

**White Paper**

# Microgrids for disaster preparedness and recovery

**With electricity continuity plans and systems**

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# Executive summary

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Despite the best efforts of electricity grid planners and operators, the number of major electrical blackouts around the world is growing year on year, whether caused by natural disaster or human triggered events. These blackouts often come at incredible cost to businesses and society at large – the recent Great East Japan Earthquake left up to 8 million people without power for over 10 days, and a cascading failure in 2012 in India left more than 9% of the world's population without electricity.

This White Paper considers preparation for, and recovering from, major electricity outages, with a focus on measures at the customer side of the electricity system. It is the fourth in a series of White Papers by the IEC MSB (Market Strategy Board), whose purpose is to ensure the IEC International Standards and Conformity Assessment services continue to contribute to solving global issues in electrotechnology.

Section 2 starts with a historical review of recent major electrical outages around the world. Out of a wide range of case studies, a key finding is that the centralized nature of power systems often means a relatively small amount of damage can cause extensive power outages. Whilst some electricity grids contain significant amounts of distributed generation, from roof-top solar systems to diesel back-up generators, often such systems were unable to operate following a major disaster, due to regulations restricting their operation when the wider power system had failed, or outside impacts such as a lack of fuel due to road blockages limiting re-supply trucks.

Section 3 focuses on planning for disasters, and the recovery from electrical outages. This section introduces BCP (business continuity planning), ECP (electricity continuity planning) and ECS (electricity

continuity system) as some of the solutions for disaster recovery, while examining how to verify the effectiveness of planning for electric continuity in the aftermath of disasters. The aim of this section is not to provide solutions to the particular challenges involved – an effort that will necessarily require the combined input of numerous organizations. Instead various broad concepts are introduced indicating how disaster preparedness and post-disaster recovery may benefit from standards and the design of plans for coordinated activity.

Section 4 offers an assessment of recent examples around facilities in Japan that maintained supply after major disaster, and refers to this as a “best practice” case. This ties together the microgrid section with the earlier planning sections. The studies include the Sendai microgrid in Japan, data centres, the Roppongi Hills (Tokyo) microgrid and an example from a Smart Energy home in Saitama, Japan. These examples from the Great East Japan Earthquake, reveal a number of microgrids, from supplying university campuses to single homes, were able to maintain supply even though the surrounding electricity network was inoperable for many days. Also examined are post evaluative references to telecommunication systems, medical facilities and semiconductor production facilities.

Section 5 explains that microgrids are a solution to many of the issues identified in the disaster review. A microgrid is a collection of controllable and physically close generators, managed in careful collaboration with local loads. By relying on a variety of generators, a microgrid system avoids many of the single-point-of-failure issues of the traditional electricity grid. Similarly, by closely managing local supply and demand, the microgrid can ensure that essential services are met, despite constraints that may exist on electricity supply. Whilst often viewed

as a means of encouraging the uptake of renewable energy, or addressing challenges of peak demand, microgrids can make a significant contribution to helping with disaster preparedness and recovery.

Section 6 talks about the penetration of microgrids and the fundamental challenges that need to be addressed before they become commonplace. Microgrids are not without their challenges, both technical and non-technical, and this White Paper considers a wide range of issues limiting microgrid uptake, from regulatory barriers to the deployment of distributed generation, to the technical challenges of operating a microgrid with a large amount of renewable energy.

Finally, Section 7 concludes with a number of key recommendations for industry, regulators, and standards organizations that should improve the preparation for, and recovery from, major disasters or electricity supply interruptions. Key suggestions are around encouraging the uptake and operation of microgrids, and, separately, implementing standards to assist the planning of disaster relief, and the comparison of these plans across different sites.

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### **Acknowledgments**

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# List of abbreviations

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## Technical and scientific terms

<b>AC</b>	Alternating current
<b>CHP</b>	Combined heat and power
<b>BCP</b>	Business continuity plan/planning
<b>DC</b>	Direct current
<b>DER</b>	Distributed energy resource
<b>ECP</b>	Electricity continuity plan/planning
<b>ECS</b>	Electricity continuity system
<b>EMS</b>	Energy management system
<b>HEMS</b>	Home energy management system
<b>MDR</b>	Microgrids for disaster preparedness and recovery
<b>MV</b>	Medium voltage
<b>PCC</b>	Point of common coupling
<b>PV</b>	Photovoltaic
<b>UPS</b>	Uninterruptible power supply

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## Organizations, institutions and companies

<b>AIST</b>	National Institute of Advanced Industrial Science and Technology (Japan)
<b>CEPRI</b>	China Electric Power Research Institute
<b>CSIRO</b>	CSIRO Commonwealth Scientific and Industrial Research Organisation (Australia)
<b>IEC</b>	International Electrotechnical Commission
<b>MSB</b>	Market Strategy Board (of the IEC)
<b>NEDO</b>	New Energy and Industrial Technology Development Organization (Japan)
<b>TEPCO</b>	Tokyo Electric Power Company (Japan)
<b>UL</b>	Underwriters Laboratories (USA)

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# Glossary

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**anti-islanding**

functionality in distributed generators preventing them from supplying electricity during loss of the wider electricity grid

NOTE A black-start is essentially a hard reset of generation resources.

**cascading failure**

chain of successive failures on a power system

NOTE Cascading failures are often associated with large, widespread system outages caused by relatively small, obscure failures in one small part of the network.

**combined heat and power****CHP**

servicing of both thermal and electrical loads from a single generation source, thereby increasing the energy efficiency of that source

**connected microgrid**

microgrid that may be connected to the utility grid

NOTE A connected microgrid may operate as a distinct island, but features a PCC that allows interaction with the utility grid (most typically to facilitate import/export of power).

**demand management**

active and dynamic control of electrical load through technical means in order to manage issues such as peak demand

**distributed energy resource****DER**

small-scale electrical load or generator (<1 MW)

**distributed generation**

electricity generation, often relatively small, located close to the particular load to which it supplies power

**distribution**

except when the standard dictionary definition applies, transfer of electricity between transmission supply points (typically substations) and individual customers

**embedded generation**

see local generator/load

**export**

<in the context of this White Paper>, flow of electrical power from the microgrid into the wider electricity network

**flywheel**

energy storage device based on high-speed rotating mass

**fuel cell**

energy conversion device that produces electricity directly from an input fuel and oxidant, without the combustion process of traditional reciprocating engines

**high voltage**

any voltage between 69 kV and 230 kV or having a value above a conventionally adopted limit

NOTE An example of high voltage is the set of upper voltage values used in bulk power systems.



**import**

<in the context of this White Paper>, when electrical power flows from the wider electricity grid into the microgrid

**intentional islanding**

deliberate separation of a set of generator resources from the utility grid

**intermittent**

non-continuous

NOTE An intermittent generation source in and of itself cannot provide a constant non-zero power output over the long-term.

**inverter**

power-electronics device that converts direct-current electricity to alternating-current electricity

**islanding**

separation of a set of generator resources from the utility grid

NOTE The microgrid is islanded if it loses the PCC.

**isolated microgrid**

microgrid that is not electrically connected to the utility grid

NOTE An isolated microgrid is a distinct island for which no PCC exists.

**load management**

see demand management

**load shedding**

deliberate deactivation of electrical loads, typically to prevent electrical network overload and outage

**local generator****local load**

generator/load installed on the microgrid

**medium voltage****MV**

any voltage between 2.4 kV and 34.5 kV or any set of voltage levels lying between low and high voltage

NOTE 1 The boundaries between medium and high voltage levels overlap and depend on local circumstances and history or common usage. Nevertheless the band 30 kV to 100 kV frequently contains the accepted boundary.

NOTE 2 The term is not used in the UK or Australia to refer to any voltage between 2.4 kV and 34.5 kV.

**microturbine**

small (<100 kW) low-emissions electricity generator based on gas-turbine technology

**microgrid**

collection of controllable and physically proximate distributed generator and load resources, incorporating multiple sources of AC power, at least one of which is based on a renewable energy source

**outage**

period when an electricity generator, transmission network or related resource is out of service

**peak demand**

maximum demand presented by an electrical load, typically infrequently, as opposed to the average demand of that load

**penetration level**

percentage contribution of power from a given source

**photovoltaics****PV**

technology that converts energy from the sun directly into electricity

**point of common coupling**

**PCC**

connection point between the utility grid and the microgrid. A microgrid may have at most one point of common coupling

**supercapacitor**

energy storage device that can provide large amounts of power for very short periods of time, with a longer lifecycle in this application than traditional batteries

**synchronization**

match phase/instantaneous voltage across or within systems

NOTE When returning from an island configuration, a microgrid must synchronize (often, resynchronize) with the utility grid.

**system stability**

capacity of a system to remain functional despite variation in operating conditions

NOTE An isolated microgrid displays stability if variations, for instance in load, do not cause the microgrid to shut down.

**transmission**

transfer of high-voltage electricity from where it is generated to the point at which it is transformed into a lower voltage for consumer supply

**utility grid**

**wider grid**

power network that resides beyond the control of the microgrid

NOTE A utility grid may be connected to the microgrid via a PCC or not at all.

**virtual microgrid**

microgrid where major components such as generators are geographically distant

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# Section 1

## Introduction

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### 1.1 Overview

Whilst recent natural disasters such as the Great East Japan Earthquake of 2011 caused horrific physical damage and loss of life, they also demonstrated the fragility of today's electricity systems. Major electricity outages around the world are growing in number and scope, bringing significant costs to local industry and the community. In the case of the recent Great East Japan Earthquake, over 8 million people were left without power, and it took 10 days to restore 95 % of the electricity supply to these customers. Another example of a significant outage was in India in 2012, which left more than 620 million people, or approximately 9 % of the world's population without electricity.

In response to these recent large-scale power outages, the IEC commissioned the present White Paper with a view to examining how best to maintain local electricity supplies after a large-scale blackout.

This White Paper considers the complex challenges involved in preparing for, and recovering from, major electricity outages, with particular focus on the "customer side" of the electricity system taken from experiences of the 2011 earthquake in Japan.

The first part of this White Paper considers non-technical issues, with reference to large unknown solutions between disasters and electric facilities; in particular, the challenge of classifying disasters and a facility's preparedness for major outside electricity and a facility's ability to cope with various magnitudes of power loss. Likewise the concept of an ECS and ECP are introduced as a critical precursor to ensuring a facility is best prepared to manage electricity outages.

Based on real experience, examples are given throughout the White Paper of best-practice methods for:

- Planning and assessing a facility's response to major disasters, and
- Recovering from disasters
- The use of new technologies such as microgrids to improve the resilience of electricity supply

The White Paper's principal focus is on one of the most recent major developments facing the electrical power industry: the concept of the "microgrid". Whilst often viewed as a means for encouraging the uptake of renewable energy or for managing peak demand challenges on the broader electricity system, microgrids have particular characteristics that can help with disaster preparedness and recovery, and these are explored throughout this White Paper.

### 1.2 Scope of this White Paper

This White Paper is the fourth in a series whose purpose is to ensure that the IEC can continue to contribute through its International Standards and Conformity Assessment services to solving global problems in electrotechnology. The White Papers are developed by the IEC MSB, responsible for analyzing and understanding the IEC's market, so as to help prepare the IEC to strategically face the future.

In response to the significant damage caused by the Great East Japan Earthquake on the 11<sup>th</sup> March 2011, a discussion of disaster recovery approaches was included in the IEC MSB meeting in Stockholm,

Sweden in June 2011. Following this, plans were put together for a project examining the opportunities and challenges microgrids may have for improving resilience against large-scale electrical disasters, or recovery from these. The proposal was based on the methods of the “Technology and Market Watch” special working group that published the IEC White Papers in the Electrical Energy Efficiency and Electrical Energy Storage projects.

Market needs are most important to the Microgrid for disaster recovery proposal, and new technologies will be developed. Among these are demand control, prioritization of loads, and further innovation for saving and storing electricity. Societal planning, investment in R&D, and standardization are also essential as seen in Figure 1-1.

That is, for base technologies, safety functions are required, and are a very important consideration in standardization activities.

All levels of society have a part to play in preparing for large-scale disasters and the subsequent recovery. As shown in Figure 1-2 various actors, ranging from public administrations to private companies and the end user, have a role in the planning of defences against major disasters and in developing responses to ensure rapid restoration of services. Consequently, this White Paper is aimed at a wide-ranging audience – from those who simply need to be aware of the latest technologies available for maintaining electricity supply following a major disaster, to the organizations charged with developing the standards necessary to realize these wider scale community benefits.

Improving the preparation and response to large-scale electrical outages is a broad and diverse area of activity, with efforts required in policy and law, regulation, standardization, and technology development. This project focussed on technical measures that may be taken towards improving

	Grid blackout	Microgrid	Recommendation
Most important needs	Recovery from disaster	Needs of ECP for disaster prevention	Police, law and regulation
Market forecast	Recovery of electric power grid	Enforcement of electricity facility	Policy for economical incentives
Technologies and forecast of commercialization	Robust smart grid	MDR technology reasonable price	R&D
Recommendation for standardization		Saving electricity demand control	Standardization time and requirement
		Robust facilities and appliances	

Figure 1-1 | Needs of MDR from market viewpoint

disaster response and resilience, with the aim of reviewing major recent disasters for the lessons that can be learnt, and examining the benefits new technologies such as microgrids could bring in this area. Throughout this White Paper, the focus is on the benefits such technology can provide to industry, as well as the challenges that may need to be addressed before such work can be implemented on a wider scale.

	<b>Responsibilities</b>		<b>Requirements</b>
<b>Public administration</b>	Community-wide disaster avoidance and response planning	→	An understanding of best practices and assessment of prevention plans for disaster resilience or recovery
<b>Standards organizations</b>	Development of standards to assist with disaster preparedness or recovery	→	Technical standards to ensure technical goals or benefits can be realized Classification standards to allow evaluation and comparison of disaster-preparedness strategies
<b>Private companies</b>	Company-specific disaster response planning	→	Plans to ensure business is appropriately prepared for major disasters and rapid recovery from disaster
	New products and technologies for disaster resilience or recovery	→	Products and technologies that can assist with disaster preparation or recovery, and that adhere to current technical standards to ensure maximum widespread benefit
<b>End users/ Consumers</b>	Education and training related to disaster preparedness and recovery	→	Detailed planning to minimize the impacts of a major disaster

**Figure 1-2 | Target audiences for this White Paper, and their needs**

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# Section 2

## Review of disasters connected with electrical facilities

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### 2.1 Analyzing previous disaster experiences

In considering the preparation for and effects of widespread electrical disasters, it is worthwhile reviewing recent major electricity outages: what exactly occurred and how the electricity supply was restored. Various nations have suffered enormous damage from natural disasters in recent years:

- The Great East Japan Earthquake on 11<sup>th</sup> March 2011 killed more than 15 000 people, destroyed 4 nuclear generation plants, and left several million people without electricity
- Numerous major industrial plants and business facilities were severely damaged by the floods in Thailand in 2011
- Hurricane Sandy killed 285 people in the USA, the Caribbean, and Canada in late October 2012, and left thousands without power

In all of these cases, in addition to the loss of life and general physical damage caused by the disaster, the effects on global commerce were a supplementary cost to society – from production interruptions at major factories to the cutting of global supply chains. Preparedness against disasters is no longer simply an issue for individual countries or regions, but has become a global issue. The risks from such disasters extend throughout the world.

This White Paper particularly focuses on major disasters that cause electrical outages. Earthquakes destroy transmission and distribution systems, including cables, towers and utility poles. Restoration of this infrastructure and the services it provides can take very long periods of time. Tsunamis, hurricanes and floods cause similar

damage to electrical facilities. Major pieces of infrastructure such as generators can be flooded or roads blocked, limiting delivery of fuel supplies to local generators. Electrical equipment belonging to consumers can be inundated with water, posing the risk of electrocution. In some regions, wild fires constitute the most severe threat to electricity transmission and distribution systems. In other regions the weight of ice from snowstorms can destroy transmission cables and towers.

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**Figure 2-1 | Ice damage to power line in China, 2008 [1]**

Major electrical outages do not just occur due to natural events such as earthquakes or storms. Often relatively minor incidents such as a small fire or a single downed transmission line trigger events that can cause cascading failures and result in widespread electrical failure, as happened in Italy in 2003 and India in 2012.





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**Figure 2-2 | Thailand floods, 2011 [2]**

A list of recent disasters that have caused major power supply loss is shown in Table 2-1. The table is not intended to comprehensively cover all the major electrical disasters around the world in recent times. Rather, Table 2-1 shows the diversity of disasters and their root cause, from natural disasters to human induced failures.



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**Figure 2-3 | Wildfires in Australia, 2009**

**Table 2-1 | Recent major electrical disasters, and their effects**

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<b>Date</b>	<b>Country/Region</b>	<b>Type of disaster/Cause</b>	<b>Impacts of disaster</b>
July 2012	India	Excessive heat (climate conditions) caused increased energy load. Loss of one transmission line caused a cascading failure. Continued demand problems exacerbated this failure over two days.	Over 620 million people lost power, requiring over 15 hours to restore 80 % of service.
October 2012	USA, East Coast	Hurricane Sandy	At least 285 people were killed across the US, the Caribbean, and Canada as a result of the storm.  The hurricane caused tens of billions of dollars in damage in the US, destroyed thousands of homes, and left millions without electric service for days.
July 2012	India	Cascading failure after 400 kV Bina-Gwalior line tripped.	The outage affected over 620 million people – about 9 % of the world population –, or half of India's population, spread across 22 states in Northern, Eastern, and Northeast India. An estimated 32 GW of generating capacity was taken offline in the outage.
July 2011	Thailand	Flood	450 people died. Widespread blackouts affecting 13 million people, some for up to 2 months.
April 2011	USA	Tornadoes (650 in total)	400 people died.  3 nuclear reactors were shut down.  Blackouts affected over 20 million people for up to 10 days.

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Review of disasters connected with electrical facilities

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<b>Date</b>	<b>Country/Region</b>	<b>Type of disaster/Cause</b>	<b>Impacts of disaster</b>
March 2011	East Japan	Earthquake and tsunami	More than 15 000 people died. 4 nuclear reactors were destroyed. Widespread blackouts affected more than 4 million homes, lasting 7 to 8 days.
January- March 2008	China	Winter snow and ice storms	129 people died, 1.66 million were relocated. About 36 000 power lines (10 kV and above) failed, 8 000 transmission towers (110 kV and above) collapsed, 2 000 substations failed.
April 2008	Western Europe	Power system operation poorly planned, resulting in cascading failure.	Widespread blackout affecting more than 5 million people for more than 2 hours.
August 2005	Indonesia	Cascading failure after one transmission line failed.	Widespread blackout, lasting approximately 7 hours, affecting 100 million people.
August 2005	USA	Hurricane Katrina	More than 1 800 people died. Estimated damage more than USD 108 billion.  Blackouts across 3 states, lasting up to 2 weeks.
December 2004	Countries bordering the Indian Ocean	Earthquake and tsunami	More than 230 000 people died.
September 2003	Italy	Cascading failure after one transmission line was damaged by a storm.	Nationwide blackout for more than 12 hours, affecting more than 56 million people.

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Annex A presents further details on several of the disasters listed in Table 2-1, provided by members of this project with local experience or knowledge of the disaster and the ensuing response. Importantly, as well as reviewing the impact of the major electrical disasters, project members provided feedback on “lessons learnt” regarding the impact of the disaster, or the recovery of electricity supply after the disaster. These lessons learnt provide valuable guidance for the focus of this White Paper and what can be done to improve the reliability and resilience of electricity supply. Focus on a number of key observations comes out of the various case studies:

- The centralized nature of many power systems means that relatively small damage, in a few key areas, can lead to extensive power outages. Often, these vulnerable areas were not identified prior to the disaster
- Today, many electricity grids contain significant amounts of distributed generation, yet such generation cannot be relied upon to maintain electricity supply after a major electrical disaster. From restrictions on the operation of solar photovoltaic systems, to lack of fuel supplies due to road blockages, there are a variety of factors that mean the availability of local distributed generation cannot be assumed
- Whilst defence mechanisms such as sea walls to prevent flooding, or uninterruptible power supply systems, may be in place, often they were inadequate for the disaster faced. In general, this is an issue of planning and analysis – facilities and end-users face significant uncertainty in how to evaluate the risks of natural disasters, or their preparedness against such risks. Without any uniform way of measuring these risks, or preparedness for them, it is difficult for facilities to evaluate their own position, to prepare detailed disaster resilience or recovery plans, or compare one facility against another
- Areas (a neighbourhood, or perhaps a single

large facility) that had a range of distributed generation, and careful management of supply and demand, were often able to maintain supply after a major electrical disaster, or at least restore supply much faster than other areas

Given the observations above, the remainder of this White Paper focuses on techniques for disaster planning and preparedness, and the use of microgrid technologies as a way of ensuring local electricity supply reliability.

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# Section 3

## Planning for disasters and post-disaster recovery

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### 3.1 Quality of planning

The range of disasters presented in Table 2-1 of this White Paper, and the accompanying case studies in Annex A clearly demonstrate that one of the key factors in minimizing the damage and costs associated with major electrical outages is the quality of planning – how well-prepared an organization was to avoid loss of electricity supply after a major disaster, and, quite separately, how well the recovery from a major electrical outage was planned.

There is significant effort needed in preparation for disaster and post-disaster recovery, involving various jurisdictions and organizations. This is an area needing substantial improvement and requiring a large amount of work, from the development of standardized ways of classifying the potential damage from various disasters, to measuring and reporting a facility's preparedness for outside electrical failure, to the preparation of detailed plans for recovery from major disasters.

The aim of this section is not to provide solutions to the particular challenges involved, as this still requires a significant amount of future work from numerous organizations. Instead various broad concepts are introduced, indicating how disaster preparedness and post-disaster recovery may benefit from standards and the preparation of plans for the provision of reliable electricity supply.

### 3.2 Continuity planning

A key requirement for any successful business is the completion of comprehensive strategic plans – to ensure that the company in question prospers,

but which also project how the business would respond to particular external events, including catastrophic occurrences that might have a dramatic impact on business performance. Such continuity plans can ensure that a successful business resumes operation as quickly as possible following a disaster.

#### 3.2.1 Business continuity planning

Perhaps the most widespread use of continuity planning is in the area of BCP, which “identifies an organization's exposure to internal and external threats and synthesizes hard and soft assets to provide effective prevention and recovery for the organization, while maintaining competitive advantage and value system integrity” [3]. BCP should consider a range of events that might affect operations, from supply chain interruptions to loss of critical infrastructure or the effects of physical or cyber-attacks. BCP involves the following stages:

- **Business impact analysis**, which splits organizational functions and activities into critical or non-critical areas. Critical functions are those where interruption would cause significant problems. Having identified the critical functions, a business impact analysis will then determine the recovery requirements for each critical function
- **Threat and risk analysis**, which is based on identifying potential threats and the necessary steps to post-threat recovery

While BCP remains a relatively new domain, uptake has been particularly successful in the information technology industries. Here, coping with major

outages – whether from communication infrastructure failures or cyber-attacks – is a critical task for organizations such as data centres. Consequently, a relatively significant amount of work has been undertaken in this area, including standardization activities that provide guidelines and codes of practice for planning against major interruptions. Relevant International Standards here include:

ISO/IEC 27001:2013, *Information technology – Security techniques – Information security management systems – Requirements*

ISO/IEC 27002:2013, *Information technology – Security techniques – Code of practice for information security controls*

ISO/IEC 27031:2011, *Information technology – Security techniques – Guidelines for information and communication technology readiness for business continuity*

ISO/IEC 24762:2008, *Information technology – Security techniques – Guidelines for information and communications technology disaster recovery services*

### **3.2.2 The effectiveness of business continuity planning following major disasters**

Whilst BCP are a growing area of attention for many companies, experience from recent major disasters suggests that more needs to be done.

In 2005, the Japanese government's Disaster Prevention Basic Plan [4] suggested that all companies should develop a BCP, and recommended a target that all large-scale companies in Japan develop and implement such a plan by 2018. By 2011, 70 % of large-scale Japanese companies and 35 % of middle-scale companies had prepared and/or were in the process of planning BCP, when the Great East Japan Earthquake struck.

However, most of the BCP did not work as planned, and lack of electricity supply was a critical

factor in the process of post-disaster recovery. Following this massive disaster, 271 companies were surveyed regarding the impact of the disaster [5]. Of these companies, 106 claimed they faced significant IT system problems after the earthquake, and 137 companies did not have a BCP. Among the Japanese companies surveyed who did have a BCP, only one company replied that their plan had worked as designed. Examples of some of the comments received include: “(We) had prepared for damage to our building, but the lack of electric power was not assumed”, or “BCP does not work for partial blackouts.”, and “It will be necessary to rework our preparedness for a major disaster.” These comments suggest that, even when preparing BCP, the widespread loss of electricity supply, or its actual effects on the business, had not been sufficiently considered. In analyzing the gap between the disaster that ensued, and the continuity plans originally developed, it is clear that long grid outages, collapse of supply chains that might affect electricity supply, or the loss of critical infrastructure, were rarely foreseen.

In effect, a revision of BCP from real experiences was essentially important and ECP became the next step for recovery.

### **3.3 Electricity continuity planning**

BCP often give only cursory attention to the maintenance and/or restoration of electrical services. Given the complexity of electricity systems and the growing popularity of distributed generation and related energy technologies in customer's premises, a new continuity plan specifically focussed on electricity supply resilience and restoration is needed in many organizations. So-called ECP will specifically consider how to rapidly restore electricity supply to a particular site, based either on outside supply or internal provision. However, the case of the provisions of the preceding section shows that a BCP may not work enough against unexpected disasters.

Certainly a BCP also an ECP should be revised based on PDCA (Plan-do-check-act) cycle on each real case of an unexpected large scale disaster.

Preparedness against disaster will never be perfect without appropriate operational strategies. Installation of a back-up system or microgrids (i.e. ECS is considered to be an investment in hardware) reinforce the preparedness against disaster. The hardware will demonstrate its full performance when it is combined with appropriate software.

Following the lead of BCP, an ECP should, as shown in Figure 3-1, include analysis of potential threats to electricity supply, countermeasures to these threats, implementation of these measures, and testing and continued improvement of the plans.

In contrast to BCP, unique electrical issues that should be considered by an ECP include:

- Alternative generation sources – the use of local back-up generation
- Dependencies outside the electrical equipment that may affect electricity supply – for example, the availability of fuel for back-up generators
- Identification of particular electrical loads, their priority for business functions, and their energy requirements

When preparing an ECP there are a number of key steps to determine the particular threats to electricity supply and steps to mitigate these risks for a given facility. For example, when preparing an ECP, it is critical to identify the risks that the various types of natural disasters may pose to a particular

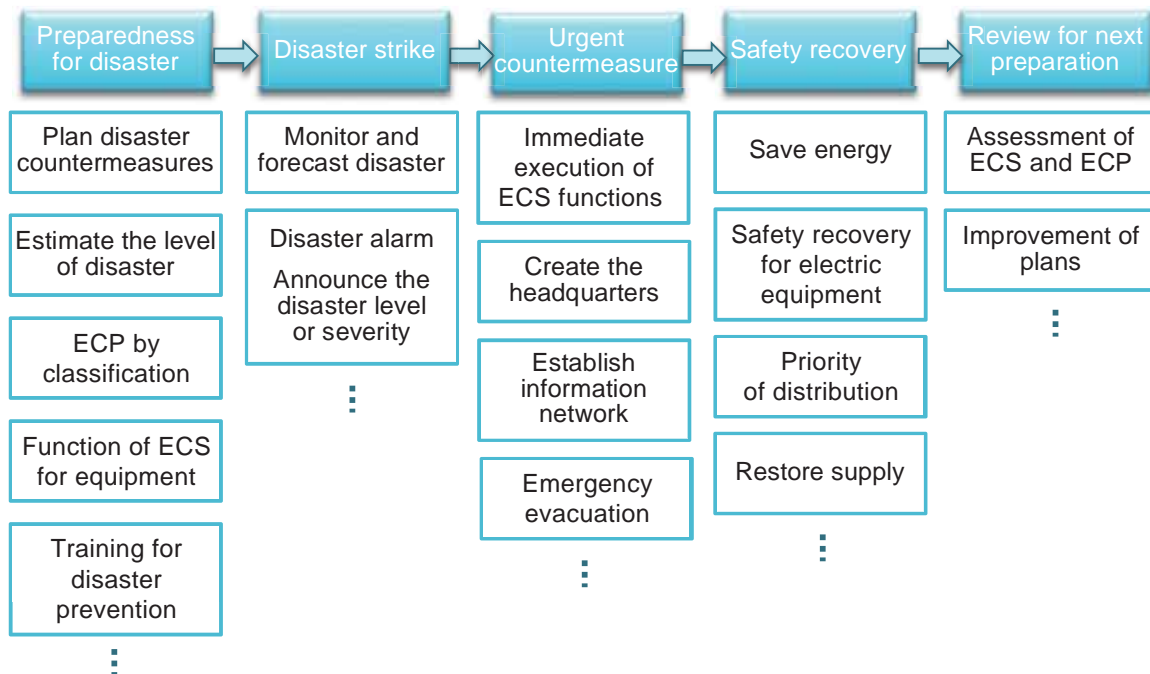


Figure 3-1 | Example of an ECP



facility. Currently, there is no standard method to classify particular types of natural disaster and their potential impact on a facility. Similarly, there is no way to compare facilities – to determine whether one facility (or design) is more resilient against a certain disaster than another.

**3.3.1 Electricity continuity systems**

The use of an ECP to detail the restoration of electricity supply after a disaster is only one step in establishing a business’s broader resilience against major electricity outages. Following the Great East Japan Earthquake, the Japanese government surveyed 571 businesses, asking “What prevented your business from continuing its functions following the earthquake?” [6].

As seen in Table 3-1, the predominant reason given for the cessation of business after the Great East Japan Earthquake was blackout. Other major influences though were not related to electricity supply such as access to gas, water, and telecommunications which are also critical to business operation.

The results in Table 3-1 suggest that whilst ECP may determine particular threats to electricity supply and the steps to mitigate risks, more plans are needed. Consider, for example, when preparing an ECP the steps necessary to identify the risks that particular natural disasters pose to a facility. Currently, there is no standard methodology to classify particular types of natural disasters and their potential impact on a facility. Similarly, there is no way to compare facilities – to determine whether

**Table 3-1 | Survey results for interruption of business after the Great East Japan Earthquake**

1	Blackout (total loss of power)	54.8 %
2	Shutdown of transportation	37.8 %
3	Shutdown of telecommunications and internet	29.9 %
4	Employees not able to travel to work	28.0 %
5	Damaged production equipment	26.6 %
6	Business clients not attended to	25.6 %
7	Water outage	25.4 %
8	Damaged office buildings	23.6 %
9	Clients facilities are damaged	22.9 %
10	Power shortage (brownouts)	20.8 %
11	Shutoff of gas supply	13.8 %
12	Damaged information systems	11.2 %

one facility (or design) is more resilient against a certain type of disaster than another.

An ECS is a macro-level plan that considers a wide range of issues influencing a facility's electricity supply and its resilience. It should not only take the continuity of local electricity into consideration, but also the other influences shown in Table 3-1.

As shown in Figure 3-2, an ECS may consider everything from the types of disaster that can impact a facility, to the individual pieces of equipment in a facility, and their own robustness.

The lower three layers in Figure 3-2 show the natural disaster level to the preparedness of markets, including disaster prevention programme, relative regulations and BCP in companies. The upper three layers show the equipment based on relative technologies for ECS and MDR. The middle layer, ECP and ECS classification, will be useful for integrating technical and non-technical matters,

electrical facilities and outside circumstances for disaster tolerance.

The design of both ECP and ECS will be a major task requiring significant standardization effort. As a first step, we make some early suggestions as to classifications.

### 3.3.2 Classification of disasters

Whilst there will always be significant unforeseen disasters, the most common disasters causing electrical outage in a geographical area can often be anticipated. It is reasonable to assume that earthquakes will continue to plague areas around the Pacific Rim. Similarly, geographies prone to large storms or flooding will continue to be at risk.

In order to plan, one must begin by classifying disasters by type. As a consequence, a number of metrics are likely to be available for comparing

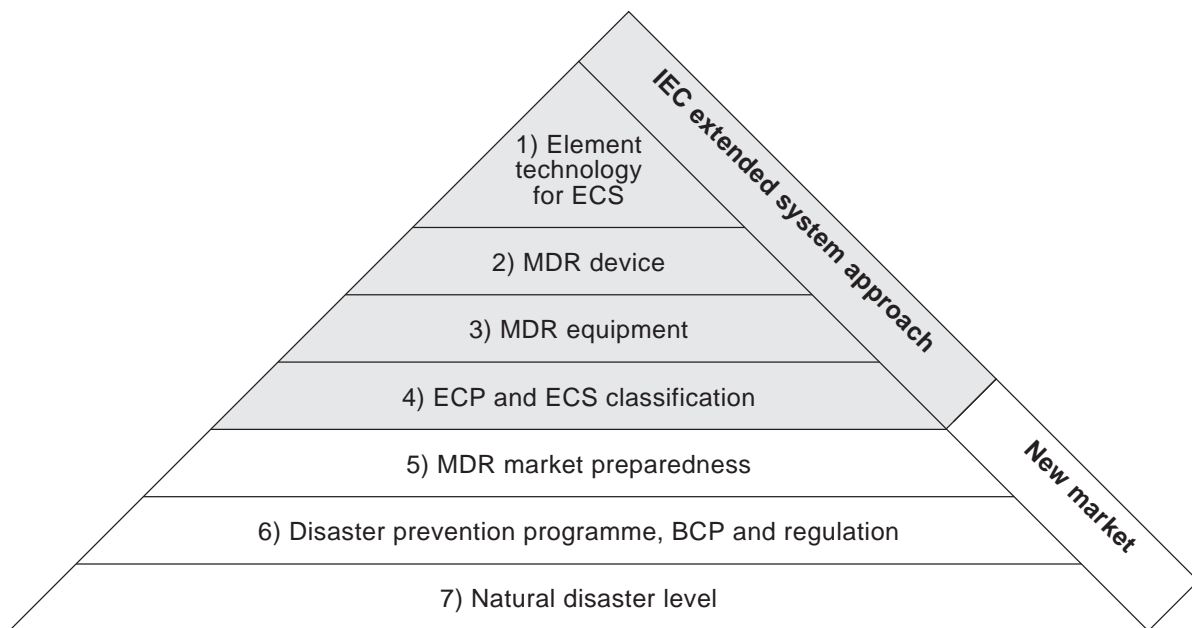


Figure 3-2 | Example of ECS architecture

likely impacts of the disaster versus the resilience measures in place.

Some examples of such disaster metrics may include:

- Flood heights
- Wind strength
- Earthquake intensity
- Lightning frequency
- Tsunami height
- Duration of inundation

The impacts of a disaster will vary depending on the country, geography and infrastructure. Such metrics may already exist in geographical or meteorological records, but in the preparation of ECP, these metrics need to be carefully selected and assessed in terms of the insight they offer regarding the likely impact on electricity supply. Much work remains to be done in this area, with the ultimate aim to standardize the way of measuring and comparing potential natural disasters, so that resilience measures can then be implemented.

### 3.3.3 Classification of facilities

Once an understanding of likely disasters and their severity has been established, a facility can then start to evaluate to what extent it is prepared against each disaster. Here, the goal is to design a standard set of metrics that can indicate a facility’s preparedness against disaster and loss of energy supply, effectively allowing the level of preparedness of each facility to be compared to one another.

The preparation of metrics to measure disaster preparedness or resilience will be a complicated exercise. This work will need to grapple with how to measure a facility’s resilience against a very wide range of potential natural disasters and how this can be distilled into a number of common metrics. Similarly, whilst “n-1” style metrics as used in the utilities industry might indicate that a facility can cope with a major infrastructure’s single failure, they do not indicate other important factors, such as length of the outage, dependencies on outside fuel supplies, etc. The goal is to standardize a way of measuring a facility’s preparedness against a variety of disasters, to allow internal evaluation (as part of a broader ECS), and comparison of different facilities.

**Table 3-2 | Example criteria for load classification**

ECS Class	Criteria			
	Reliability	Interruption	Fluctuation	Others
1	Required reliability of power supply	Acceptable interruption period	Acceptable fluctuation of voltage and frequency	
2				
3				
4				
5				
...				
XXX				

**3.3.4 Classification of loads**

When classifying a facility’s resilience against an electrical outage, it is critical to have a detailed understanding of the loads in the facility. We suggest there are at least two further classification standards needed:

**1) Classification of load energy requirements**

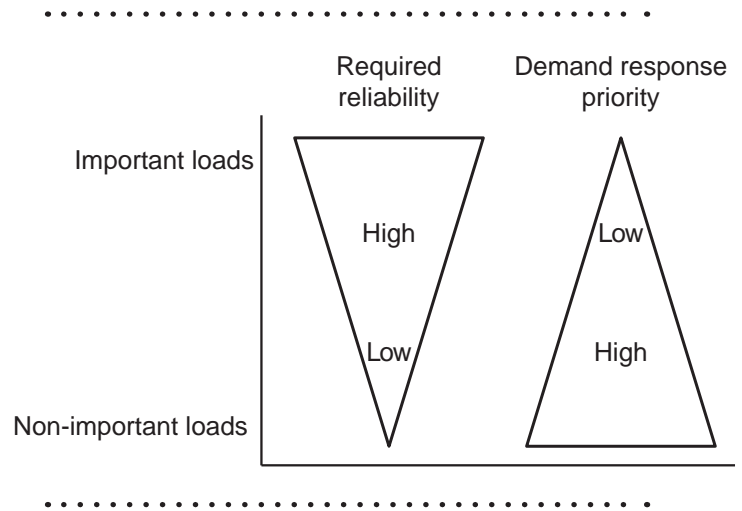
Different loads can accommodate different levels of power quality, and/or length of supply failure, without having significant economic effect. There is currently no standard method or metrics to specify a load’s electricity supply requirements. Such classifications may be based on individual pieces of equipment, where classes of load are introduced based on metrics such as:

- Acceptable supply interruption duration
- Acceptable supply frequency range
- Acceptable supply voltage range

These metrics can then be assembled to form various classifications of loads, with one example classification shown in Table 3-2. Again, much work is needed here to standardize classifications to capture the wide variety of loads and their requirements, yet remain concise and readily interpreted.

**2) Classification of load priorities**

When preparing an ECP for a facility, it will be critical to understand the priority of various loads and their energy requirements. For example, one common response in times of constrained supply is to shed low-priority loads in order to maintain supply to critical infrastructure. Such low-priority loads might also be used to earn a facility income, by participating in wider demand-response schemes (during regular supply), where a facility owner is paid to shed loads at times of peak system demand. As shown in Figure 3-3, loads that cannot cope with supply interruption are also unlikely to be useful when a demand response or load shed is needed.



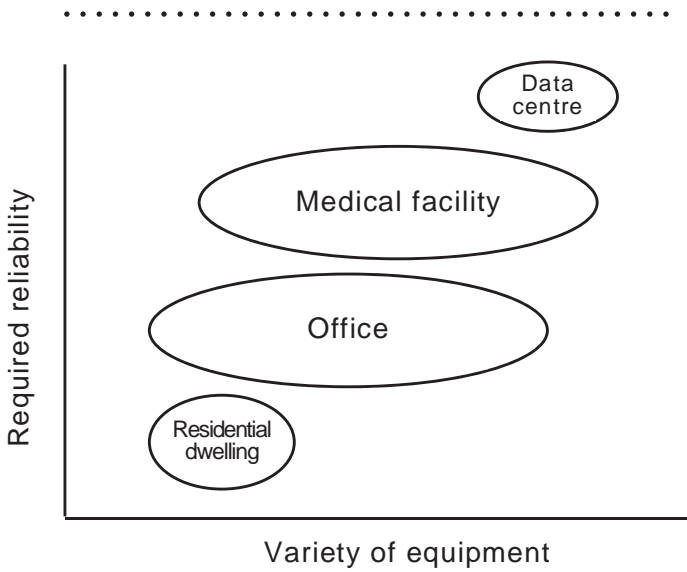
**Figure 3-3 | Prioritization of load**

There is currently no standard way to indicate the priority of various loads in a facility. The application of such a standardized assessment may include:

- Communication of priority loads when preparing ECP
- Programming and inter-operability of technical systems such as automated energy management systems. If standardized classification schemes are in place, this will ease the implementation of such automated control systems

Importantly, the definition of a particular load’s priority and supply requirements may vary in application, over time, or operating environment. Classifications both by type of operation facility, and equipment, are possible, as shown in Figure 3-4. A medical facility has critical loads (such as a respirator) and non-critical loads (such as an entertainment system for patients). An office building has no critical loads, but the computer systems are very important for business continuity. Dwellings usually have no high priority loads unless a resident uses a home medical care system (such as a dialysis machine).

These steps come together in an ECP as shown in Figure 3-5, where the detailed planning of resilience and restoration must include an understanding



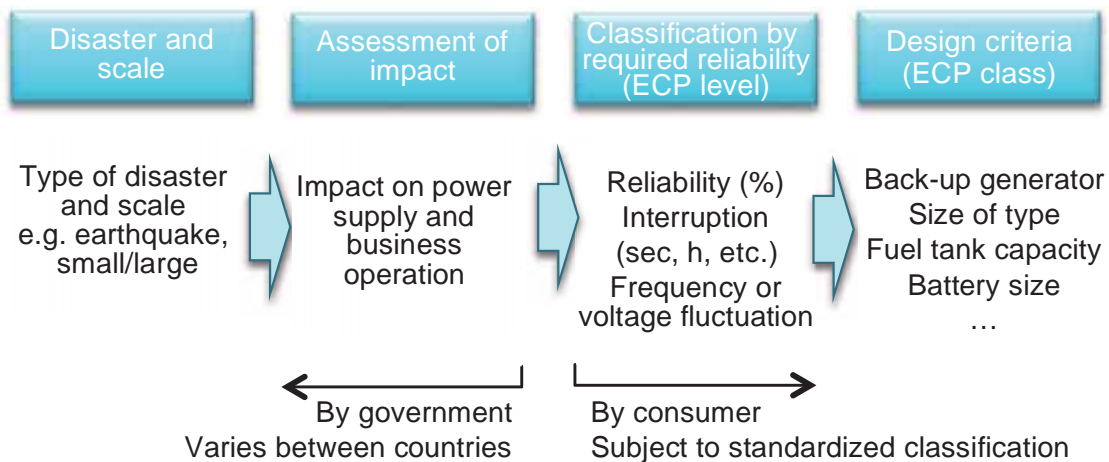
**Figure 3-4 | Required power supply reliability**

of the disasters or risks facing a facility, metrics to evaluate a facility’s readiness against these issues and guidance on the choice of additional infrastructure to improve resilience.

### 3.4 Markets for electricity continuity systems

There are a number of likely markets, and users, for ECS. On a “macro” level, governments may use an ECS to provide resilience against community-wide disasters. A government-focussed ECS might include:

- 1) Reviewing the strength, scale and estimated damage from likely disasters based on prior experience
- 2) Completing shelters and refuge plans
- 3) Completing emergency services for police, fire stations, hospitals, etc.
- 4) Completing ECS for individual shelters and emergency services
- 5) Training for disaster response



**Figure 3-5 | Assessment and classification stages in an ECP**

On the other hand, companies may also manage their own company or facility-specific ECS. A company-specific ECS might include:

- 1) Making decisions about the locations of company facilities by ECS assessment
- 2) Continuity planning for core facilities after a disaster has occurred
- 3) Including disaster and ECS analysis in any investment decisions

Whilst the focus of ECS for a private company is ultimately business continuity, such systems can bring other benefits. For example, when considering the addition of local generation to add electricity supply redundancy, such generation may also lower operating costs by reducing the dependency on expensive grid electricity. Ultimately, the careful planning needed to prepare a detailed ECS is likely to bring additional benefits in energy expenditure, return on capital, and so on.

### **3.5 The consumer market of electricity continuity systems and disaster relief functions**

An additional market to consider as part of the ECS is the consumer market. By best practice, renewable energies (i.e. photovoltaic and batteries) used in HEMS are effective for maintaining energy during disasters. These HEMS played an important role when rolling blackouts were instituted in March 2011 after the Great East Japan Earthquake.

In this specific case, it was only after the incident that consumers recognized the fact that distributed generations, such as photovoltaic generations and CHP systems that are installed to realize CO<sub>2</sub> zero emission houses are successful in quickly recovering electricity supply in the case of disasters.

As it was in best practice, the HEMS that originally intend CO<sub>2</sub> reduction effectively functioned as ECS in case of the earthquake disaster. Such houses are penetrated very fast after that. For example, 5 356

sets of fuel cell CHP were installed in the houses that were built by Sekisui House, a Japanese house builder. 80 % of the newly constructed houses by them are equipped with photovoltaic generations. In addition, during a blackout, the switching on of the electrical system must be automatic, since manual operation by residents cannot be expected at that time in general houses.

After the Great East Japan Earthquake, more than 50 % of new homebuyers prefer the houses with advanced systems that contribute to CO<sub>2</sub> reduction and work as ECS. The main future specifications of such ECS for residential dwellings are mentioned below. Moreover, the ECS type home network is shown in the Figure 3-6. Such houses are important, concrete examples of the microgrid that integrates DER.

The abovementioned MDR functionalities must be integrated into daily operation by the consumer (users), ensuring that users will become familiar with their own operation of the HEMS and can thus be prepared for blackouts.

For example, the sequence of ECS related events in a smart home can be examined below as disaster-relief functions:

#### **1) Detecting loss of power from the grid**

- Delinking function for grid and microgrid
- Power supply and monitoring functions from batteries to microgrid
- Checking function for safety inside microgrid
- Communication tool to check safety of connected appliances before recovery from blackout
- Minimizing power loss and saving conversion loss by DC power

#### **2) In case of using renewable energies**

- Penetration ratio (efficient utilization), capacity of batteries, ECS class should be well balanced
- Assessment ECS class is needed for the

installation site of PV, wind power

**3) Relation with demand response**

- Selecting appliances depending on the priority
- How to consume the limited power and select appliances
- Setting priority for battery power

**4) Use of Electrical Energy Storage (EES) contributes to ECS classification**

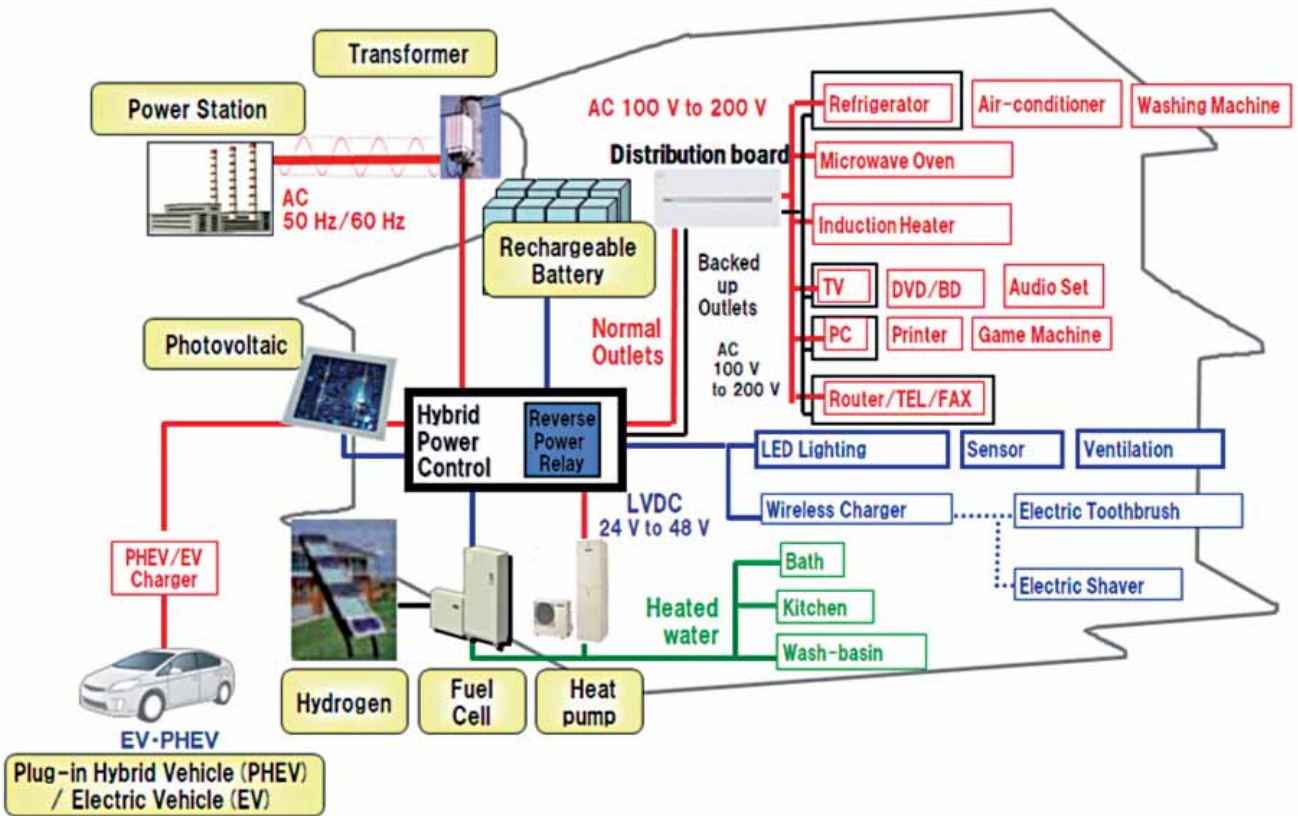
- Adding ECS functions for disaster relief by EES to daily system making the implementation easier

**5) Electric Vehicles (EVs) can return charge to the home during blackouts**

Microgrid technology is now extended not only to the electricity industry but also to other electric industries and consumers.

International Standards are needed and necessary in ECS and should be promoted in order to position these technologies over sectors of electrical industries and encourage collaboration between each industry.

In the cases above, standards are necessary for safety and interconnecting. Figure 3-6 provides an example of an ECS home energy network.



**Figure 3-6 | ECS type home energy network from electrical energy efficiency and electrical energy storage**

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# Section 4

## Post evaluation review of Japanese electrical facilities and examples of best practice against disasters

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### 4.1 General

The Great East Japan Earthquake has also enabled to evaluate the preparedness of industrial facilities for possible disasters. Focusing on electrical facilities of some of the most important social service organizations, it is critical in moving forward that these businesses must be able to keep their operations open, and to continue to have electricity available to them. Hereafter are post-event observations of telecommunication systems, medical facilities and semiconductor factories.

The cases outlined in this section are very useful in showing how specific facilities coped with major disasters and subsequent electrical outages.

Three best-practice cases are then presented to show how to maintain electricity reliability in challenging circumstances based on microgrid concepts.

### 4.2 Telecommunication systems

Telecommunication systems are a critical part of society, and rely on a constant power supply. Facilities such as mobile communication base stations or telephone exchanges are classified based on their importance. High demand facilities are given top priority and low demand facilities are given less priority.

In addition to back-up generators and UPS, mobile generators and mobile telecommunications equipment are also commonly used in a modern telecommunications system. Operation and management of these devices is considered an important challenge following any widespread

disaster. It will be necessary to deliver mobile generators or refuel the generators. Appropriate management of equipment and human resources is important.

In the example of the Great East Japan Earthquake the damage to telecommunication facilities was widespread. Many communication cable routes were destroyed, as were facilities including buildings and equipment. Power supply was lost. Japanese authorities responded as per their pre-prepared disaster plans. They dispatched mobile generators and alternative telecommunication facilities such as mobile base stations, and personnel to maintain working equipment and fix damaged apparatus. Throughout the disaster recovery effort the authorities needed to work very closely with other utility providers.

### 4.3 Medical facilities

A major challenge facing medical facilities is that the electrical load normally increases following a disaster. When a region is hit by a disaster the injured seek treatment and medical facilities have to take care of these patients even if the facilities themselves are damaged.

In this context, a secure power supply is critical for medical facilities to continue functioning, as power interruption may cost lives. Typically, only large medical facilities are equipped with back-up generators and UPS, as these backup supplies cannot be economically justified for medium/small facilities. Even where back-up generators exist, refuelling after a major disaster is often problematic, due to limited fuel supplies, or the difficulty of getting



fuel to the site due to road damage, etc. Prioritizing medical equipment and supplying power only to critical loads is a crucial component of disaster planning for such facilities, in order to minimize back-up supply fuel consumption. Diversifying the range of energy sources (e.g. electricity, natural gas and kerosene) can improve the robustness of the supply.

#### 4.4 Semiconductor production facilities

Japanese equipment and material suppliers are leading players in the global semiconductor industry. It is estimated that Japan-headquartered equipment companies collectively capture about a 35% share of the global semiconductor industry spending per year.

Semiconductor production facilities require high reliability and a high quality of power. Any interruption to supply, even a short voltage drop, can cause incredible damage. In many semiconductor facilities, the shut-down and start-up process after an electrical outage can take up to 11 days.

Given these constraints, most semiconductor production facilities are equipped with a range of back-up systems such as UPS and generators, as shown in Table 4-1.

The Great East Japan Earthquake heavily damaged a number of semiconductor production facilities. Outside electrical infrastructures such as transmission and distribution infrastructures were also destroyed. In many facilities, the production areas have no windows and therefore no lighting without a power supply. Following the Great East Japan Earthquake, this made recovery works at each facility very difficult. In many cases, it took up to a month to resume power supply to the facility.

#### 4.5 Data centres

Data centres are considered to be one of the best examples of an industry with relatively mature plans for disaster preparation and recovery. For example, after the Great East Japan Earthquake, no critical damage to data centres was reported.

In Japan, the Data Centre Facility Standard (DCFS) was developed by the Japanese Data Centre Association to classify data centres and their resilience to electricity supply failure. The Tier Classification System [7] and TIA-942 Standard are widely used in the data centre industry to classify data centres and their reliability, including against energy supply failure. The DCFS standard is based on the Tier classification (TIA-942). The Tier classification defines the required power supply

**Table 4-1 | Typical power supply systems in a semiconductor production facility**

Outage type	Effect	Duration	Protection device
Power quality variation (from lightning, etc.)	Voltage deviations	Seconds	UPS
Outside electricity supply failure	Electricity supply interruption	Hours	Back-up generators
Major disaster	Long-term blackout	Days	On site internal supply (permanent)

reliability of data centres as shown in Table 4-2 and Table 4-3. Requirements for associated electrical equipment such as transformers buildings, security, air-conditioning and communication systems are also defined to ensure power availability.

The DCFS is based on defining system requirements such as redundancy of back-up generators and UPS to fulfil reliability standards. Ability to cope with a major failure (N+1) and two major failures (N+2) respectively are required for Tier 4. Recommended

minimum operating periods for back-up equipment are also defined.

In the Great East Japan Earthquake no service interruption occurred from DCFS-compliant data centres.

#### 4.6 Sendai microgrid

The Sendai microgrid is designed as an ideal power supply system that can simultaneously provide

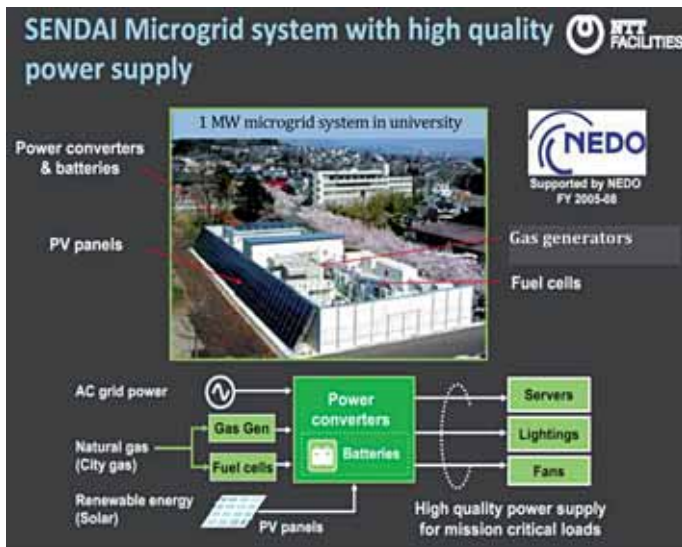
**Table 4-2 | Data centre tier classification system**

	<b>Tier 1</b>	<b>Tier 2</b>	<b>Tier 3</b>	<b>Tier 4</b>
Centre reliability	99.67 %	99.75 %	99.98 %	99.99 %

**Table 4-3 | System requirements for data centre reliability standards**

<b>Requirements</b>				
	<b>Tier 1</b>	<b>Tier 2</b>	<b>Tier 3</b>	<b>Tier 4</b>
Independent power supply (to servers)	Single	Single	Multiple	Multiple
Back-up generator	N/A	N	N	N+1
UPS	N	N	N+1	N+2

<b>Recommendations</b>				
	<b>Tier 1</b>	<b>Tier 2</b>	<b>Tier 3</b>	<b>Tier 4</b>
Fuel supply for back-up generator	N/A	12 hours	12 hours	12/24 hours
UPS duration	N/A	5 minutes	5 minutes	10 minutes

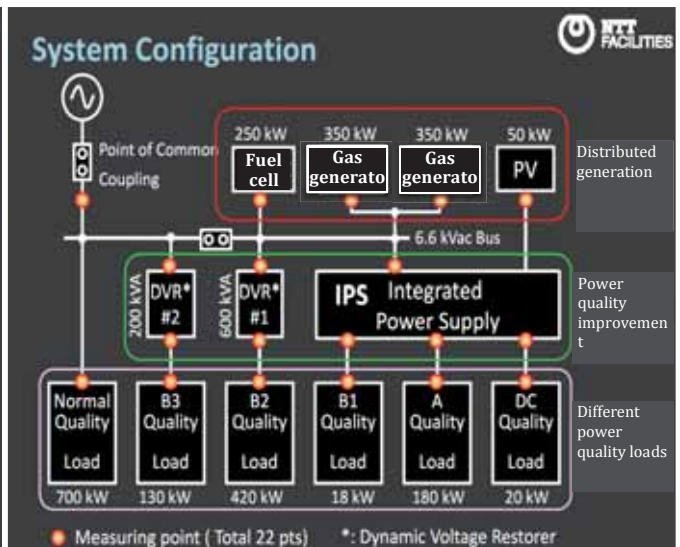


**Figure 4-1 | Sendai microgrid overview**

services with multiple power quality levels. The microgrid was developed by NTT Facilities and was installed on the campus of Tohoku Fukushi University in Sendai City (see Figure 4-1).

The Sendai microgrid is an integrated 1 MW power system consisting of power electronics equipment, storage batteries, and distributed generators (gas engine generators, solar cells, and fuel cells). It can easily interconnect and disconnect with existing utility power grids. In normal operation, the Sendai microgrid is connected to a utility grid and improves the level of power quality for the hospital, welfare care facilities, and university buildings on the campus. The microgrid can disconnect from the utility grid after a power outage and continue supplying power to essential loads or facilities without interruption (see Figure 4-2).

Immediately after the Great East Japan Earthquake, services continued to be supplied with high quality power from the microgrid by using energy from solar cells and storage batteries. Since the gas supply network in the city of Sendai was intact, the gas engine generators were soon able to restart after power failure at the utility grid, and function



**Figure 4-2 | Configuration of Sendai microgrid**

as the main power supply of the microgrid (see Figure 4-3).

The Sendai microgrid had been extended after the four years demonstration and could use heat as well as electrical energy. The gas engine generator sets and fuel cells worked as CHP units, producing heat for hot water and space heating for the nearby buildings, as well as electrical power.

The Sendai microgrid ensured that many patients in the hospital and in the medical and welfare buildings were able to survive and maintain their health. The Sendai microgrid provided many victims who had experienced unprecedented suffering with not only an energy supply but also a sense of hope and peace of mind. This real-life story demonstrates the effectiveness of the microgrid in ensuring electricity supply during the disaster.

## 4.7 Roppongi Hills (Tokyo)

Located in central Tokyo and opened in 2003, Roppongi Hills is a city within a city, providing residential space, offices and recreational facilities

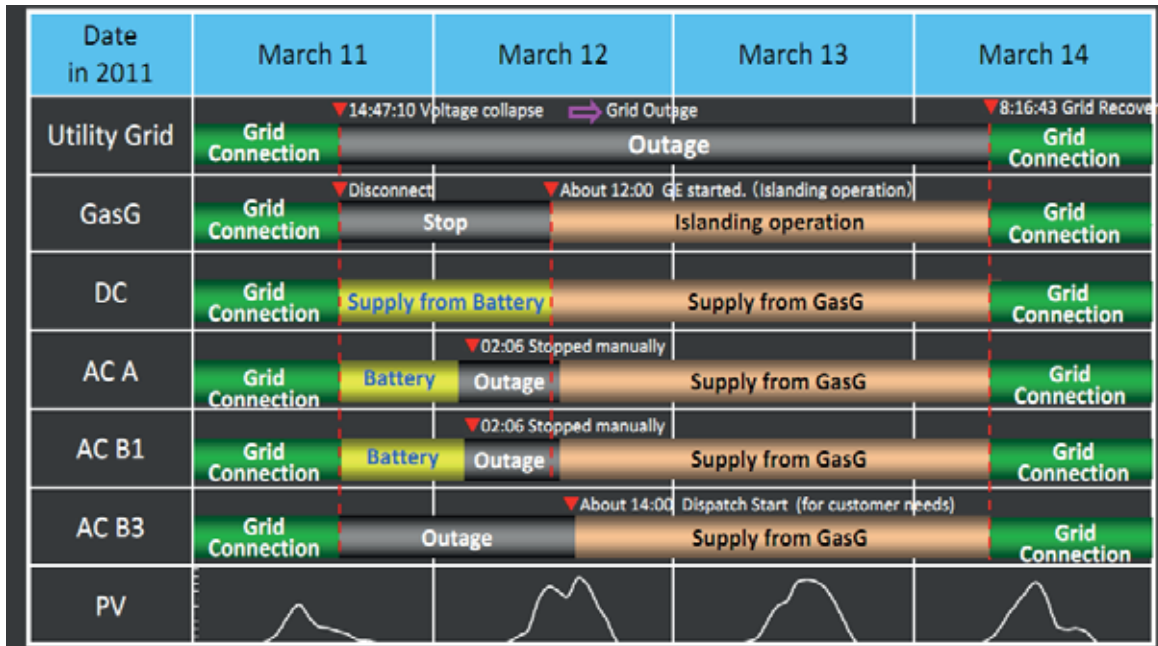


Figure 4-3 | Changing sources of power supply from Sendai microgrid after major earthquake

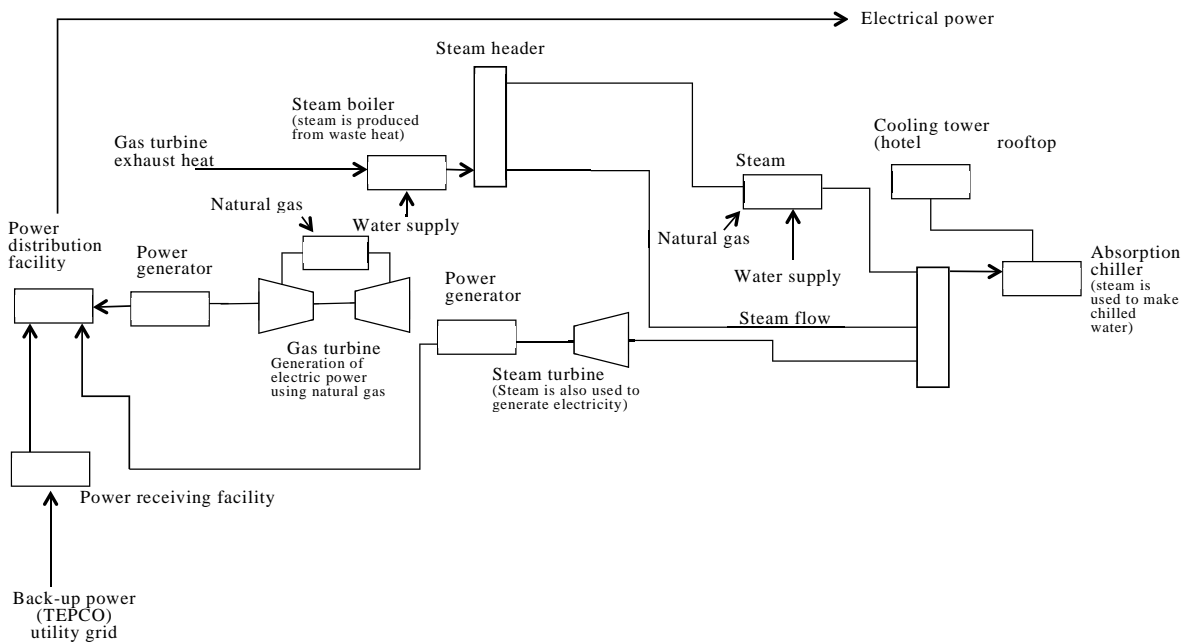


Figure 4-4 | Approximate topology of the Roppongi Hills microgrid system

all within one building complex. Roppongi Hills covers a geographical area of 84 800 m<sup>2</sup> with a total floor area of 724 500 m<sup>2</sup> and took 17 years to build.

A state of the art energy system was installed during the construction of Roppongi Hills, as shown in Figure 4-4. The system is based around 6 natural gas fired turbines (6 360 kW each), with enough capacity to cover the site’s entire electricity demand. These turbines also provide steam for space heating and cooling (via absorption chillers), with cooling water and steam reticulated around the site.

Given its dependence on natural gas supply, the Roppongi Hills system featured careful design of the gas mains to ensure reliable supply. This includes:

- Topology of the gas supply system – the gas supply is configured in a loop, providing dual supply directions to most loads, meaning redundancy is built-in
- The use of medium-pressure gas supply and pipelines. Medium-pressure gas pipelines are more resistant to disasters than the electrical power transmission infrastructure – there has been no interruption of medium-pressure gas supplies in Japan during any natural disaster
- Even if natural gas supply is interrupted, Roppongi Hills has an emergency kerosene-fuelled power generation system

The strength of the Roppongi Hills energy supply system was proved after the Great East Japan Earthquake. No blackouts occurred at Roppongi Hills at the time of the earthquake, yet the broader TEPCO area instituted rolling blackouts in the surrounding suburbs from the 14<sup>th</sup> to 27<sup>th</sup> of March 2011, due to the loss of the Fukushima Daiichi Nuclear Power Plant.

Since the Roppongi Hills energy system supplied electricity during wider grid outages, local tenants could continue their normal lives and business.

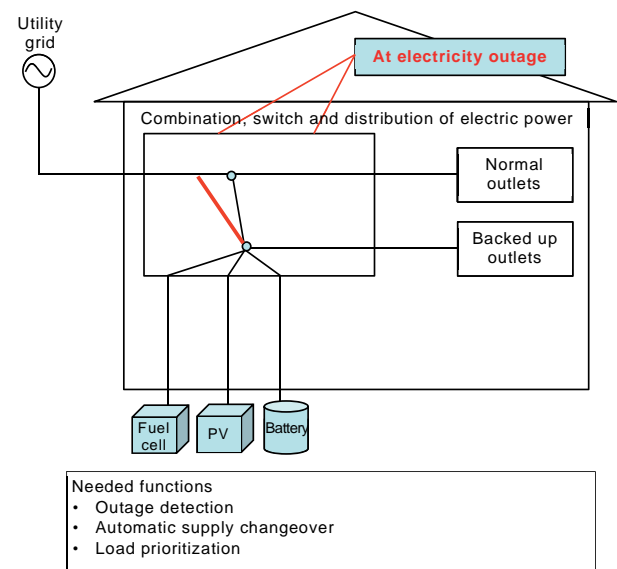
Moreover, the Roppongi Hills system was actually called on to export power to the wider utility grid, providing up to 4 000 kW to the surrounding area during the blackouts.

Whilst a very reliable energy source, the Roppongi Hills energy system has another advantage as it operates with very high efficiency, using 16 % less energy and producing 18 % lower CO<sub>2</sub> emissions than a conventional facility of similar size, primarily due to the use of heat pumps and local natural gas.

#### 4.8 Smart energy system for residential dwellings

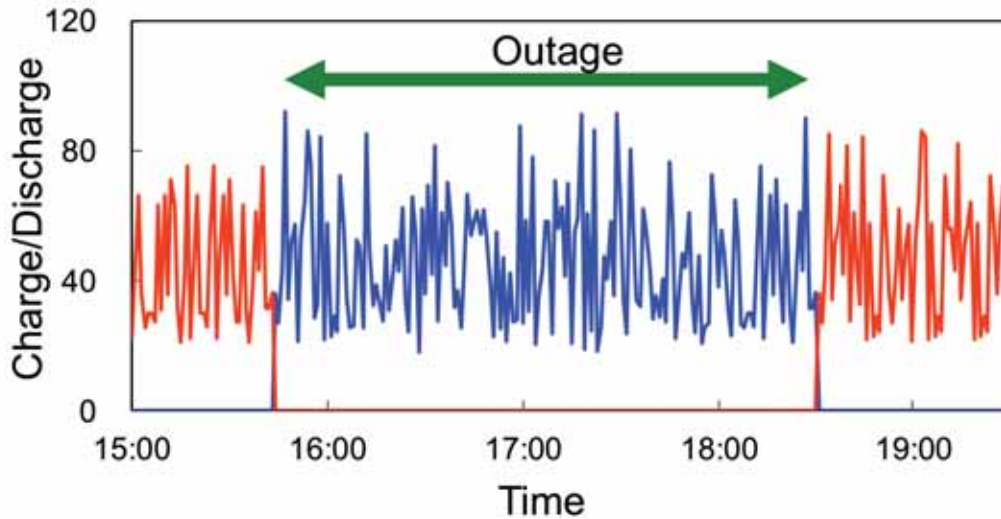
Whilst previous examples focused on large-scale deployments, microgrids also offered benefits to residential buildings following the Great East Japan Earthquake. A “smart energy system” microgrid

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**Figure 4-5 | Switching grid connection during blackout**



Battery supplied power during blackout (3.40 pm to 6.40 pm).

**Figure 4-6 | Battery operation at blackout**

was installed in a residential house in Saitama, Japan, in February 2011. The system is based around a photovoltaic generation system (4 kW) and Li-ion battery (1.5 kWh), with an associated home energy management system. The electricity from the photovoltaic system can be used to charge the battery, and thus made available for night-time supply. The system can automatically change from grid-connected mode to islanded mode and back, incurring a brief 20 ms to 30 ms interruption to supply when switching. This system is commercially available today, at a price of USD 10 000 to USD 20 000.

The residential microgrid system played an important role when rolling blackouts were instituted in March 2011 after the Great East Japan Earthquake. In this case, circuit breakers were automatically opened and the house's electricity system switched to a microgrid when the external power supply was lost as shown in Figure 4-5. At this point electricity

was supplied from the battery and/or PV system, as shown in Figure 4-6. The residents could then enjoy a completely normal life even though the external grid was shut down.

Whilst the smart energy system demonstrated a strong ability to provide continuity of power supply in case of blackout, the cost of energy storage remains a challenge to a more extensive uptake of these residential-scale systems.

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# Section 5

## Microgrids

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### 5.1 General

Electricity systems have undergone significant changes in the past 10 years. For example, there has been a rapid uptake of new, relatively small generation technologies referred to as distributed generation, and in many countries electricity load has continued to grow dramatically. These changes are often considered a challenge to electricity system operation. However, one of the most recent concepts, that of the microgrid, can actually be an asset to system operation, particularly when considering disaster preparation or recovery.

One way of managing the increasing complexity of our electricity systems is to group distinct distributed resources such as generators or loads, so that they represent a single generator or load to the wider electricity system. When such loads and generators are located within close geographical proximity of each other, such a system is often referred to as a microgrid. More specifically, in this work we define a microgrid as a collection of controllable and physically proximate distributed generator and load resources, where there are multiple sources of AC power and at least one of these is based on a renewable energy technology such as wind or solar energy.

A microgrid may or may not be connected to the wider electricity grid. We define an isolated microgrid as one that is not connected to the utility grid in any way, shape or form, but is a distinct island for which no PCC exists. We define a connected microgrid as a microgrid that can be connected to the utility grid. It may operate as a distinct island, but features a PCC that allows interaction with the utility grid (most typically to facilitate import/export of power).

There are a number of reasons microgrids are now receiving significant attention. They are a way of coordinating the growing number of sites with local on-site generation. For example, an industrial estate with roof-mounted solar cells and a gas-powered back-up generator can be transformed into a microgrid by adding intelligent control systems to the generators, then linking these to load controllers to form a dynamic self-contained energy system. Microgrids also represent an entirely new way of powering remote or rural communities – rather than one centralized (often diesel-powered) generating station, these communities can be powered by a large number of low-emissions generators, linked with appropriate load control. As the range of possibilities between these two examples is quite wide, to assist with any ambiguity regarding what is a microgrid, Table 5-1 provides some examples of what, in this work, is not considered a microgrid.

An example is a connected microgrid system deployed at an industrial campus. Power is obtained from the grid to supply loads (the offices), as a conventional site, but can also be obtained from embedded generation, including a wind turbine, solar photovoltaic panels and a micro-turbine. All these feed power to the site via inverters. A battery is equipped with a special two-way power inverter that can both absorb power when excess is available or supply it when there is a shortage.

If embedded generation is greater than the required load, excess power can be exported to the grid via the two-way PCC. The site can also be isolated from the grid at the PCC, in which case the loads are supplied from the embedded generation only. In these circumstances, the EMS must carefully control which loads are allowed to draw power, in order to



**Table 5-1 | What is NOT a microgrid**

Commonly used name	Typical example	Why this is not a microgrid
Local renewable energy system	A single building with a local renewable energy system (for instance, a solar generator)	The loads and generators in such a system rarely exhibit any form of intelligent, dynamic control. There are rarely multiple sources of AC power in such systems.
Local back-up power supply	A single building with a local back-up power supply (such as batteries or a fossil-fuel generator)	Typically such systems operate using a single generation source or battery supply, so do not fit our definition of a microgrid having multiple AC sources.
Grid-connected peaking plant	Relatively large (>1 MW) generators interspersed throughout a distribution network for meeting peak demand	Connected to a broader distribution system, there are multiple points of connection to the wider grid, violating our definition that a microgrid has one single point of connection.

balance supply with demand. Fluctuations in the renewable generation caused by changing weather conditions are balanced by judicious charging and discharging of the batteries, under the control of the EMS. Some of the key features of this microgrid that set it, and microgrids in general, apart from more traditional power distribution systems are:

- The use of distributed generation sources, including renewable and CHP generators
- The introduction of dynamic load control systems
- The use of multiple inverters
- The ability to island the system, and
- A point of common connection (for connected microgrids)

These features may occur in isolation in traditional electricity systems, but combine to form a unique set of opportunities and hurdles when deployed as a microgrid. These are explored in the following sections.

## 5.2 Benefits of microgrids

### 5.2.1 To end users

One of the major benefits of microgrids is that they typically reduce emissions associated with electricity generation, and/or increase the efficiency of generation. Such benefits come from the distributed generators used in microgrids, which are often based on low or zero-emission generation sources – from highly efficient gas turbines through to renewable energy systems. As well as the efficiency of the generator itself, their close proximity to loads means the efficiency of distributed generators can be further improved by utilizing their waste heat – for example, to heat or cool nearby buildings. The overall efficiency is also improved because the transmission losses are reduced as well.

Microgrids also allow end users to become autonomous in their energy provision. By operating

their own network of local generators and coordinated loads, microgrid owner/operators can end their reliance on the wider electricity grid. By maintaining the ability to island from the wider grid, a microgrid can ensure robust and reliable supply for its enclosed loads, isolated from faults on the wider electricity system. The microgrid can also provide enhanced power quality compared with the wider grid, useful in critical applications such as semiconductor manufacture. This additional resilience is one of the main benefits of microgrids in relation to the challenge of disaster relief, and will be further explored in later sections of this White Paper.

### **5.2.2 To utilities/distribution companies**

One of the recent changes in modern electricity networks has been the increasing uptake of distributed generation. Whether it is solar cells for renewable supply or reciprocating engines providing CHP solutions, distributed generators are now quite common in a modern electricity system.

Distributed generation poses a number of challenges to the operation of electricity systems. It can reverse the direction of power flow in certain parts of the network. This can cause problems in networks designed on the assumption power will flow in one direction only. Further, to maintain power quality in the network, it may be necessary to individually manage each of the operating generators. With large numbers of generators possibly operating at any one time, centralized management of individual distributed generators across the entire electricity system can be a cumbersome task.

Microgrids ease the challenge of controlling large numbers of distributed resources by making distributed generation control an internal process, operating within the microgrid. For example, by managing a large number of distributed generators on an industrial campus as a microgrid, we are able to abstract the challenges of coordinating and controlling multitudes of distributed resources away from the wider utility grid. Each generator is

managed internally to the microgrid, and the entire microgrid appears as only one single generator to the broader electricity system. Here the microgrid, with its single point of connection to the wider electricity system, implicitly aggregates all the resources within the microgrid to appear as a large, single controllable resource. Ultimately, with microgrid technologies, today's electricity networks can operate with large amounts of distributed generation yet can use conventional command and control techniques.

Microgrids can also assist with peak electricity demand – the spikes in consumption that result in under-utilized electricity distribution infrastructure and often drive electricity price increases. In an attempt to better manage peak demand, load management technologies are being developed that coordinate a variety of electrical loads so the total electrical consumption adheres to a set of constraints. This technique is particularly beneficial in a microgrid situation, where loads can be managed to match time-varying distributed generation capacity, as well as network throughput capacity. An example is where load management on a building air-conditioning system is used to match the electricity consumption of the load with the supply available from the renewable energy sources, reducing the need for fossil-fuel generators while maintaining occupant comfort in the buildings. Ultimately, such active load management means that the microgrid can be operated with less generation held in reserve, improving broader system utilization and reducing capital costs.

Microgrids can also assist power systems to operate with significant renewable electricity generation. The traditional view of electrifying remote areas was that whilst some renewable sources could be included, a large centralized fossil-fuelled generator was needed to provide “spinning reserve” and act as inertia for the generation system. Microgrids challenge this theory: they are designed around multiple small generators, without any single large source of inertia. It is not uncommon now to find

microgrids operating with greater than 50 % of the electrical load being met by renewable generation supply.

### 5.3 Microgrids for disaster relief

Microgrids are inherently suitable for maintaining electricity provision during or after a disaster. It is first worthwhile reviewing what electrical outages typically mean for power system infrastructure, and then how microgrids can help.

Faults on power distribution systems can occur for a variety of reasons, from hardware failure through to physical interruptions from storms or animal intrusion. Protecting system assets from such faults are devices such as circuit breakers, reclosers and fuses, which isolate faulty network components and allow re-routing of power in an attempt to maintain the function of remaining assets. While some aspects of power system operation and fault response are automated, all systems still require significant manual oversight and intervention. In short, even today, often the only way a utility knows there has been an outage in the distribution system is when a customer calls to report it.

One of the core challenges to the reliable operation of contemporary power systems is their radial, centralized nature. Essentially, system-wide failures can occur if there is a failure at any central point of the system, and there are significant limits to the dynamic reconfiguration possible. Though some reconfiguration can occur at the edges of the network, the core structure remains in place, is difficult to change *in situ* and is at risk of failure.

As presented earlier in this White Paper, despite the best efforts of engineers to maximize system reliability, modern centralized power systems remain prone to unexpected failure, whether from cascading failures or widespread geographical disasters. Microgrids can dramatically improve the reliability of such power systems. The first instance of such reliability improvement occurs at the local site of the microgrid. In times of disaster, an islanded

microgrid can continue operation, maintaining local power supply autonomously.

Microgrids can also improve the reliability of supply more broadly than their immediate vicinity. If the wider grid is operational but strained, a microgrid can assist by reducing the load on the wider grid, or even exporting power from the microgrid to a broader area. As well as power management, microgrids can also help with voltage and frequency control in such situations.

If the wider grid is not functioning, a carefully managed local microgrid may be able to restore power supply to its immediate neighbourhood by, in essence, temporarily broadening the region of the microgrid to create a larger islanded region around the microgrid. Such scenarios need particularly careful management to ensure electrical safety and maintain the reliable operation of the microgrid itself.

### 5.4 Microgrid associated technologies

Technologies associated with microgrids range from particular types of generation, through to energy storage devices, load controllers, and the underlying control and coordination systems. Common technologies are listed below:

**Microturbines** are a fixed generator based on gas-turbine technology. These typically operate in the 25 kW to 100 kW range, and consist of a turbine, electricity generator and inverter interfacing the turbine with the wider electricity grid. Microturbines have relatively clean exhausts, usually operate on natural gas, and may be part of a CHP system (see below).

**Batteries** are increasing in prevalence as a way of providing reserve power during outages and for smoothing the output of renewable energy sources. There is an increasing range of battery technologies available for deployment into electricity grids, from traditional lead-acid technologies through to newer

flow-battery designs. Batteries are interfaced to the electricity grid through an inverter/charger.

**Flywheels/supercapacitors** offer an alternative to battery storage, with very high power outputs possible at a lower cost. The focus on such systems is the power available, rather than the total energy stored – batteries can supply power for longer, but flywheels and super-capacitors can supply very large amounts of power in a short time, more cheaply and with a longer lifetime than a battery.

**Fuel cells** produce electricity from an input fuel and oxidant, but without the combustion of typical fuel generators. They offer very high efficiency and low emissions, but are currently very expensive.

**Renewable generators** such as solar PV or wind turbines are growing in prevalence as their reliability improves and price of generated electricity approaches that of non-renewable sources.

**CHP systems** improve the efficiency of distributed generators by capturing waste heat and utilizing it in a downstream process. Typical applications of CHP systems are in heating buildings, where the waste heat from the generator is used to directly heat a building, or cooling, where the waste heat is used in a heat-driven-cooling process to cool a building.

As well as the key generation and load technologies introduced above, a number of “infrastructure” technologies are required to fully realize the features described in our earlier microgrid vision:

- Advanced high-speed control methods to maintain microgrid stability and provide intelligent and dynamic operation, despite having no central point of grid “inertia”
- Advanced sensing, diagnostics, forecasting and adaptation technologies to provide the microgrid control system with detailed and up-to-date information on the status of the microgrid. Care must be taken to ensure that a minimum number of sensors are used and that the total capital outlay is also minimized

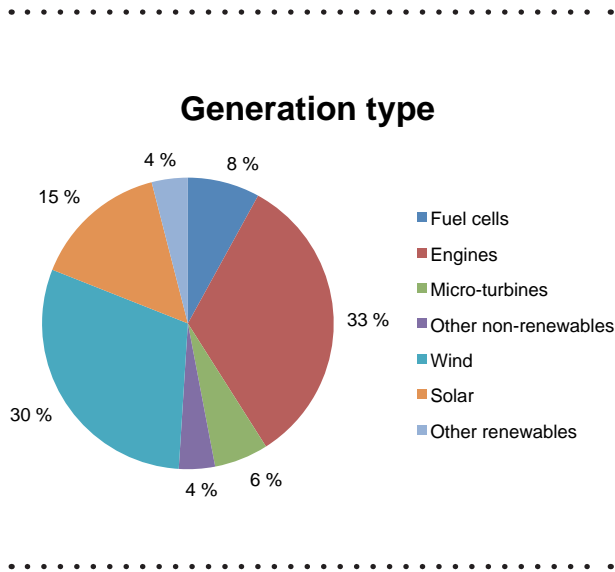
- Integrated communications systems to link the various resources in the microgrid to ensure reliable operation, even during typical communication outages

### 5.5 Microgrids around the world

Although the microgrid concept has only been formalized in recent years, there are numerous real-world networks that satisfy at least some of the requirements of a functional microgrid. These practical installations provide valuable insight into both the operational issues that must be addressed and the advantages that are offered within the new power paradigm.

As shown in Table 5-2, many of the installations around the world so far do not quite meet the full microgrid vision detailed earlier on in this section. Many of the systems installed thus far are based on simple bi-generation setups (most often wind-diesel), with a non-renewable source used to offer baseline support to an intermittent renewable technology. These generation sources are seldom co-located with loads. Instead they mimic the prevailing centralized generation and distribution approach, albeit with a more interesting mix of outputs, a smaller range and lower capacity. Since most such systems are used to service small remote communities, such as those in Bremer Bay, Australia, on Cape Verde Islands and on Flores Island (to name but a few), it also seems unlikely that they offer any level of control over loads, be it through demand management or otherwise. The consequence is that while these simple networks may aid in understanding the interaction between generation types, use of batteries and, to some extent, community acceptance of decentralized power, they are insufficiently complex to provide a full understanding of the issues facing microgrids, or their benefits in disaster relief.

When examining general trends, Figure 5-1 indicates that wind turbines are by far the most popular renewable generation technology in

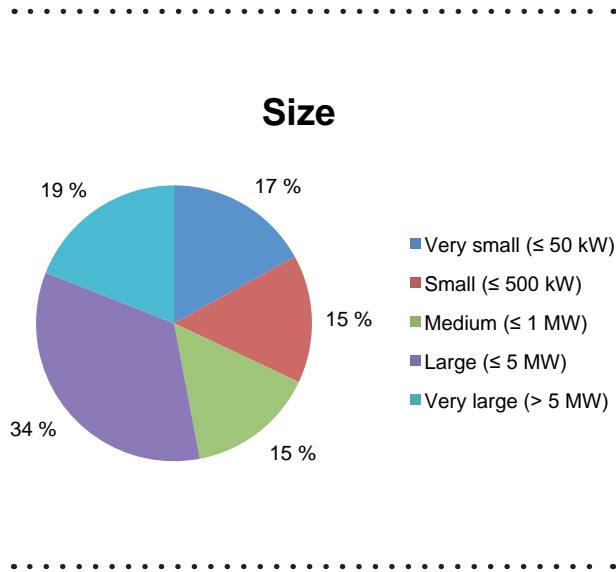


**Figure 5-1 | Composition of microgrid installations around the world**

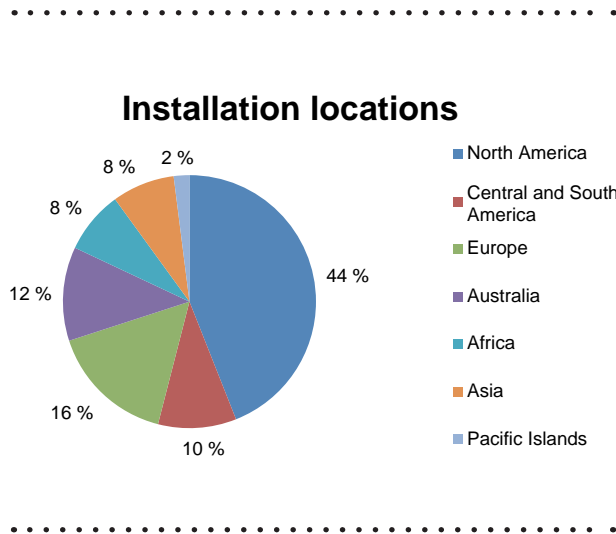
microgrids around the world. Fuel cells are relatively common, used in 19% of all microgrids, despite their fledgling nature as a technology and relative expense. Indeed, fuel cells are used more frequently than the much more mature microturbine technology.

In the case of total peak capacity (see Figure 5-2) there is a reasonably even distribution of microgrid types across the reviewed systems. These range from microgrids that generate less than 20 kW to those which produce more than 60 MW, and there is ample evidence that real-world installations are robust under a variety of load scenarios.

With respect to regions conducting microgrid research (see Figure 5-3) North America has clearly become a dominant player, partly in response to renewed government interest in evolving the utility grid after a series of crippling black-outs. Although Asia is home to only 8% of total real-world systems, Japan is becoming an increasingly strong presence, with impressive government support and a group of relatively complex microgrids already completed. Australia represents 12% of the reviewed microgrids, but most of these are very simple wind-diesel



**Figure 5-2 | Sizes of microgrids around the world**



**Figure 5-3 | Microgrid installation locations**

systems designed to service remote communities. Only the CSIRO and King Island installations offer a more complex mix of generation.

**Table 5-2 | Some examples of microgrids from around the world [8]**

Name	Location	Research/ Features	Capacity	Storage	Generation types					
					Fuel cells	Reciprocating engines	Microturbines	Other non-renewables	Wind	Solar
Kythnos microgrid	Kythnos Island, Greece	Services a remote community No utility grid connection (operational since 2003)	12 kW PV 85 kWh battery 5 kW reciprocating engine	Battery		x			x	x
Island of Utsira microgrid	Island of Utsira, Norway	Research and development project Fully autonomous Linked to mainland by sea cable Services 10 homes	1.2 MW wind 50 kWh battery 5 kWh flywheel 48 kWh electrolyzer 10 kW fuel cell 55 kW reciprocating engine	Battery, flywheel and hydrogen	x	x			x	
Bornholm Island microgrid	Bornholm Island, Denmark	Services a massive 27 320 customers (domestic, agricultural, commercial) Uses load and generation forecasting Connected to Sweden via cable	65 MW total	Unknown					x	

## Microgrids

Name	Location	Research/ Features	Capacity	Storage	Generation types					
					Fuel cells	Reciprocating engines	Microturbines	Other non-renewables	Wind	Solar
Kyotango city virtual microgrid	Kyotango, Japan	Virtual microgrid that links an energy control centre to distributed resources installed on the utility grid  Supply and demand controlled via internet	50 kW PV 50 kW wind 250 kW fuel cell 400 kW reciprocating engine 100 kW battery	Battery	x	x			x	x
NTT Facilities' Tohoku Fukushi University microgrid	Tohoku Fukushi University, Sendai, Japan	Services 5 university buildings, an aged care facility, high school and water treatment plant  Uses AC and high-voltage DC; connected to utility grid	50 kW PV 250 kW fuel cell 700 kW reciprocating engine 800 kVA battery	Battery	x	x				x
Hachinohe Regional Power Grid	Hachinohe, Japan	Uses CHP Allows island mode via manual control Does not export power Includes control for demand/supply and battery charge/discharge  Features weather forecasting	70 kW PV 20 kW wind 510 kW reciprocating engine 100 kW battery	Battery			x		x	x

## Microgrids

Name	Location	Research/ Features	Capacity	Storage	Generation types					
					Fuel cells	Reciprocating engines	Microturbines	Other non-renewables	Wind	Solar
CSIRO Energy Technology Centre microgrid	Newcastle, New South Wales, Australia	Real-world system designed to also operate as an experimental facility Allows islanding, import and export of power	110 kW PV 60 kW wind 150 kW turbines	3 kinds of battery, fourth type planned			x		x	x
Verve Energy's Bremer Bay wind-diesel system	Bremer Bay, Western Australia, Australia	40% wind penetration Currently an isolated microgrid, with plans for future utility grid connection (though export is unlikely)	1.3 MW reciprocating engine 660 kW wind	Unknown		x			x	
King Island microgrid	King Island, Tasmania, Australia	18% wind penetration Services the island community	110 kW solar 1 MWh battery 2.45 MW wind	Flow-battery	x				x	x
Cape Verde wind-diesel systems	Cape Verde Islands	collection of remote islands with wind-diesel systems Wind penetration levels between 14% and 6%	Between 4 MW and 12 MW reciprocating engine Between 600 kW and 900 kW wind	Unknown		x			x	
Powercorp Flores Island microgrid system	Flores Island, Azores, Portugal	Studies have investigated impact of penetration levels on system stability Achieved >50% wind penetration	600 kW reciprocating engine 1.48 MW hydro 600 kW wind	Unknown		x			x	



## Microgrids

Name	Location	Research/ Features	Capacity	Storage	Generation types					
					Fuel cells	Reciprocating engines	Microturbines	Other non-renewables	Wind	Solar
CICLOPS microgrid	Soria, Spain	Designed for experimentation Not strictly a microgrid as the three sources are coupled to a single common DC bus	20 kVA reciprocating engine 595 Ah battery 5 kW solar 7.5 kW wind	Battery		x			x	x
CESI RICERCA microgrid test facility	Milan, Italy	Features CHP Reconfigurable topology Allows island mode Includes load banks	7 kW reciprocating engine 24 kW solar 8 kW wind (simulated) 10 kW bio-mass 105 kW microturbine 3 kW fuel cell 108 kW battery 100 kW flywheel	Battery and flywheel		x	x	x	x (simulated)	x
Chengde microgrid	Chengde, China	All renewable energy; Connected to rural power grid	60 kW PV 90 kW wind 180 kWh storage	Lithium battery					x	x
Zhangbei microgrid	Zhangbei, China	100 % PV/wind penetration Serves a research department (100 kW) Uses generation forecasting Allows isolated and grid-connected mode	120 kW PV 20 kW wind 400 kWh storage	Lithium battery					x	x

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# Section 6

## Penetration of microgrids

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### 6.1 Challenges and barriers

Whilst microgrid technologies hold great promise as a transition path to low-emissions electricity networks, and as a way of improving the reliability or resurrection of supply during disasters, a number of fundamental challenges need to be addressed before they become commonplace. These challenges are both technical and non-technical.

#### 6.1.1 Technical challenges

Below are some of the fundamental technical challenges to be addressed to enable wide scale microgrid uptake.

##### 6.1.1.1 Synchronizing multiple small generators

The use of multiple distributed generators can pose significant challenges in a microgrid that is not currently connected to a functioning wider grid. In short, without the “inertia” provided by the wider grid, the multiple small generators lose any form of central stabilizing force. This can cause problems, particularly with frequency and voltage stability. Such issues are solved by developing intelligent control schemes that synchronize the various devices. But there are trade-offs. They typically rely on having a relatively fast and ubiquitous communications network available to link the various microgrid components. Ultimately, although solutions exist, the operation of a power system based on many small components rather than one large generator is a more complex task than current engineering approaches are accustomed to.

##### 6.1.1.2 Intermittent generation sources

Distributed generation based on renewable sources, such as wind or solar, can pose an extra challenge to microgrid development. The intermittency in the power supply available from renewable generation (caused by, for example, wind gusts or clouds passing overhead) means that not only is power flow bi-directional, but the power being fed into the system from such sources at any one time can vary randomly. Solutions here range from the use of batteries or other energy storage to smooth out generation intermittency, through to tighter coupling of supply and demand to ensure demand matches intermittent supply, and forecasting techniques that can aid system management by predicting the profile of future generation.

##### 6.1.1.3 The use of inverters

In a microgrid, inverters convert the DC output of the generator to AC, control the frequency of this supply, monitor power flows in the network, and provide basic fault and isolation protection. The challenge to successfully integrating inverters into the microgrid is being able to facilitate parallel operation of inverters serving potentially heterogeneous sources, without loss of synchronization, propagation of harmonics or loss of stability in general. Having a small number of inverters presents a challenging, but well-studied, dilemma. If the inverters use centralized or master-slave control, current sharing is enabled but high-bandwidth links are required to facilitate the distribution of error signals [9]. In contrast, distributed, on-board (to the inverter) control reduces the bandwidth but at the cost of synchronization difficulties [9]. Though such

techniques appear well understood, they focus upon systems with very few inverters. For larger microgrids with numerous inverters, the available literature is less comprehensive and doubts remain as to the scalability of those techniques proposed for small-scale systems. In particular, given the complex interactions that may occur between inverters [9], there is increasing potential for problematic emergent phenomena to appear as the size grows. Predicting and controlling such behaviour is difficult and has not been sufficiently explored in earlier work.

#### **6.1.1.4 Planning and design of microgrids**

A large number of quite different devices make the design of microgrids quite complex. Issues of installation cost, environmental impact, line loss, grid connectivity, reliability, resource longevity, reuse of waste heat, capacity for intentional islanding and physical constraints all affect the decision-making process. Often, a goal such as maximized reliability will conflict with another such as minimized operating costs. Overall, the complexity means heuristics or rules-of-thumb for microgrid design are inappropriate if an optimal or near-optimal system configuration is required. Sophisticated design tools using artificial intelligence approaches are needed for optimal microgrid planning, and such tools are only now being realized.

#### **6.1.1.5 Islanding**

A central benefit of the connected microgrid, particularly in disaster relief, is the capacity to ride-through failures which occur on the utility grid, with limited loss of localized service. By rapidly disconnecting from a faulting system (intentional islanding), adjusting local generation and shedding non-priority loads, particularly high levels of reliability can be guaranteed for priority resources on the microgrid. However, achieving this goal is not straightforward. First, the fault condition on the wider grid must be detected. Then, the microgrid

must transition to island mode in a controlled manner – with the variety of distributed resources cooperating, and the loads being batched to the available generation capacity, which may include shedding some low-priority loads. Finally, when the fault on the wider grid is cleared, the microgrid must be able to make the transition back to normal service. Managing each of these phases is a significant technical challenge, and much work remains to develop reliable, flexible and affordable microgrid controllers that can realize these goals.

#### **6.1.1.6 Microgrid modelling**

Microgrids are expensive to install and set up for research purposes. Researchers and developers often rely on software tools to model and then predict the performance of microgrids but there is no single tool available that is immediately suitable. Further, in spite of the fact that many DER have existed for some time, there are few accurate models of wind turbines, solar PVs and fuel cells, along with their associated controllers, currently available [10] to use in existing modelling tools. There is likewise no consensus on models used for the economic planning of microgrids. Research is currently underway to develop various models that serve the needs of the particular research interests of the modeller, for example, optimal operation based on 30 minute demand data [11], [12]. Models of real time markets are being developed [13] to investigate how microgrids can operate as autonomous entities within the wider market.

Ultimately, the entire area of microgrid modelling, from engineering to economic, is relatively immature, and needs significantly more work.

#### **6.1.1.7 Microgrid protection**

In general, devices, such as circuit breakers, that detect and isolate faults in electricity systems are specified assuming that the source has an available fault current much higher than the load.

In a microgrid, electricity can often flow in multiple directions, depending what state the microgrid is in at a particular time. This makes the planning and operation of protection systems quite a challenge. Compounding these challenges, faults may be difficult to detect in microgrids, which often do not have high fault currents, unlike the traditional macrogrid. In such circumstances, a short circuit scenario may be difficult to detect, as the short circuit current was similar to the regular operating state of the microgrid.

### **6.1.2 Non-technical barriers**

As a new technology that represents a fundamental shift in how we operate our power systems, a number of non-technical barriers to microgrid operation also exist.

#### **6.1.2.1 Cost of microgrids**

A barrier to the uptake of microgrids is often the perceived higher financial cost of DER compared with generation in centralized power stations. In particular, the higher per-kilowatt price of distributed generators is often cited as a drawback, while doubts remain about the on-going maintenance and operation costs. Recent studies however have found that the cost of generating power in a microgrid is comparable with present electricity supply, as long as support for PV is available [10]. Moreover, in developing countries without infrastructure, DERs may be more likely to be cost effective, since their installation cost must be compared with that of installing high voltage transmission lines [14].

Financial cost features regularly in optimization studies of microgrids, typically offset against other desired properties, such as CO<sub>2</sub> reduction. A great deal of effort is being given to developing microgrid models that will help calculate this offset. A case study of the hypothetical installation of DERs in a hotel reveals a 10% cost saving and 8% CO<sub>2</sub>

saving [15]. Behind these models are assumptions about the cost of electricity sourced from traditional power stations, which may prove incorrect when a CO<sub>2</sub> tax (or a similar mechanism) is imposed or costs change as a result of new technologies.

#### **6.1.2.2 Business models**

Compounding the cost challenges of microgrids is the broader problem of calculating their returns, in order to justify their commercial benefits to a business. In a simple analysis, a microgrid may only operate as a system to provide uninterruptible power after a wider electricity outage. Calculating the financial benefit from this service, versus the cheaper and less complicated option of insurance can be a challenging prospect.

More sophisticated uses of microgrids may in fact earn the owner a return – as discussed earlier in this White Paper, microgrids may participate in demand side response or similar programmes, earning a return for the response they provide. Whilst conceptually relatively simple, estimating the actual returns from such concepts is quite difficult – currently, the returns from participation in demand side markets vary dramatically based on jurisdiction, location and what incentive programmes are currently in place. Add complications such as varying fuel prices, and the risks inherent with new technology, and calculating a business return from microgrids is a challenging task.

#### **6.1.2.3 Risk evaluation**

Whilst one of the key benefits of microgrids is to help with preparedness and recovery from major electricity outages, the actual risk a particular plant faces against such disasters is often poorly understood. As shown in many of the case studies in this White Paper, humans are generally poor at estimating risks and their consequences, the likelihood of major electrical outages, their length, and subsequent effects on business. It

is understandable that stakeholders may also underestimate the benefits a microgrid may offer.

#### **6.1.2.4 Policy, regulation and standards**

The microgrid concept is relatively new, so it is not surprising that the regulatory framework for integration of microgrids into the wider grid is still developing [16]. Getting this framework right is crucial, as it deeply affects the economic benefits of microgrids [17]. It is clear that the current framework poses some barriers for the uptake of microgrids [15]. For example, IEEE Standard 1547 requires that grid-connected power inverters can detect a grid fault and will shut down in that event. Consequently, commercial inverters are designed to do just that, and there is no incentive for them to offer island transition and support of uninterruptible supply in microgrids. This standard is driving research into the static switch, which can disconnect and reconnect in sub-cycle times [18].

At the operational level, there is no agreed policy relating to the way microgrids should behave under different operating conditions, such as with light or heavy loads, with or without grid connection or after communication failure (see, for example, [19]). Research into standards is being conducted for the operation of microgrids [20] and a new generation of energy management systems is being designed to meet the challenges, in particular to meet the requirements of International Standard IEC 61970 [21]. The work as yet is in its early stages.

The potential for a microgrid to be owned by different entities with conflicting interests is also problematic. Policies should address how investment and maintenance costs should be apportioned between parties, what loads are to be disconnected in the event of faults and what (if any) compensation should be due in the event of a loss of power.

#### **6.1.2.5 Training**

Perhaps one of the greatest challenges to the widespread acceptance and uptake of microgrid technologies is the general lack of familiarity with the basic concepts behind them. As a relatively new technology, there is a lack of confidence in dealing with the concept and in some cases ill-informed preconceptions about their challenges. This concern exists among legislators, electricity systems operators and even technical personnel responsible for microgrid design and installation. Perhaps the latter category is the most worrying – currently, in many countries and jurisdictions, there is a general lack of awareness around the design and construction of electrical systems with embedded generation, two-way power flows, islanding and other key characteristics. Such issues can certainly be addressed by professional development programmes, and need to be a key consideration for the widespread uptake of these technologies.

## **6.2 Future trends**

As a rapidly developing technology, it is always difficult to predict how the broader industry around microgrids may develop. When considering the use of microgrids for disaster relief, it is worth exploring some of the possibilities. The following sections introduce some of the most recent concepts being considered.

### **6.2.1 Virtual microgrids**

This White Paper defines a microgrid as having a number of generation sources located geographically close to each other. Intuitively, to have any benefit, generators must be connected to the same electrical network, yet some of the benefits of microgrids are possible with generators remaining geographically distant. Such a scenario can be referred to as a virtual microgrid.

One commercial example of a virtual microgrid is with deregulated energy markets, where an electricity retailer may benefit from distributed generation sources. When a retailer is exposed to volatile electricity markets, it may use demand management, or distributed generation, to help manage its financial risk. In this situation, the retailer benefits simply by being able to dispatch generation to reduce its total overall load profile. It does not matter where the generators are located, or how they are electrically connected, as long as they are customers of this particular retailer.

In the context of disaster preparedness or relief, virtual microgrids may be relevant because they bring a situation in which the entity controlling the microgrid may have to manage a number of disparate devices, residing in geographical locations that have experienced quite different conditions during the electricity outage.

### **6.2.2 Resource networks**

This White Paper has focused on microgrids as a network of electricity generators, yet in many applications, electricity is only one of the key resources at play. Water, gas and other resources have their own distribution networks, and these may interact with that of the microgrid. Ideally, when considering broader resource management questions, it is important to consider the interplay between these various resources.

Recent research suggests that a microgrid should not be studied as a network of electrical devices, but, rather, as a network of key resources and functions. This might include the provision of reliable electricity and water supply, the use of natural gas, and perhaps the provision of heating or cooling.

Whilst research or development around microgrids of multiple resources is relatively immature, for now we can make one key conclusion regarding microgrids for disaster relief and preparation. As was seen in the Roppongi Hills case study, for an electrical microgrid that may be dependent

on other resources, such as gas fuel supplies, factoring in such dependencies will be critical to reliable microgrid operation.

### **6.2.3 Clustered microgrids**

In this White Paper, microgrids have generally been considered as a standalone entity, with the focus being on how a single microgrid can restore or maintain electricity supply within itself or (for example) the challenges of managing multiple resources within one microgrid. When microgrids proliferate, a number of microgrids could possibly be coordinated together. Such coordination would involve using a hierarchical structure. With no hierarchy, large numbers of microgrids being controlled by one entity essentially face the same challenges as in operating today's macrogrid. On the other hand, adding too many levels of hierarchy adds overheads to the system, wasting resources and slowing responsiveness.

In relation to disaster relief or preparedness, clustered microgrids would have an impact similar to that of the concept of virtual microgrids discussed earlier. They would add to the management complexity, but at the same time bring additional flexibility to the power system.

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# Section 7

## Conclusions and recommendations

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### 7.1 Conclusions

Large-scale disasters, from natural disasters such as the Great East Japan Earthquake and tsunami, to man-made disruptions such as the cascading supply failures in Europe or India, come at a huge cost to local communities, businesses and society at large. Such costs are often caused by the electrical outages frequently associated with widespread disaster. Unfortunately, the number of widespread electrical outages is growing. With our modern dependence on electrical energy, it is clear that the current state of affairs needs to change. We need a way of strengthening our electricity supply against disasters and, in the worst-case scenario, providing rapid restoration of supply.

The predominant reason given for the cessation of business after major disasters such as the Great East Japan Earthquake is the interruption of electricity supply. Often, such supply interruptions were not anticipated, or adequately planned for. In considering the case studies of major electrical disasters around the world, it is clear that more needs to be done in planning for electricity supply failure, and preparing plans for the restoration of electricity supply and continuation of business. Improving plans and resilience against electricity supply failure will require a broad range of activities – from the preparation of standard ways to classify the potential impact of disasters, or a facility's own resilience against disaster, to identifying dependencies such as fuel supplies after road blockage, or even prioritizing energy demands during times of constrained supply. An initial starting point may be to take a similar approach as in the burgeoning area of BCP, and for individual businesses to carefully plan the continuity of electricity supply, and all it entails.

ECS and ECP will be useful for administrations, companies and end-users. In governments, leadership is necessary so that they enhance the plan of disaster countermeasures and provide examples for the countermeasures. It is strongly expected that companies enhance their planning by including ECP as a business system and by developing and adding functions to their products aimed at contributing to the preparedness and the quick recovery against disasters. These evaluation methods require the IEC aid and supervision. For end-users, education and training are very important.

ECS and ECP must be designed for each market based on scalability and interoperability. Standardized guidelines could propose electricity continuity, evaluation against disasters, certification for insurance against disasters and assessment of ECP and ECS (see Figure 7-1).

One technology that can play a significant part in planning for more resilient and reliable electricity supply systems is the microgrid, which builds on the benefits of distributed generation technology. Distributed generation, in the form of local gas or diesel engines, through to rooftop solar systems or even energy storage devices, is a relatively common part of today's electricity systems. Distributed generators are now an accepted means to improve the reliability of electricity supply at their host site, acting as uninterruptable power supplies. Yet today we are failing to realize the full potential of distributed generators. By coordinating multiple distributed generators, and integrating control of loads with this function, we realize the concept of a microgrid. Microgrids bring additional benefits, such as improved reliability (no single



point of failure), lower emissions through providing for renewable energy supply, and even allowing for the export of power to wider areas of the electricity system.

This White Paper presents some examples of microgrids around the world, also reviewing in detail a number of microgrids that were able to maintain electricity supply even after major disasters. In these examples, ranging from single houses through to a data centre or even broader commercial campus, the resilience of the electricity supply improved dramatically by having a carefully planned microgrid based around a diversity of electricity generators, operating closely with loads, and tied together with an intelligent energy management system.

As a new technology, microgrids are not without their challenges. As well as detailing the potential benefits from microgrid technology, this White Paper also examined some of the challenges to their operation, from technical challenges such as the lack of standards that specify common control interfaces between devices in microgrids, through to non-technical challenges such as appropriate

business models to support the business case for microgrid development.

Following the examination of the recent major electrical disasters, the response to these disasters, and the availability of new technologies such as microgrids, several recommendations can be made for policy-makers, industry and standardization organizations, aimed at improving the resilience of our communities against electrical failure.

## 7.2 Recommendations for policy-makers and regulators

### 7.2.1 Encourage the development of electricity continuity planning and systems

An ECP and ECS will ensure that potential disasters have been considered, and local plans have been developed for the restoration of power supply, emergency lighting, telecommunications, and water and sewerage fa-

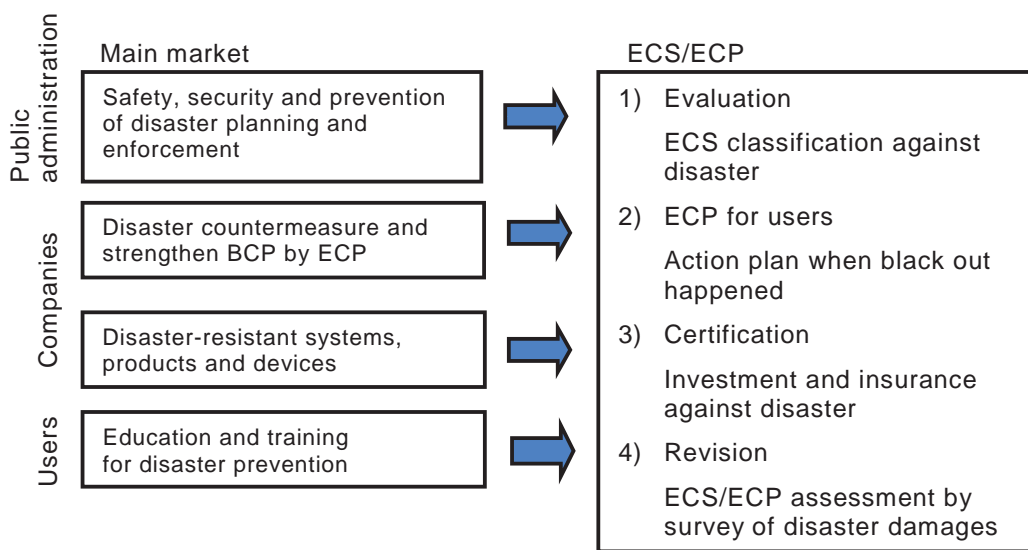


Figure 7-1 | Main market for ECS/ECP

cilities immediately following the loss of electricity supply.

### **7.2.2 Consider the interaction of energy supply and supporting utilities**

When developing disaster recovery plans, regulators need to consider the interaction of outages between the end user's energy supply system, and supporting utilities such as telecommunications or gas supply. These systems have proven critical to one another's operation, yet are often considered in isolation.

### **7.2.3 Remove barriers and consider incentives for demand-side measures**

Policy makers should consider the benefits that could be achieved from distributed generation, load management and microgrid technologies, effectively removing regulatory barriers to their operation. In many jurisdictions, there is little incentive for utilities to encourage such technologies, and securing permission for grid connection can be a cumbersome process.

## **7.3 Recommendations for utilities, industry and researchers**

### **7.3.1 Develop electricity continuity plans**

Whilst many industries have disaster response plans, these are generally focussed on the orderly shutdown of a plant following a major disaster, in order to preserve human safety and minimize environmental issues. Industries should also develop plans to re-establish their operations, particularly after widespread electricity outages. Such plans may consider the use of local generation, the priority of loads, and other key service dependencies. Such plans are likely to rely on standards (yet to be developed) that include specifying the nature of potential disasters, and

the resilience of a particular facility against these disasters.

### **7.3.2 Consider microgrids as a broader electricity system asset**

Today, most thinking around distributed generation or microgrids sees them as only beneficial to a local site. Yet microgrids offer many benefits to the wider electricity system, both in normal operation, as well as following a disaster. If regulators, operators and owners start to consider microgrids as a broader asset to the electricity system, reduced barriers, reduced costs and greater impact are likely to result.

### **7.3.3 Design microgrids to contain a significant amount of renewable generation**

Whilst microgrids have great potential to provide uninterrupted energy supply, many of the case studies in this White Paper showed that microgrids that rely on diesel or gas supply are likely to suffer from limited fuel availability after major disasters, which will limit their usefulness. Whilst microgrids that are predominantly based on renewable energy will require advanced control mechanisms, additional energy storage, load and supply integration, they bring many benefits for disaster preparedness and resilience.

### **7.3.4 Design microgrids and related technologies around "plug and play" principles**

Microgrids are currently "bespoke" technologies that are engineered from scratch to coordinate multiple generators and loads, for one particular deployment. Today's microgrids do not allow an operator to easily bring a new load or generator into the microgrid, and coordinate it with all the other components, or to easily introduce a microgrid to

a new site. To reduce the cost of microgrids and increase their uptake, a “plug and play” mechanism needs to be developed, allowing for simple addition of devices to – or reconfiguration of – the microgrid, without the need for major additional engineering work.

## **7.4 Recommendations for the IEC and its committees**

### **7.4.1 Develop guidelines to classify a facility’s disaster preparedness**

There is currently no uniformly accepted standard that describes how resilient a particular facility is against outside electricity supply failure. Whilst this White Paper provides some early suggestions for a classification framework, more work is needed to develop a classification system that covers a wide range of facilities and potential disasters. Such standards are critical to the preparation of detailed electricity continuity plans for a local site, and the comparison of such plans across different sites. These are desirable to be specified as cross-cutting guidelines.

### **7.4.2 Develop guidelines to classify how a microgrid operates**

Once a facility has a microgrid in place, there are many ways it may operate – it may be able to autonomously re-connect to the grid, it may have only ten minutes of local energy supply, it may not be able to operate islanded, etc. There is currently no uniformly accepted standard that helps to understand how microgrids behave, or interact with the wider electricity system. Whilst this White Paper provides some early suggestions for a classification framework, more work is needed to develop a system that covers a wide range of microgrids and potential operations.

### **7.4.3 Review the above guidelines when major disasters happen**

It is always difficult to predict the impact and likely best responses to a particular disaster, so much can be learnt from the analysis after a major disaster such as the Great East Japan Earthquake, and the responses that ensued. All organizations should revise their preparatory material following a major disaster – from electricity continuity plans for one particular business, through to classification systems, and/or IEC International Standards.

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# Annex A

## Case studies

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### General

In order to provide a starting point to understand the level of disruption a natural or man-made disaster can impose on the supply of electricity to the world's population, nine case studies are presented here. The studies represent a cross-

section of events that caused large numbers of electricity customers to be affected.

Besides the historical facts given in each case study in Tables A1 to A9, a "lessons learnt" summation is also provided. These lessons will allow utilities, planners and standards providers to develop guidelines in preparing for future outages.

**Table A1 | Case study 1: Hurricane Sandy, USA, 2012**

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<b>Disaster name and date</b>	Hurricane Sandy (superstorm) 29 October 2012
<b>Duration of electricity outage (macrogrid)</b>	See Figure A1-2
<b>Duration of electricity outage (internal to site)</b>	Approximately 10 days
<b>Duration between disaster and electricity supply failing</b>	From minutes to no more than a couple of hours with respect to the storm eye making landfall
<b>Number of people affected</b>	More than 8 million customers (i.e. more than 20 million people)
<b>Total generation capacity lost (MW)</b>	300 MW in Manhattan's thermal power plant; 9 MW solar rooftop outside Philadelphia; 3.2 MW Linden PV solar farm; preventive shut down of 3 250 MW in 3 nuclear power plants
<b>Total transmission/distribution capacity lost (MW)</b>	Unknown. Little damage to the transmission portion but significant damage to the distribution portion
<b>Estimated cost of disaster</b>	US Government estimates at more than USD 70 billion
<b>Type of facility that was affected</b>	Telecommunications central office

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**What caused the electricity supply failure**

Superstorm Sandy was a post tropical cyclone (hurricane with low temperature centre of circulation) that affected the Northeastern US in late October 2012. Although Sandy’s wind speeds were at the low end of hurricane strength, Sandy’s extensive size caused a large storm surge that affected coastal areas. Even when the winds were not particularly intense compared to many other hurricanes, the presence of many trees in this area and the large size of the storm caused many outages, mostly at the power distribution level of electric grid, in this case mostly overhead lines.

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**How was electricity supply restored (internal to site)**

Verizon’s Garden City Central Office building, powered by seven UTC 200 kW fuel cells in grid connected mode and by three 1.6 MW diesel engine-generators in grid islanded mode never lost power.

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**How was electricity supply restored (macrogrid)**

By conventional means. Power restoration in the general area where this site is located (Long Island) was considered to be uncommonly slow [22] which prompted an investigation by the State of New York on the electric utility serving this area (Long Island Power Authority) and the resignation of LIPA’s president.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

Little damage to the power grid leads to extensive power outages. Buried infrastructure tends to be more resistant to hurricanes but damage takes significantly longer to be repaired. Microgrids powered by sources using natural gas may be a good solution for hurricane-prone areas. Several sites relying on onsite standby diesel generators lost power due to engine fuel starvation originated, in turn, by diesel and gasoline supply disruptions.

Also to be considered:

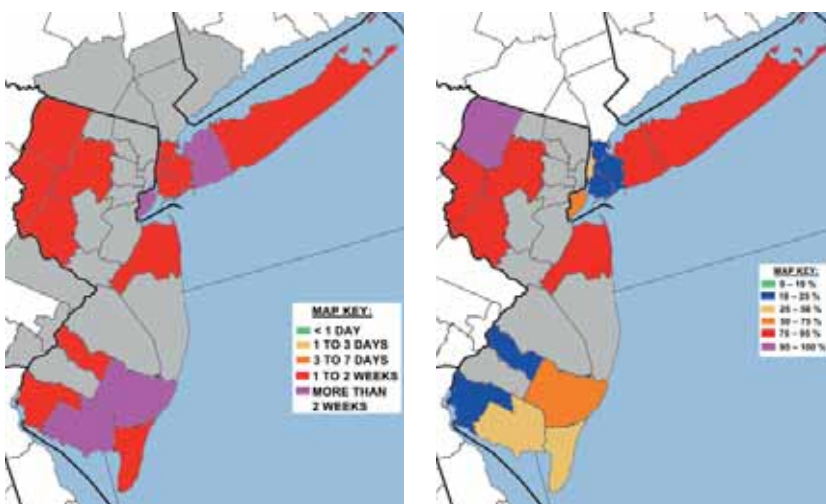
- Proper vegetation management is important to avoid trees falling on utility lines
- Back-up generators should be tested for their reliability to ensure that in the event of power loss they can be switched on without problem. Storing enough fuel for these generators to operate for more than one day is advised
- Most grid-connected solar PV systems were not operational because of safety systems installed to protect utility workers and grid integrity on restart (anti-islanding feature). Availability of even a limited amount of renewable energy, such as solar or microwind, combined with energy storage and a secure grid disconnect mechanism, would allow buildings to provide critical services over an extended period of time
- Microgrids, supported by distributed energy generation, are a potential solution, as they allow decentralized energy distribution at a community-based scale. The application of district heating, cooling and energy plants and renewable energy generation is more scalable, cost-effective and resilient at a community level than their use in individual building applications. Water treatment and other critical services can also be provided more cost-effectively within a community-scale microgrid



Figure A1-1 | Seven 200 kW fuel cells at Verizon's Garden City Central Office on 3<sup>rd</sup> November 2012 [23]



Figure A1-3 | Preliminary information on the percentage of power grid components damaged during superstorm Sandy [23]



Outage incidence indicates the peak percentage of electricity customers in a county experiencing a grid power outage with respect to total number of electricity customers in the county.

Figure A1-2 | Superstorm Sandy: preliminary information about power grid outages duration (left) and incidence (right) [23]

**Table A2 | Case study 2: Great East Japan Earthquake and Tsunami, 2011**

<b>Disaster name and date</b>	Pacific coast of Tohoku Earthquake Tsunami (the Great East Japan Earthquake and Tsunami) 11 March 2011
<b>Duration of electricity outage (macrogrid)</b>	Maximum duration 99 days
<b>Duration of electricity outage (internal to site)</b>	N/A
<b>Duration between disaster and electricity supply failing</b>	Immediate (but further destroyed by tsunami within minutes of the earthquake)
<b>Number of people affected</b>	8.45 million houses
<b>Total generation capacity lost (MW)</b>	28 000 MW (including overall earthquake)
<b>Total transmission/distribution capacity lost (MW)</b>	Included in the above item
<b>Estimated cost of disaster</b>	JPY 25 trillion (including overall earthquake)
<b>Type of facility that was affected</b>	N/A

**What caused the electricity supply failure**

The Great East Japan Earthquake occurred at 2.40 pm on 11<sup>th</sup> March 2011. The seismic centre was 130 km east of the Tohoku region of Japan. A magnitude 9.0 earthquake, it was the largest earthquake in Japan’s history, and the focal region was vast – 500 km by 200 km (= 100 000 km<sup>2</sup>).

The earthquake triggered a tsunami which hit the length of Japan’s east coast, with water reaching a height of more than 10 m and peaking at more than 40 m. It was also the largest tsunami in Japan’s history.

The Pacific coast of east Japan suffered catastrophic damage. The tsunami wave crashed over seawalls and the body of water went up river reaching several kilometres inland, flooding a total area of 561 km<sup>2</sup>.

As the wave crashed through, it carried with it rubble, ships and vehicles. That debris was then dragged out to sea before being washed back inland, again and again.

The water and heavy debris destroyed many buildings and severely damaged others with collapsed ceilings damaging electrical cabling and equipment.

Power systems including generation plants, power lines and substations were also destroyed by the tsunami. The Daiichi Fukushima Nuclear Plant was hit by water 15 metres high at 3.27 pm and at 3.35 pm 40 to 50 minutes after the earthquake.

All power was lost including the back-up generation system which then disabled cooling of the nuclear reactors. This chain reaction caused hydrogen explosions and melt-downs at 3 reactors. Thermal power plants on the coastline were also damaged by the tsunami. None of the reactors could resume operation.

4.4 million customers of Tohoku Electric Power Company and 4.05 million customers of TEPCO lost power after the earthquake.

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**How was electricity supply restored (internal to site)**

Data centres could continue operation thanks to back-up generators. A microgrid facility in Sendai, also continued to supply power.

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**How was electricity supply restored (macrogrid)**

Electricity supply was restored by 19 March to the area supplied by TEPCO, and the number of homes without power was reduced to 160 000 in the area supplied by Tohoku Electric Power Company. Rolling blackouts were conducted on 28 March due to the shortage of power supply in the TEPCO area, caused in turn by the destruction of power plants.

Again 400 million homes lost power because of aftershocks on 7 April.

It took 99 days (18 June) for complete restoration.

Mandatory power savings of 15% were implemented in the Tohoku Electric Power Company and TEPCO areas in the summer of 2011.

Municipal government refused to agree to the resumption of operation of nuclear power plants after maintenance. This decision caused electricity shortages in many regions of Japan that had not been damaged by the tsunami or the earthquake.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

The tsunami was unprecedented, and existing breakwaters and seawalls were demonstrably inadequate in protecting the coastline. This has led to a revision of the potential scale and nature of disasters in the area.

The disaster plan designed to prepare for such events is now being revised. The region's large power plants, including nuclear and thermal power plants, are located along the coastline for cooling water and refuelling. The tsunami demonstrated that critical facilities such as these must be installed higher above sea level.

Damage to electrical facilities, including nuclear power plants, caused loss of power for long periods, resulting in a critical accident.

The tsunami also highlighted the importance of increasing power interchange capacity and the need to install local photovoltaic generation and batteries. Rolling blackouts severely affected the private sector and also demonstrated the importance of providing a minimum power supply to business facilities that need continuous power supply.

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**Table A3 | Case study 3: Chinese winter storms, 2008**

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<b>Disaster name and date</b>	Chinese winter storms 2008
<b>Duration of electricity outage (macrogrid)</b>	About 2 months from the beginning of the storms to restore power supply to all customers
<b>Duration of electricity outage (internal to site)</b>	Not a microgrid case
<b>Duration between disaster and electricity supply failing</b>	N/A
<b>Number of people affected</b>	129 people died; 1.66 million were relocated, and many more were affected in power, communication and traffic systems interruption, house collapse and damages to crops
<b>Total generation capacity lost (MW)</b>	N/A
<b>Total transmission/distribution capacity lost (MW)</b>	About 36 000 power lines (10 kV and above) failed; 8 000 transmission towers (110 kV and above) collapsed; 2000 substations failed
<b>Estimated cost of disaster</b>	Direct economic loss: nationwide more than RMB 0.15 trillion; power industry about RMB 25 billion
<b>Type of facility that was affected</b>	Transmission lines/towers, distribution lines/ poles, substations

**What caused the electricity supply failure**

A series of long-lasting winter storms with heavy snows, ice and abnormally cold temperatures caused heavy icing on power grid facilities, exceeding the designed ice thickness the facilities should be able to withstand. Coal supply for thermal power plants was affected by interruption of transportation.

**How was electricity supply restored (internal to site)**

Not a microgrid case

**How was electricity supply restored (macrogrid)**

Hundreds of thousands of utility staff, thousands of emergency mobile generators and a huge amount of power network equipment and materials were engaged in the task of de-icing, rush repairs and rebuilding power facilities.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

Many of the power systems' deficiencies were exposed, including grid structure and strength, generation mix and distribution, coal supply to power plants, power supply to power system communication links, anti-icing and de-icing measures, disaster precaution/monitoring, emergency response training of utility staff and customers, etc.

Theoretically, microgrids might be able to help maintain power supply to critical customers, or even support in grid splitting and recovery. But concerns were raised on how microgrids can contribute to fighting such long-lasting winter storms, since the transportation of fuels to them may be interrupted, and the sunshine for PV generation is weak due to the bad weather.

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**Figure A3 | Ice-damaged transmission tower, China [1]**

**Table A4 | Case study 4: Hurricane Ike, USA, 2008**

<b>Disaster name and date</b>	Hurricane Ike Landfall on 13 September 2008
<b>Duration of electricity outage (macrogrid)</b>	See Figure A4-5
<b>Duration of electricity outage (internal to site)</b>	N/A
<b>Duration between disaster and electricity supply failing</b>	In some areas, such as the southern tip of the Bolivar Peninsula, power was lost about 12 hours before the hurricane eye made landfall. In the Ohio River valley outages started more than a day after Ike made landfall in Texas
<b>Number of people affected</b>	About 4 million customers (more than 12 million people)
<b>Total generation capacity lost (MW)</b>	2 050 MW in Sabine Power plant
<b>Total transmission/distribution capacity lost (MW)</b>	Unknown. Little damage to the transmission portion but significant damage to the distribution portion
<b>Estimated cost of disaster</b>	USD 30 billion in 2008
<b>Type of facility that was affected</b>	Not a microgrid case

**What caused the electricity supply failure**

Hurricane Ike made landfall on the north-eastern coast of Texas on 13 September 2008 as a category two hurricane in the Saffir-Simpson scale (maximum of 5). Although its wind strength was moderate, its large size created a storm surge typical of much stronger hurricanes, which levelled several coastal towns (see for example Figure A4-1). Having caused significant damage in Texas, the remnants of Hurricane Ike moved north and east towards the Ohio River Valley, where it combined with a cold front. This combination created a significant storm that caused major power outages in the Ohio River Valley, more than 1000 miles from Ike’s landfall point. As a result of these combined effects, Hurricane Ike is still to date the worst hurricane in terms of power outages that have ever affected the US Gulf Coast area – even worse than Hurricane Katrina (see Figure A4-2).

**How was electricity supply restored (internal to site)**

The site shown in Figure A4-3 is an apartment complex in the northern tip of Galveston Island. Power to this site was restored by the deployment of a portable diesel generator provided by the local utility company and that was connected to the distribution portion of the electric grid. Hence, it can be considered an ad-hoc microgrid.

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**How was electricity supply restored (macrogrid)**

By conventional means. These conventional means included the deployment of transformers on wheels (see Figure A4-4) to restore service in damaged substations and replacement of thousands of damaged poles and hundreds of miles of overhead conductors. Power restoration in the general area where this site is located took more than 2 weeks. Power restoration and damage intensity information are shown in Figure A4-5.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

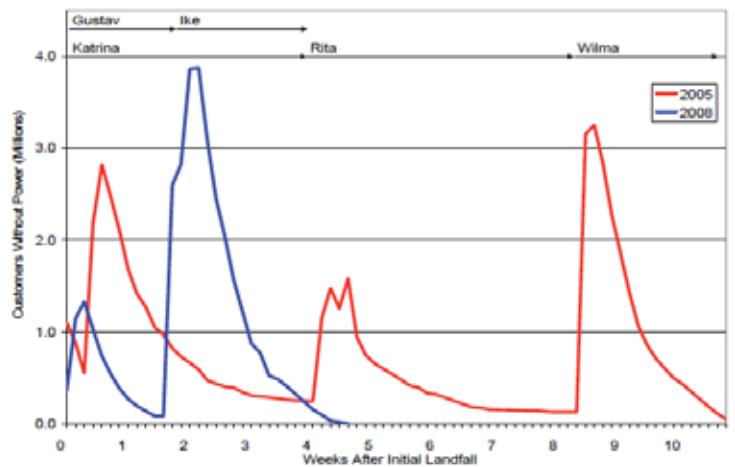
Little damage to the electricity distribution grid can lead to extensive power outages. Existence of a microgrid may have prevented loss of service in most of the areas affected by this hurricane. Deployment of ad-hoc distributed generation reduced the power outage duration in specific sites. Natural gas distribution service was not significantly affected by this hurricane except in relatively small areas where the damage was extreme.

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**Figure A4-1 | Gilchrist, Texas, after Hurricane Ike [24]**



Source: OE/ISER Situation Reports.

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**Figure A4-2 | Power outage information of the 2005 and 2008 hurricanes that affected the USA [25]**



Figure A4-3 | Apartment complex in Galveston Island, Texas, powered by a portable generator connected to the distribution portion of the grid [24]



Figure A4-4 | Portable transformer used to restore service in a damaged substation [24]

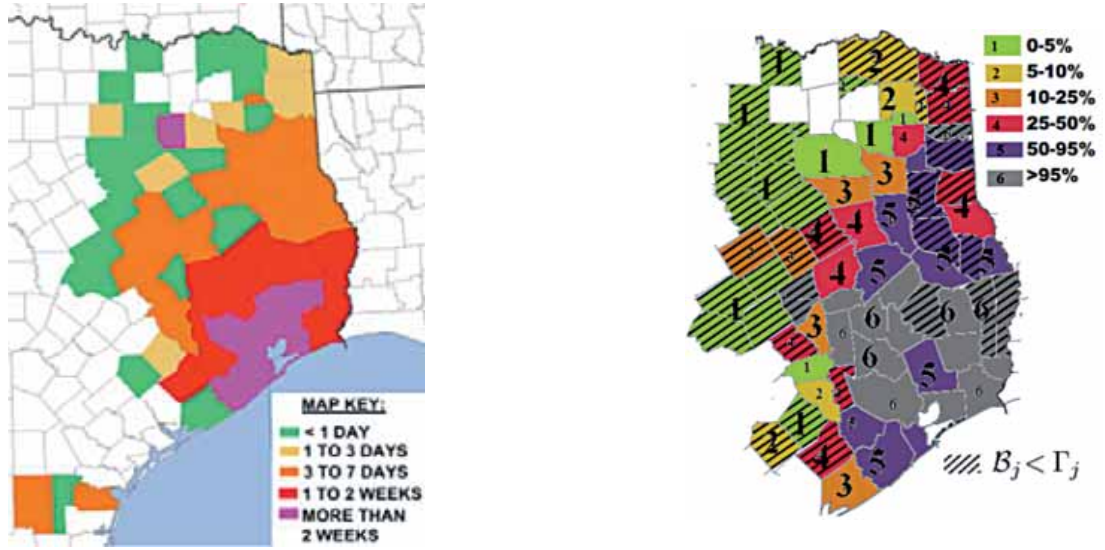


Figure A4-5 | Power outage duration (left) and intensity (right) due to Hurricane Ike [22] [24]



Figure A4-6 | Power grid damage from records obtained with field damage assessments [24]

**Table A5 | Case study 5: River floods, Thailand, 2011**

<b>Disaster name and date</b>	River floods in Thailand August-December 2011
<b>Duration of electricity outage (macrogrid)</b>	None
<b>Duration of electricity outage (internal to site)</b>	0 to 2 months depending on location
<b>Duration between disaster and electricity supply failing</b>	1 month
<b>Number of people affected</b>	13 million; 450 people died
<b>Total generation capacity lost (MW)</b>	None
<b>Total transmission/distribution capacity lost (MW)</b>	135 MW (lost or shutdown)
<b>Estimated cost of disaster</b>	USD 45 billion, mostly economic opportunity loss
<b>Type of facility that was affected</b>	Industrial estates, homes and communities

**What caused the electricity supply failure**

Although river floods occur every year in the central areas of Thailand, the 2011 flood was the worst in the previous 50 years. Storms hit the north of Thailand in July-August. Massive volumes of water moved south and overflowed rivers in the north and central areas. Flood water levels reached more than two metres in some places. Due to the flat plains of the region, the flood waters and their effects remained for 2 to 3 months. Hundreds of thousands of people had to be evacuated. Factories in industrial estates had to be closed and electricity supply shut down. Some transmissions and distribution poles went down and medium voltage substations were also flooded.

**How was electricity supply restored (internal to site)**

Not a microgrid case

**How was electricity supply restored (macrogrid)**

There was minimal damage to the macrogrid as none of the energy production facilities were in flood areas. Electricity services were quickly restored to homes and factories after the water receded. Some substations that were temporarily closed due to flood could be activated using spare parts.

**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

Flooding from rain can be anticipated many weeks before it arrives. Accurate prediction about its volume, speed and direction can prevent or lessen the severity of the disaster. Electrical equipment such as high voltage transformers can be elevated to avoid the floodwater. Thailand does not have a microgrid. These floods show that if a microgrid facility is in the vicinity of a flood area, its capability is jeopardized.

**Table A6 | Case study 6: Typhoon-19 (Japanese cyclone), 1991**

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<b>Disaster name and date</b>	Typhoon-19 (Japanese cyclone) 27-28 September 1991 as an example
<b>Duration of electricity outage (macrogrid)</b>	Maximum duration: 157 hours and 42 minutes (Chugoku Electric Power Company)
<b>Duration of electricity outage (internal to site)</b>	N/A
<b>Duration between disaster and electricity supply failing</b>	The following data were recorded in the area of Chugoku Electric Power Company: <ul style="list-style-type: none"> <li>▪ 28 September, 1.00 am: just after the passage of Typhoon-19, 1.6 million houses (40 % of all houses of Chugoku area) lost power</li> <li>▪ 29 September, midnight: restoration of transmission and distribution lines was almost finished, but still 0.1 million houses were without power</li> <li>▪ 30 September, early morning: 0.53 million houses lost power again because of rain together with salt from seawater</li> </ul>
<b>Number of people affected</b>	62 people died and 1 499 people were injured 4.7 million houses lost power (10 % of all houses in Japan)  NOTE In the area of Chugoku Electric Company where the damage of the typhoon was largest, 1.6 million houses (40 % of all houses of Chugoku area) lost power
<b>Total generation capacity lost (MW)</b>	N/A  NOTE The lost generation capacity was not very large, but transmission and distribution lines were heavily damaged by strong winds and salt from seawater. The major impact to the generation plant was the damage to bus-bar insulators from salt
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**Total transmission/distribution capacity lost (MW)**

The following data were recorded in the area of Chugoku Electric Power Company (no available data for all of Japan):

- Transmission: 24 power lines failed, and there were 28 incident points caused by the collapse of a steel tower (by strong wind) and salt from seawater
- Distribution: 1 900 distribution poles failed (causing 64 % power failure of distribution lines). 14 000 failures of pole transformers by salt from seawater, and 3 500 utility poles collapsed

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**Estimated cost of disaster**

Payment of insurance: JPY 568 billion

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**Type of facility that was affected**

Not a microgrid case

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**What caused the electricity supply failure**

The years 1991 and 2004 were bad for typhoons in Japan. In 2004, more than 10 typhoons hit Japan. In 1991, one big typhoon (Typhoon-19) had a large impact.

On 27 September 1991 at 4.00 pm, Typhoon-19 made landfall in the Nagasaki prefecture and proceeded north along the shoreline of the Japan Sea. Typhoon-19 was very large: its central pressure was 940 hPa, its maximum wind speed at the centre was 50 m/s, the storm covered more than 25 km<sup>2</sup>, it was 300 km in diameter, with the broader area of strong winds covering 15 km<sup>2</sup> from the centre of the storm.

There were record-high winds especially in the Chugoku area. Along its course, many power failures were caused by damage to transmission and distribution lines caused by strong winds. Power equipment was also damaged by salt from seawater over a wider area and the salt damage was exacerbated by rain after the passage of Typhoon-19, which caused secondary power failures – or extended the duration of power failures, some to more than 157 hours.

It took 6 days to restore power completely after the damage caused by Typhoon-19.

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**How was electricity supply restored (internal to site)**

Not a microgrid case

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**How was electricity supply restored (macrogrid)**

The power utility company conducted the restoration. Shortly after the passage of Typhoon-19, they started replacement of the collapsed utility poles, steel towers and other power equipment including snapped transmission and distribution lines.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

The power utility company is continuously making efforts to reduce the length of power outage after each disaster. They are making transmission and distribution networks with redundant supplies, constructing stronger utility poles, and making power equipment resistant to salt damage.

For example, in 2004, Typhoon-18, similar in size to 1991's Typhoon-19, hit the Chugoku area. But the damage from Typhoon-18 was remarkably reduced. Only 350 utility poles collapsed, approximately 1/10 of the number in Typhoon-19. 0.95 million houses suffered power failure, approximately 60 % of those affected by Typhoon-19.

The best way to prepare is by predicting more accurately the course of the typhoon. By using the meteorological satellite, the typhoon position is measured every hour, and the predicted course of the typhoon for the coming 24 hours is updated every 3 hours. With better warning, people can go home from school, office, etc., to prepare. Factories can shut down their machines and facilities to avoid unexpected power failure that would damage machines, and prepare to restart.

As for the microgrid, the effects of the typhoon are largely the collapse of utility poles, snapping of transmission and distribution lines, salt damage by seawater etc. A microgrid system that consists of underground distribution lines and substations would be preferable. A facility-level microgrid with private power generation would also be preferable.

A typhoon usually passes in a day and does not damage transport systems supplying fuel. One or two days' fuel stock may be sufficient for private power generation.

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**Table A7 | Case study 7: Victoria bushfires, Australia, 2009**

<b>Disaster name and date</b>	Victoria bushfires, Australia (Black Saturday) 2009
<b>Duration of electricity outage (macrogrid)</b>	Several days
<b>Duration of electricity outage (internal to site)</b>	3 500 homes were lost over months to reconnect
<b>Duration between disaster and electricity supply failing</b>	Immediate
<b>Number of people affected</b>	173 people died
<b>Total generation capacity lost (MW)</b>	N/A
<b>Total transmission/distribution capacity lost (MW)</b>	N/A
<b>Estimated cost of disaster</b>	N/A
<b>Type of facility that was affected</b>	Rural homes and communities

**What caused the electricity supply failure**

Bushfire in south-eastern Australia is a constant threat and in 2009 major outbreaks and strong westerly winds fanned the fires to a new level of intensity. Roads were blocked and people killed attempting to drive away from the fires.

The intensity of the fire front destroyed entire towns. The restoration of power supply was not so much hindered by the fire damage, although many poles had to be replaced and new wire strung.

**How was electricity supply restored (internal to site)**

Not a microgrid case

**How was electricity supply restored (macrogrid)**

Reconstruction of burnt power poles

**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

The electricity supply systems in rural Victoria are largely 22 kV supported on wooden poles. In the case of the Black Saturday fires, the fires’ speed over the ground reduced the incidence of burnt power poles. In these fires the large brown coal burning power stations which generate the electricity were not affected and continued to generate throughout the emergency.

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Line crews from the distribution companies were quickly on the scene restoring electricity supply but in most cases the houses which they had supplied had been destroyed.

Nevertheless, it is folly to use wooden poles in fire-prone areas. Whilst current practice is to use concrete poles for new construction, millions of older, wooden poles remain, with regulators apparently powerless to influence the distributors to upgrade their old wooden pole assets.

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**Table A8 | Case study 8: Cyclone Tracy, Darwin, Australia, 1974**

<b>Disaster name and date</b>	Cyclone Tracy, Darwin, Australia 25 December 1974
<b>Duration of electricity outage (macrogrid)</b>	Several months; last customer connected 6 months later
<b>Duration of electricity outage (internal to site)</b>	4 days to hospital and emergency services
<b>Duration between disaster and electricity supply failing</b>	Immediate
<b>Number of people affected</b>	50 000
<b>Total generation capacity lost (MW)</b>	Minimal
<b>Total transmission/distribution capacity lost (MW)</b>	Complete city system lost
<b>Estimated cost of disaster</b>	Unavailable
<b>Type of facility that was affected</b>	City of Darwin

**What caused the electricity supply failure**

Extreme cyclonic event directly overhead- Cyclone Tracy category four storm. Cyclone Tracy was a very severe tropical cyclone that hit Darwin (population 50 000) with great precision in the early hours of Christmas Day in 1974. Wind speeds were not recorded as all wind speed recording equipment was swept away. However, reverse engineering of the failures of engineered structures produced estimated wind speeds of between 320 km/h and 350 km/h.

**How was electricity supply restored (internal to site)**

Not a microgrid case

**How was electricity supply restored (macrogrid)**

Most buildings and much of the electricity supply system were destroyed. The electricity supply system consisted of a heavy oil-fired steam power station, 66 kV transmission system and 11 kV and 22 kV distribution mostly on overhead steel poles. The power station was damaged but not destroyed and was able to generate electricity by day 4 to supply the Royal Darwin Hospital. Damage to distribution lines was the main holdup in reconnecting those customers who were capable of taking supply and the last customer requiring reconnection was connected in June 1975, about 6 months after the cyclone.

The principal problem for the electricity system was distribution damage. The distribution assets were not just destroyed by the high winds but by the flying debris of thousands of houses blowing apart and impacting on distribution assets.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

The lesson for microgrids in cyclone areas is simple – build the distribution underground and harden the power stations and substations against the effects of wind, water and debris damage.

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**Figure A8-1 | Cyclone Tracy, Darwin, Australia, 1974 [26]**

**Table A9 | Case study 9: Cascading failure, Italy, 2003**

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<b>Disaster name and date</b>	Blackout in Italy 28 September 2003
<b>Duration of electricity outage (macrogrid)</b>	A black out affected the entire Italian grid, with the exception of the Sardinia island. The duration was from 3 to 20 hours, depending on the zone of the country
<b>Duration of electricity outage (internal to site)</b>	N/A
<b>Duration between disaster and electricity supply failing</b>	The initial event was a tree flashover of a high voltage line, feeding Italy from Switzerland, at 3.00 am, on Sunday, 28 September 2003.  The blackout happened about 30 minutes later
<b>Number of people affected</b>	56 million people
<b>Total generation capacity lost (MW)</b>	In sequence, all the interconnecting lines between Italy and neighbouring countries were lost as well as all the generation units in Italy  When the blackout happened, the load of the Italian grid was about 27 500 MW, well below its peak. The Italian grid was fed by its internal sources with 20 500 MW and by import of 7 000 MW
<b>Total transmission/distribution capacity lost (MW)</b>	N/A
<b>Estimated cost of disaster</b>	A precise analysis is not available. Some independent sources estimate the cost at about EUR 390 million. This is an estimate and the situation might have been worse if the disaster had happened on a workday
<b>Type of facility that was affected</b>	N/A
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**What caused the electricity supply failure**

The supply failure originated at the loss of an interconnecting line (called “Lukmanier”, a 380 kV line from Switzerland to Italy) early on a Sunday morning, caused by a tree flashover. The attempt to reclose the line was unsuccessful due a too high phase angle.

After that event, another interconnecting line (called “San Bernardino”, a 380 kV line) became overloaded and the operators decided to reduce the Italian import of energy. However, the measures taken were not sufficient (probably because they underestimated the reduction necessary) and the latter line also tripped, probably due to a sag of the cables, overheated by the current in excess of the rated value, with a consequent tree flashover. This latter event is still uncertain.

In a few seconds, other lines interconnecting Italy to France, Austria, and Slovenia tripped in sequence, leaving Italy isolated from the rest of the European grid. Automatic load shedding was put into operation in Italy but the voltage and frequency in the northern Italy grid began to collapse too much and in sequence the power stations on duty began to trip too. In two minutes the entire Italian grid lost its generation capacity and a general blackout was unavoidable.

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**How was electricity supply restored (internal to site)**

Not a microgrid case

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**How was electricity supply restored (macrogrid)**

The plan to restore the entire grid was put into operation immediately after the failure by the transmission and distribution system operators. However, due to the extent of the blackout, the procedure for restoring the power was slow and the entire Italian grid was completely restored after 20 hours. In some parts of the country the energy was lost for few hours only, while other parts waited a full day before having energy again.

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**What lessons can we learn about electricity supply resilience, restoration, or microgrid operation from this disaster?**

The various commissions that investigated the blackout said that the major causes were the unsuccessful reclosing of the first line that tripped and lack of a sense of urgency by the grid operators after this event, especially regarding the overload of the second line that tripped in sequence. The various reports said that a natural event and human error in incorrectly evaluating the situation were the basis of the blackout.

Could microgrids have been a solution? Probably not on such a large scale, since microgrids are not a solution for a nation-wide disaster.

However, microgrids could possibly have been a solution on relatively small scales, like grids for single communities, or for single industries that need a high quality of service in terms of energy supply, or for urban electric transport in order to provide regular service. The power for these microgrids can be provided by distributed generators (either renewable or conventional ones) and each microgrid must be controlled by its own power management system in order to be able to operate in an island mode.

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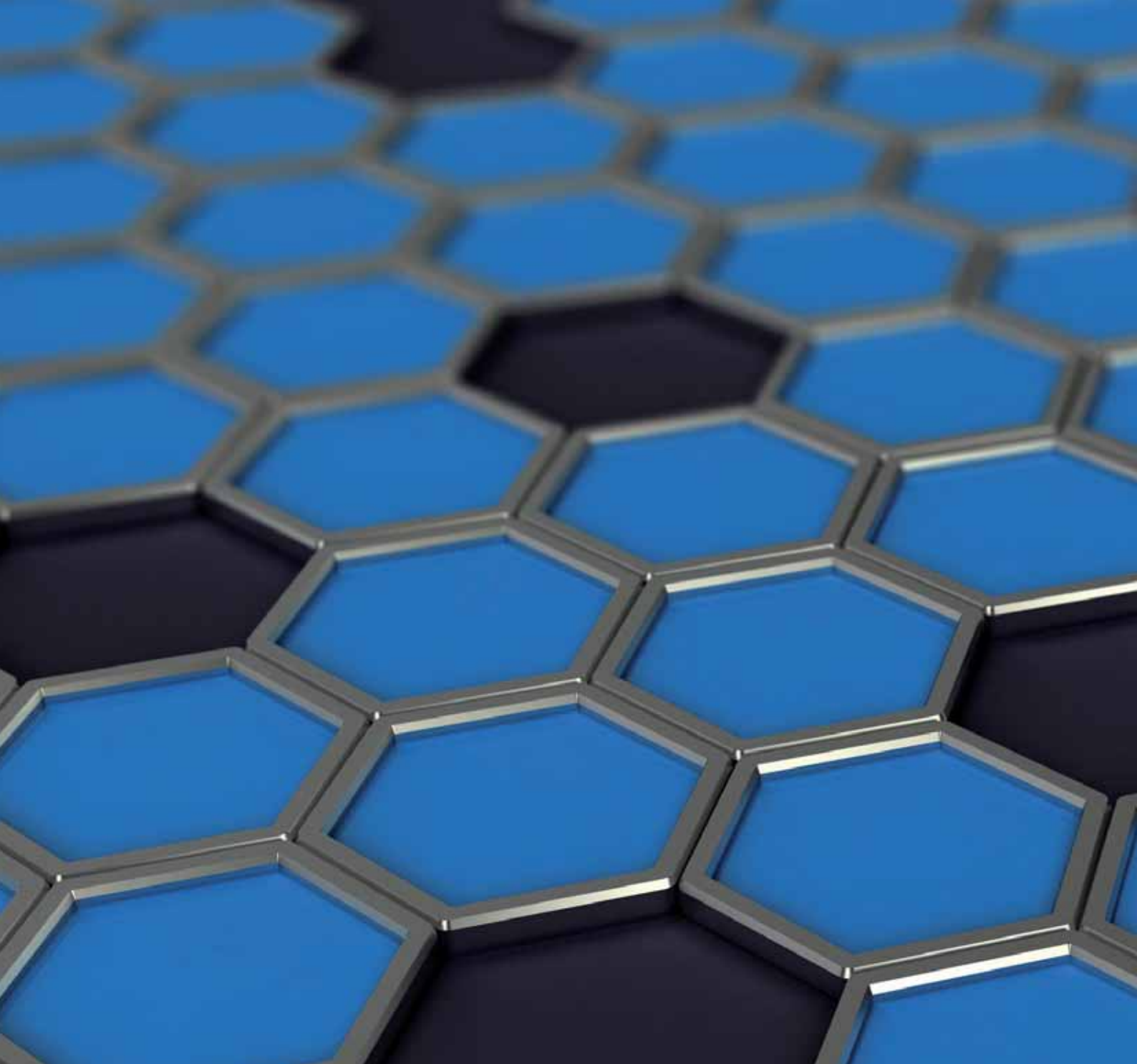
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