fact that power shortages negatively affected business operations nationwide; the impact was not limited to disaster-affected areas. According to a government survey, power outages were the most influential factor on business continuity [30]. This was confirmed by another survey [70]. The Council on Competitiveness-Nippon (COCN), a group of top Japanese enterprises, established a working group to study "Resilient Economy" in 2011 and 2012 [71]. The report emphasized that backup systems or "independent energy systems" with DER such as microgrids can improve the resilience of demand-side energy continuity. The report also mentioned the potential benefits of a smart community that successfully shares electricity among consumers. The government revised the BCP Guidelines in August 2013 in response to the recommendations of the COCN's working group. The interruption of the supply chain, including electricity continuity, needs to be considered regarding BCP, as the report indicated "the importance of including broad responses to risks and consideration of the supply chain, etc., and indication of the necessity of a flexible business continuity strategy for handling such risks" [72] (Fig. 5).

Backup generators, batteries and photovoltaic generation, management systems, and other DER measures can improve resiliency. A microgrid can continue to supply power in independent mode when the power supply from the external grid is discontinued. However, even if a microgrid is installed, it is important to consider how to share limited power resources with other consumers. For example, if there is a complex that consists of offices, cafes, banks, and clinics with a peak load of 1 MW and a 500-kW backup generator, how do tenants share the power supply in case

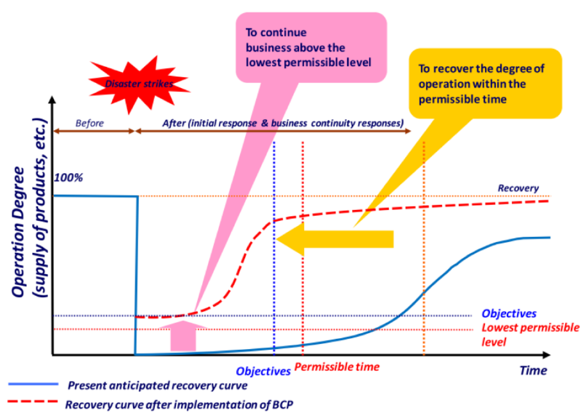

Fig. 5. *Concept of a business continuity plan [72].*

of a blackout? Should the clinics be given priority? What if the offices have PC servers that are critical for their business continuity and the security of their information?

C. Penetration of Onsite Generation Systems

After the GEJE, backup systems, including onsite generators, were recognized as crucial to improving the resilience of business operators. Battery systems or emergency generators can continue to supply power in the short term in cases of a power outage. Onsite generators, operated in parallel mode, can be used as long as fuel is available and can reduce the effects of a power shortage. However, it is not easy to economically justify backup systems.

Nevertheless, the installation of onsite generation increased after the GEJE [73]. Unfortunately, a complete survey or statistics on the penetration of backup systems are not available. The installation of combined heat and power systems (CHPs) increased in the 1990s and peaked in 2004 with approximately 1300 installations, then decreased year by year as the price of natural gas increased. In 2010, only around 200 systems were installed per year. After the GEJE, the number of installations significantly increased: approximately 900 units were installed per year from 2012 to 2014 [32]. The decrease in the price of fuel and increase in the price of electricity meant there was a slight economic justification for onsite generation. The METI initiated a subsidization program for onsite generation that financially supported installation and fuel costs. This program not only supported the installation of new systems, but also retrofitting costs for previously closed-down systems. Between 25% and 50% of costs were subsidized [74]. The program was intended to reduce peak electricity demand in the service areas of utilities whose supply capability was considered insufficient.

Backup generators have two constraints: generation capacity is limited and does not cover all loads and fuel storage is limited. When the power supply from the external grid is interrupted by a large disaster, nobody can be sure when it will resume and fuel for backup generators is limited. Important loads that require backup power are usually connected to a different bus. Power outlets for important equipment should also be clearly distinguished from normal outlets. If the total demand exceeds the generation capacity, a blackout occurs. Prioritization or categorization of loads based on importance is essential when utilizing backup power.

D. Smart Community Projects

Resilience in the face of natural disasters has become an important value in Japanese society. In particular, electricity continuity is critical in the disaster response process. The Japanese government initiated subsidization programs to encourage municipalities to improve their electricity continuity. The government also funded smart community projects in the Tohoku region to encourage the construction of more resilient and smarter communities [75]. The Ministry of Land, Infrastructure, Transport and Tourism (MILT) subsidized the installation of battery, photovoltaic, and gas/diesel generation systems in disaster response bases such as public buildings, hospitals, and schools to be used as shelters [76]. The Ministry of Environment subsidized the installation of microgrid systems, which improve energy resiliency and reduce carbon footprints through renewable energy [77], [78]. The METI also has a subsidization program for smart communities. Ishinomaki City in Miyagi Prefecture initiated the "Eco-safety Town Project" with funding from METI. The project aims to improve electricity continuity in cases of emergency and energy saving through the installation of photovoltaic generation and battery systems in public facilities that will be used as disaster response bases. The municipal government, Toshiba, and ToPo collaborated on the planning, design, construction, and operation. Energy management systems were installed in residential dwellings, commercial facilities, and public facilities such as schools [79]. A photovoltaic generation system (300 kW) has a Li-ion battery (360 kW/120 kWh) and is controlled to compensate for fluctuations in output and reduced peak demand. The battery can also be used to supply electricity to streetlights in case of power outages [80], [81], [82].

E. Electricity Continuity for Medical Services

Medical services are one of the most important city services when a disaster occurs. In addition to the strength of building structures, infrastructure including electricity, gas, water, and fuel is critical to maintaining the function of hospitals. Two thirds of the 33 disaster response base hospitals in the Tohoku region needed to limit the number of patients they accepted during the GEJE [83].

After the GEJE, multiple stakeholders discussed and reviewed the lessons from the GEJE, including that of IRCH, and subsequently revised the design guidelines for medical facilities [84]. However, it should be noted that most engineering resources are used for purposes other than electricity continuity, since hospitals have many unique equipment and facilities; e.g., only a single page was dedicated to electricity continuity in a 240-page document on BCP in hospitals [85].

Although most hospitals in Japan, including disaster response base hospitals, are privately owned and experience financial challenges, the review of backup systems can be expected to rise. The Ministry of Health, Labour and Welfare financially supported the implementation of these systems through subsidization, and the MILT initiated a funding program to subsidize municipal governments for half of the costs of disaster response facilities, including backup generators and batteries for disaster response base hospitals [76].

F. Market Development of Office Buildings to Support Business Continuity Plan

After the rolling blackouts and electricity saving campaign, business continuity and electricity resiliency became important values for business operators and citizens. Office buildings with systems intended to improve business continuity, such as backup systems, began to be recognized as having extra value. Shimizu Corporation, a major Japanese construction firm, began to promote "eco-BCP," which aims to increase electricity continuity and reduce carbon footprints through the installation of CHP and energy-saving technologies such as LED lighting [86]. Tokyo Gas, the largest gas utility in Japan involved in the development of Roppongi Hills, joined a renovation project in Tamachi, Tokyo. A fuel cell CHP, natural gas-fired generators, solar thermal water heaters, and natural gas-fired boilers and chillers will be installed and will supply electricity and heat to adjacent facilities, including a hospital in case of a blackout [87].

G. Demand Response as a Countermeasure Against Power Loss

The importance of demand response, which was previously not seen to be realistic in Japan, attracted attention after the rolling blackouts and the electricity saving campaign in summer 2011 [88]. Demand response became an important element of smart community demonstration projects, which were founded by METI and conducted in Yokohama, Toyota, Keihanna, and Kita-kyushu from 2011 to 2014. Demand response was tested with citizens' involvement and the potential of peak reduction was quantitatively evaluated [89] [90]. One of the issues in the implementation was that customers did not obtain any monetary incentive for the institution of demand response. The government decided to establish a "negawatt" market that rewards demand reduction by customers when electricity supply and demand are out of balance; it should be ready by April 1, 2017 [91], [92].

H. Contribution to International Standardization

Japan has been leading the international standardization of resiliency. The Microgrids for Disaster Preparedness and Recovery Project (MDR Project) was established by the Market Strategy Board (MSB) of the International Electrotechnical Committee (IEC) in 2012. The MSB identified the principal technological trends and market needs in the IEC's fields of activity, utilizing 15 top-level technology officers. The project studied the possible contribution of international standardization to improving disaster preparedness and recovery throughout the world. The MDR Project was proposed and led by Japanese experts.

The project covered electricity continuity to consumers during disasters and resilience improvement, especially on the demand side, was also discussed. The project proposed an electricity continuity plan and system (ECP and ECS, respectively), as well as ranking and classifying of the importance of loads [53]. Assessment of the possible type and scale of disasters, and the accompanying damage, is necessary to develop an ECP. Facilities and loads such as lighting, PC servers, and medical equipment should be categorized by importance or priority from the viewpoint of business continuity. Then, strategies on how to protect those facilities and loads from damage and maintain their electricity supply should be developed. Metrics on the importance of loads or facilities and resiliency are needed to encourage investment in ECS features, such as backup systems. The metrics would support business operators' decision making by enabling quantitative analyses of the tradeoff between investment (the cost of ECS) and return (improved resiliency).

Following the MDR Project, the discussion continued in the working group on City Service Continuity of System Evaluation Group 1 (SEG1: Smart Cities). The author served as the leader. The discussions and feasibility studies on the international standardization of demand-side resilience from the viewpoint of city service continuity were conducted conjointly by international experts [93].

V. EXPERIENCE OF A FLOOD IN JOSO IN 2015

Heavy rain by a typhoon caused the Kinugawa River to flood on September 10, 2015 [94], [95]. The Kinugawa River flows from Nikko in Tochigi Prefecture and travels through various provinces for 180 km before merging with the Tonegawa River and continuing on to the Pacific Ocean. Considerable damage was caused; for example, a hydraulic power station failed at the headstream. The most severe damage, however, happened near the middle of the river.

Joso City is located 50 km northeast of Tokyo, with a population of 64 000 and an area of 124 km^2; it is a typical municipality, with many rice fields. The flow level of the river increased the day before the flood, and the water ran over the banks at noon on September 10. The flood area expanded over a short period of time, and at the peak of the floods, one third of the city, or 40 km^2, was covered with water. Approximately 7000 people, including those from an adjacent city, were evacuated to shelters. The power supply for 11 200 households and tap water supply for 11 800 households were interrupted [96]. There was no city gas supply in the area.

In 2009, Joso City had distributed hazard maps to all households that showed the area expected to be affected during a flood [97]. The actual flood area matched the prediction well [98]. The city hall was expected to flood up to 2 m according to the hazard map, and this prediction was almost correct. Although flooding in the building was expected, the backup generator was installed on the ground; it failed and the city hall lost power during the emergency. Citizens evacuated their homes and moved to designated shelters, including the city hall. Those shelters were also flooded and not prepared. Many people lost their vehicles, which they left parked at the ground level.

The Fire and Disaster Management Agency of Japan surveyed the state of emergency generators in the 47 prefectures and 1741 local municipalities (cities, towns, and villages) after the flood in Joso [99]. It found that 265 local municipalities did not have emergency generators. Fuel tanks had less than 24 h capacity in half of the municipalities. Of the 1476 local municipalities with backup generators, 512 were at risk of flooding, similar to what happened in Joso, and 199 were not prepared for flooding at all. Therefore, 464 local municipalities (265+199), or a quarter of Japanese local municipalities, were at risk of a blackout in case of a flood, and 10% of all municipalities owned backup generators that would not work during a flood. Damage to electrical facilities caused by submersion can be seen in many natural disasters, such as Hurricane Sandy in the United States [100], so this must be taken into consideration.

VI. IMPROVING RESILIENCY THROUGH BACKUP SYSTEMS

Backup systems, such as backup generators or microgrids, are effective in improving demand-side resiliency, as proved in the example of the Sendai Microgrid. Though backup systems are commercially available, the largest challenge to large-scale implementation is the cost. Maximizing the cost benefit by fully utilizing limited capacity encourages the penetration. The real-life examples of backup systems and comprehensive simulations ensure that this is a valid way of preparing for disasters.

To encourage business to install backup systems, it is necessary to classify the importance of loads, develop management systems that can supply electricity to the loads according to the importance, and develop metrics to measure resilience. Backup systems incur additional cost. The system should cover important loads in order to maximize the cost benefit and fully utilize the system's limited capacity. Loads should be ranked or classified according to their importance. PC servers or life support equipment should be considered the most important, lighting should be considered less important, some elevators should be available (but not all), and smartphone chargers can be flexible. The total electricity demand must not exceed the capacity of the backup system, or it will fail. It is also necessary to develop a management system that controls the electricity supply and loads, because it is difficult to manually switch on/off power to the different loads. Quantitative analysis examining how backup and management systems improve resiliency is also necessary. These metrics enable a cost versus benefit analysis and support the decision making of business operators.

Case studies and comprehensive simulations are important tools to ensure disaster preparedness. In a natural disaster, two or more challenges often happen simultaneously (e.g., a flood and a blackout in Joso). A backup generator is effective during blackouts, but electrical systems must also be protected from the possibility of flooding. In Joso, measures against blackouts and floods were designed separately. To avoid such mistakes, case studies that examine various scenarios should be developed. Then simulations can be conducted to see if all measures, including equipment and operations, work effectively.

Other service interruptions—including city gas or tap water—also need to be taken into account. If the installed backup generator needs city gas as fuel or cooling water, any service interruption can be critical. A refueling plan is needed, including how to obtain the fuel and who will deliver it.

VII. CONCLUSION

This study comprehensively outlined and analyzed the experiences of and lessons learned from the GEJE from the viewpoint of demand-side resiliency. Damage to power systems and power supply capability through power source loss, best practices (including microgrids), post-disaster responses, and lessons learned were all discussed.

One of the lessons learned from the GEJE is that the influence of a natural disaster may last a long time and seriously affect a nation's economy; the damage to power stations, including Fukushima Daiichi, caused by the tsunami caused a lengthy power shortage in Japan. It is difficult to completely prepare for the destructive surge of a tsunami; however, the successful case of a substation in Hachinohe provides a good example. Preparedness against natural disasters by not only utilities' systems but also customers' facilities is important from the viewpoint of demand-side resiliency, so that customers can continue to conduct business after a disaster occurs.

Based on a review of the damage to power systems, this paper discussed countermeasures against tsunamis, focusing on redundancy and fast restoration. However, instituting a perfect form of protection against a tsunami is challenging.

The importance and effectiveness of onsite generation and microgrids to business continuity were recognized through best practices such as the Sendai Microgrid or IRCH. The installation of such systems increased after the GEJE. Since they are not easy to economically justify, financial support, such as subsidization by the government, is important. Fuel storage is a critical constraint of backup systems, and refueling strategies need to be considered. Sharing the limited power produced by onsite generation is also important to ensure electricity is provided to important loads when microgrids are operated in independent mode.

Recognition of the importance of electricity continuity for BCP led to the development of a new market for office buildings that have higher electricity continuity. Business continuity and electricity resiliency have become important values for business operators and citizens. Metrics on the importance of loads, facilities, and resiliency are needed to encourage investment in ECS by supporting the decision making of business operators and enabling quantitative analyses of the tradeoff between cost and resiliency improvement.

One of the byproducts of the power shortage in Japan was demand response. The electricity saving campaign forced business operators and citizens to opt into a demand response program manually. Demand response has been recognized as an important measure for peak reduction in a society that does not have enough power supply capability. This recognition and experience triggered the initiation of a "negawatt" market.

Many lessons can be learned from Japan's experience of the GEJE, and it can be seen that certain responses from stakeholders, including governments, business operators, engineers, educators, and citizens, are necessary to build more resilient societies and save lives.

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