MAKING URBAN POWER DISTRIBUTION SYSTEMS CLIMATE-RESILIENT

Yunfeng Yue

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ABBREVIATIONS

ADB	Asian Development Bank
COVID-19	coronavirus disease
DAS	distribution automation system
DER	distributed energy resource
DMC	developing member country
DRE	distributed renewable energy
EMP	emergency management plan
GPD	grid partitioning design
HILF	high-impact and low-frequency
kW	kilowatt
MW	megawatt
PRC	People’s Republic of China
SCADA	supervisory control and data acquisition
SHS	solar home system

EXECUTIVE SUMMARY

The coronavirus disease (COVID-19) pandemic resulted in unprecedented social, health, and economic impacts globally. But it is also a wake-up call in terms of looking into emergency management and resilience levels of infrastructure in countries around the world.

Building back better and enhancing urban infrastructure resilience have become more urgent and important. Energy has played a critical role in fighting the pandemic by helping provide basic daily necessities, health services, and work-from-home facilities including digital connections. In providing energy that is indispensable for a livable city, power distribution systems face significant instability and uncertainty; this puts forward higher requirements for energy resilience.

The Asian Development Bank (ADB) is committed to aligning its operations with the Paris Agreement, and it is currently revising its energy policy. A greener, smarter, and more sustainable energy system in Asia and the Pacific shall be supported by ADB's operations for coping with future disasters.

In ADB's Strategy 2030, "making cities more livable" and "building climate and disaster resilience" are two of the seven operational priorities. About 2 billion people live in urban areas in Asia and the Pacific, and more will migrate from rural to urban areas. ADB (2021) estimates that 64% of the population will dwell in cities and adjacent areas by 2050. By building a resilient power distribution network, countries can effectively adapt to various disturbances as well as address the high-impact and low-frequency threat to achieve a safe and reliable power supply and ensure social and economic development.

Against this backdrop, this working paper investigates solutions that can contribute to building a strong, robust, and resilient power distribution network. First, it describes the major internal and external risks and challenges that urban power systems face. The paper outlines vulnerabilities against the main features of building resilient power distribution networks. Second, it puts forward a range of detailed solutions based on case studies that highlight the capacity of risk perception, system flexibility, hardware endurance, emergency response, and outage recovery. Third, it describes the role of renewable energy and microgrid in improving the resilience of future power distribution networks.

Resilience enhancement measures are not only technical solutions and means of strengthening assets. They also involve capacity building and emergency management. This paper aims to help ADB's developing member countries in building a more resilient urban energy infrastructure.

I. CHALLENGES TO THE URBAN POWER DISTRIBUTION SYSTEM

Urbanization and energy infrastructure. Rapid urbanization has been seen in many countries in Asia and the Pacific during the past decades. The urban residents in this region increased from 375 million in 1970 to more than 2 billion in 2019 and will increase by another 1 billion in the next 30 years, pushing the regional urbanization rate to about 64% by 2050 (ADB 2021). With more than 80% of the global gross domestic product generated in cities, urbanization plays a leading role in sustainable growth (World Bank 2020). The prosperity and development of modern cities depend on infrastructure facilities and services. However, the widespread city expansion placed a huge strain on infrastructure development. Facilities such as transport, hospitals, water supply, sanitation, waste management, energy, and telecommunications are classified as lifeline infrastructure, which are underdeveloped and underfunded in most cities in developing member countries (DMCs) of the Asian Development Bank (ADB) (UNESCAP 2019).

A strong, robust, and resilient urban distribution network is an essential part of "building back better" under ADB's Strategy 2030 Operational Plan for Priority 4: Making Cities More Livable (ADB 2019).

Pandemic-related concerns. The coronavirus disease (COVID-19) pandemic makes electricity indispensable. Under the lockdown situation as a result of COVID-19, uninterrupted power supply has become an obviously critical input for basic services such as health care, food production and supply, and online businesses providing basic social needs. Also, a smooth electricity supply is necessary for household-level activities such as working from home, online schooling in a comfortable indoor environment (air-conditioning), and making online services available for essential activities such as bill payments, online shopping, etc.

Challenges to urban distribution networks. As most of the energy comes from outside of the city, the power system, especially the electricity distribution system, is a pivotal lifeline facility for people and all other dependent sectors. However, urban distribution networks face an increase in uncertainty, disturbances, and risks, causing power interruptions and outages. The disturbances and risks are both internal and external to the power system as summarized in Table 1. The external risks include natural hazards, military conflict, terrorist or cyberattacks, and other extreme events occurring due to the high-impact and low-frequency (HILF) threat. Large-scale power blackouts will not only result in tremendous economic losses, but also cause huge social impacts and casualty accidents. The internal risks, besides outages caused by equipment failures, include fluctuating generation from variable-output renewable energy such as high-penetration distributed photovoltaics, and the demand for massive charging of electric vehicles. Many countries are also facing the challenges of power system reliability issues and brownouts.

Major threats to urban power distribution systems from extreme weather events. ADB's DMCs in Asia and the Pacific region encounter increased incidence of extreme weather events. Unprecedented natural calamities such as Typhoon Molave in the Philippines (2020) and the Uttarakhand Mountain floods in India (2013) are a few examples that exhibit how extreme events have impacted socioeconomic growth and sustainable development. The Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation identified that climate change has already changed the severity and frequency of some extreme weather and climate events in some global regions.

Table 1: Main Challenges to Urban Power Distribution Networks

Category	Event	Impact
External Risks		
Climate and natural hazards	Storm/typhoon Flood Fire Earthquake Extreme high/low temperature	Damage to power facilities, power outages, unavailability of power generation equipment
Pandemics	COVID-19	Change of load profile, staff contraction, maintenance risk
Sabotage	Cyberattack	Part of or all system control failure, power shutdown
	Terrorist attack/military conflict	Damage to power facilities, energy outages
Internal Risks		
Intermittent power supply, fluctuation of load	Solar power or wind power generation interconnection Major loads on or off-line	System overload, voltage fluctuation, poor power quality
Weak system design	Low redundancy of system structure	Cascade power failure
	Lack of distributed power source and spinning reserve	Prolonged recovery
	Inadequate system control	Low flexibility
Equipment failure	Substation breakdown Line fault/short circuit Communication failure Aged/overloaded equipment	Partial power outage, loss control of the system
Operation and management	Improper maintenance, maloperation	Line or equipment failure, prolonged power outage

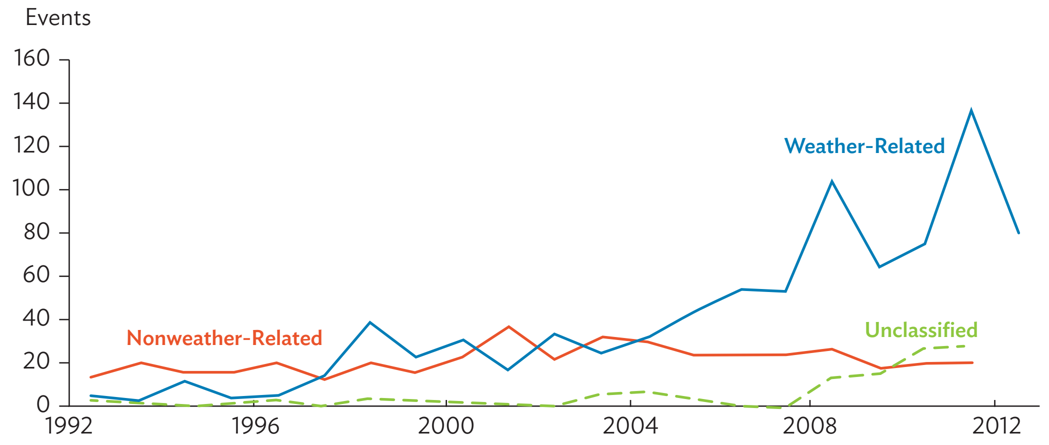
COVID-19 = coronavirus disease.

Source: Author.

Extreme weather events ravaged public infrastructure and became the main cause of power outages around the world (Nicolas et al. 2019). The economic loss due to power outages caused by extreme natural hazards, such as thunderstorms, hurricanes, and blizzards, has increased dramatically in recent years. Even in developed nations like the United States, extreme disasters have become the primary factor leading to blackouts in the power grid (Figure 1). From 1980 to 2021, the United States has suffered a total of 310 weather disasters at a total cost exceeding $2 trillion (NOAA 2021).

In the southern region of the People's Republic of China (PRC), freezing rain from January to February 2008 caused severe damage to power facilities. Over 172,000 high-voltage transmission towers of the State Grid Corporation collapsed, 12,000 were damaged, and 153,000 kilometers of low-voltage lines broke down. Consequently, power outages spread among more than 170 counties and cities and resulted in a direct economic loss of over $1.54 billion (Hu and Hu 2008).

Figure 1: Observed Outages to the United States Bulk Electricity System, 1992–2012



Source: The United States Energy Information Administration.

Cities in Bangladesh's coastal regions are no stranger to disasters and have suffered more from power outages by cyclones or floods in recent years (IFRC 2020). In May 2020 when cyclone Amphan hit the Bangladesh coast, 1,600 power poles and lines were torn down, 725 transformers were damaged, and about 20 million out of 36.5 million customers were plunged into darkness (Hossain and Murtuza 2020). The cities of Barisal, Chandpur, Chittagong, Cox's Bazar, Jessore, and Khulna all suffered from the devastation caused by both the cyclone and COVID-19 (Shetu 2020).

II. POWER DISTRIBUTION SYSTEM RESILIENCE CONCEPT AND FEATURES

Vulnerability. The distribution network is the terminus of the power system, providing "last mile" connectivity to consumers. Compared with the transmission grid, the resilience of the distribution network is naturally vulnerable because of the following: (i) low-voltage equipment or poles are fragile and designed with lower strength; (ii) the distribution network has a low degree of automation with minimal remote metering, protection, switching, and control devices; (iii) there is lack of redundancy as distribution systems are often not designed following the N-1 principle; (iv) protection measures are simple in configuration for lower voltage, and the recovery relies primarily on manual operation; and (v) in some cities, overhead cables of telecom, internet, and cable TV networks are messily entangled with power lines and poles, which poses a risk for all the networks.

Concept of resilience. Resilience is the ability of a system to withstand a major disruption within acceptable degradation parameters, adapt its own state in the event to reduce losses, and recover within an acceptable time and composite cost and risks (Haimes 2009). In 1973, ecologist Holling first introduced the concept in his article, *Resilience and Stability of Ecological Systems,* and in 1996, further categorized resilience into ecological resilience and engineering resilience.

Tangled power lines. Poor power distribution networks can affect supply, as in Dhaka and Khulna, Bangladesh (photos by the author).

Resilience engineering is a multidisciplinary design that enables a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions (Hollnagel et al. 2010). The concept has been widely used in many engineering disciplines.

Urban power distribution system resilience. In electricity distribution networks, resilience refers to adaptability and the ability for fast recovery in response to uncertain changes or disturbances. As shown in Figure 2, when a resilient distribution network encounters a small disturbance in the system, it can flexibly adjust and adapt to changes in conditions. Under extreme conditions, part of the distribution network's function is disrupted, but critical loads can still be supported, and the system can quickly revert to its normal state.

Key Features to Achieve Distribution System Resilience

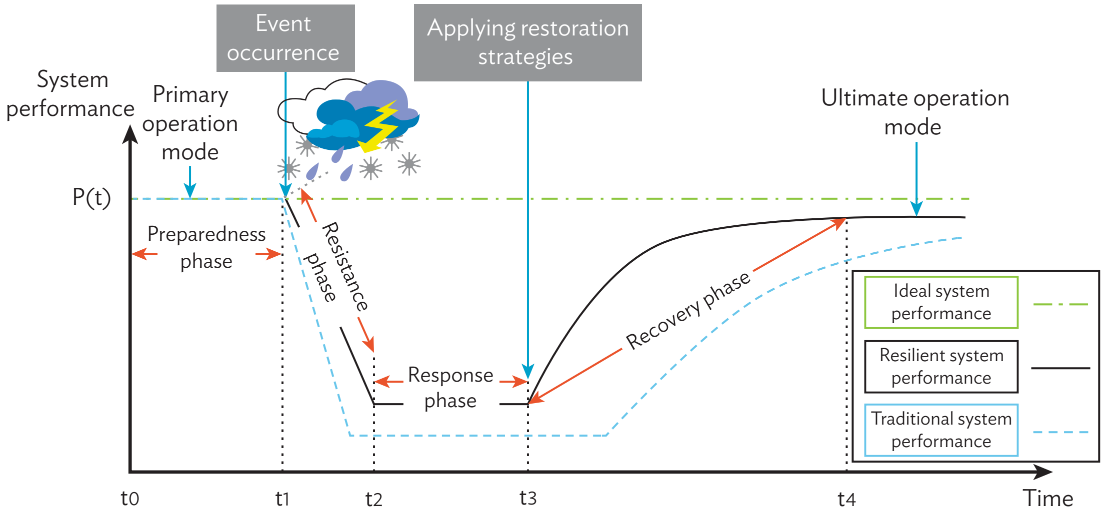
Risk perception. This refers to the ability to acknowledge, recognize, measure, and anticipate the changing environment, disturbances, and operational status before the disturbance occurs, including the ability to analyze the possible impacts.

System flexibility. The distribution system shall be flexible, controllable, and resourceful for the anticipated disturbances. The system can adjust itself in real time and adaptively respond according to the changing environment and minimize the impact on the system.

Hardware endurance. This is the ability to withstand, absorb, and resist physical damage or external stress caused by the disturbances. It also refers to the ability to guarantee service to critical loads (uninterruptible consumers such as hospitals).

Emergency response and outage recovery. This is the ability to quickly respond, react to minimize the losses, and restore electricity service to the public and critical loads after the damage caused by the disturbance.

Figure 2: A Resilient Power System in the Face of a Disruptive Event



Source: M. Mahzarnia et al. 2020. A Review of the Measures to Enhance Power Systems Resilience. *IEEE Systems Journal*. 14 (3). pp. 4059–4070.

Among all the challenges, distribution network resilience emphasizes the response to extreme HILF events, such as climate change; increasing frequency of small interference events, such as high proportion of distributed renewable energy (DRE) resources; and increasing cybersecurity incidents. The resilience of the distribution network should be planned and designed from the energy system perspective, focusing on the coordination and joint improvement of system perception, adaptability, endurance, and recovery. Of course, economic feasibility and efficiency are also important—in this context, investment in system resilience is in effect an insurance policy.

III. SOLUTIONS TO BUILD URBAN DISTRIBUTION SYSTEM RESILIENCE

A. Developing Risk Perception Capabilities with Information and Communication Technology Support

The risk perception capability of the distribution system is built on meteorological data, equipment electrical data, and load data collected in real time by various sensors in the system and historically recorded. The online and off-line data reflect the evolution of external risks and system operating conditions. Through data mining, analysis, and simulation, specific external risks and potential duration, as well as locations and impacts can be predicted. In this way, early warnings can be issued and preventive measures can be taken in advance.

With meteorological data, many simulation models have been set up aiming at natural hazards, such as ice storms, fires, and typhoons, to study the development and impact on the power grid (Yang et al. 2018). Many utilities in cities are taking steps to install online monitoring devices on the facilities (Box 1). The general monitoring system structure is shown in Figure 3.

Box 1: Online Monitoring Device Installed on the Facilities of Shenzhen Power Utility

The Shenzhen Power Grid is one of the mega urban power grids with the highest power supply load density and supply reliability in the People's Republic of China. The supply area is 2,421 square kilometers, with 3.3 million customer accounts and covering more than 10 million people. The maximum load is 19.13 gigawatts, and around 92.34 billion kilowatt-hours of electricity are sold every year, with the system average interruption duration index of 24.6 minutes.

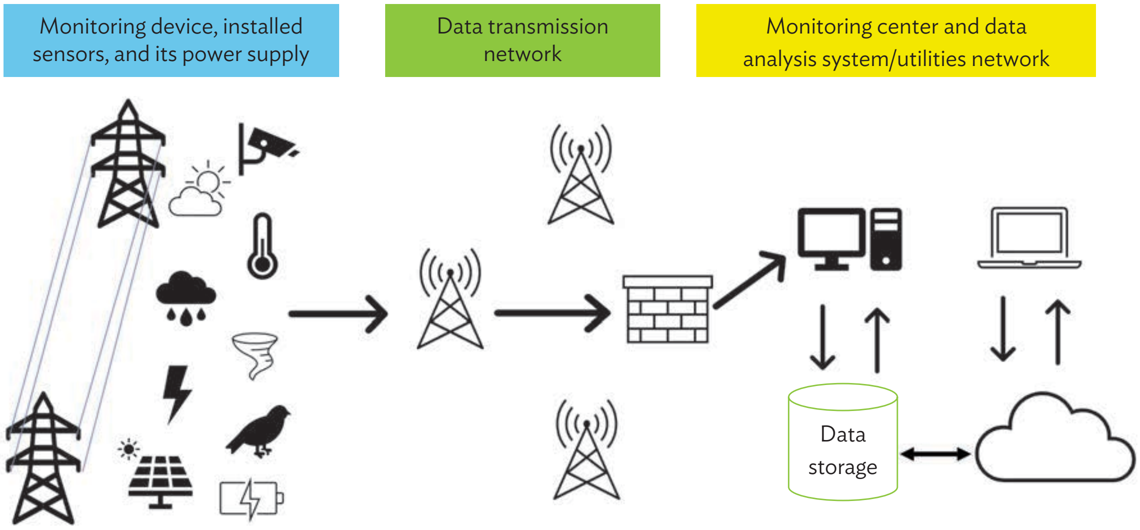
The power grid in Shenzhen is often hit by typhoons and heavy rains. To improve the reliability of the power grid and mitigate the impact of natural hazards, the Shenzhen power utility started to install online monitoring systems for power lines on a pilot basis in 2013, including video, images surveillance, infrared scanning, meteorological devices, and tower stability monitoring.

The monitored data on temperature, humidity, and wind speed plus videos and other imageries are uploaded to the control center through the communication network. Some image data can be analyzed and processed on-site. The data analysis shows real-time status of facilities, weather development, and other risks.

Besides the weather forecast, online monitoring also covers insulator contamination and line zinc oxide arresters, environmental safety, theft control, and wire temperatures. With the information of the conductor (i.e., temperature, tension, sag, and meteorological conditions), the prevailing maximum capacity of the conductor can be calculated. In case of emergency load transfer, the transmission capacity can be fully utilized. This monitoring system also enables the use of dynamic line ratings, which allows more energy throughput in specific grid segments without overheating the lines.

Source: *China Southern Power Grid*. Shenzhen's power supply reliability takes the lead in entering half an hour in major domestic cities. https://www.sz.csg.cn/xwzx/gsxw/202103/t20210308_1119.html.

Figure 3: System Architecture for Online Monitoring



Source: Author.

In Japan, utilities found that the growth of renewable energy led to insufficient transmission capacity of power networks. The online monitoring device would also help to maximize usage of the existing capacity by measuring temperature and current of the conductor in real time and dynamically controlling the power flow (Sanda et al. 2018).

The online monitoring data comprises information on ambient temperature, wind speed, insulator contamination, wire temperature, galloping, ice, and snow.[1] The data is transmitted via optic fiber, wireless public network such as General Packet Radio Services, code division multiple access, or third-generation cellular technology (3G) network. The power source can include batteries supplied by solar energy or wind solar hybrid (or other renewable energy) so that monitoring can continue during operational disruptions.

The fault rate of urban distribution networks is higher than that of high-voltage transmission grids. In addition, the low-voltage network at 10 kilovolts and below is rarely equipped with electrical information collection and monitoring devices, making it difficult for fault prediction and fault location. However, some scholars have developed an early risk warning scheme to identify typical faults based on different natural hazard scenarios (Liu, Zhu, and Ma 2015). With the continuous improvements in power grids, data-driven models with higher operating efficiency have gradually become one of the popular risk-prediction methods for facilities under extreme weather (Guikema and Quiring 2012; Guikema et al. 2014).

B. Enhancing System Flexibility for Resilience

The flexibility of a distribution network is derived from various distributed power sources and variable network topology design, supported by distribution automation, microgrid energy management, and other smart grid technologies. Redundancy and resourcefulness are key features for flexibility. A resilient distribution network can adjust its own operating status according to different disturbances and hazards. Before disruptive events, operators can change the operation mode and network connections according to the forecast information to reduce outage scale as much as possible and ensure the continuous power supply for critical loads.

Many distributed devices can provide flexibility support for the distribution network, including the devices that provide active power (such as energy storage, microgas turbines, and photovoltaics) and the devices that provide reactive power (such as shunt capacitors, static var compensators, and power inverters). Under a normal operation mode, these devices and equipment can support the stable flow and quality of power, avoiding the negative impact caused by fluctuating loads and intermittent renewable energy output. When there is a power outage caused by damage to the transmission grid or upstream lines, the distributed power generation can provide backup power from the end of the distribution network, and the system runs in an island mode and continues to supply power and support for the black start.

Grid topology is the key to urban grid flexibility as it enables network reconfiguration and flexible dispatching operations. Generally, urban distribution networks adopt "closed-loop design and open-loop operation" in topology with radial structures to customers requiring low voltage. Flexibility of mature urban distribution networks is reflected in the design of redundancy and grid partitions, such as ring network structure and double-sided power supply structure.

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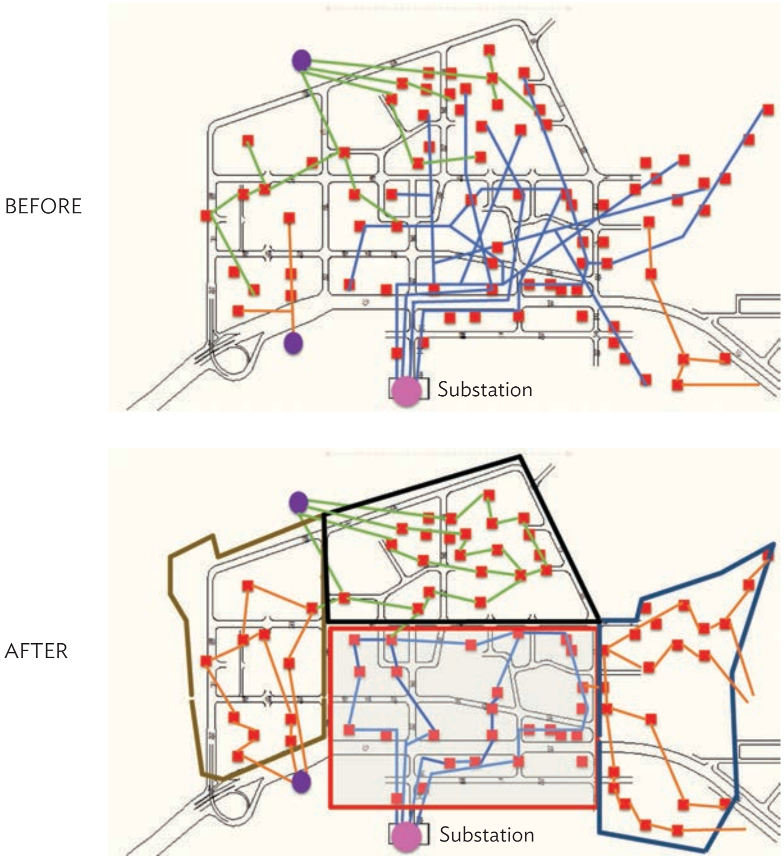
[1] Galloping is rapid vertical motion due to wind action on conductors with a layer of ice or wet snow, which occurs on all types of conductors used in overhead power lines. It can cause insulator or fitting damage and line trips.

The grid partitioning design (GPD) is a modular-based design methodology starting from the low-voltage to the high-voltage grid. As shown in Figure 4, before rehabilitation, the distribution network was radial with complicated connections and irregularities. The GPD method zones load according to their region and category, integrate and redesign the existing power supply lines and equipment, making the distribution network easier to manage and increasing the redundancy for higher reliability. This method divides the distribution network into many small subnetwork modules. If distributed generation, energy storage, and control equipment are added to these modules, it will become a microgrid. These subnetworks are interconnected through both high-voltage and low-voltage systems. The main grid substations are designed and configured according to the load density and load grade. The power exchange among the subnetwork was controlled to a minimum in normal operation. When a disaster strikes, the modules of the network can back up each other and the damaged districts can be isolated to ensure the power supply of other regions, minimizing the total outage area (Box 2).

The distribution automation system (DAS) is another important tool for utilities to implement flexible control of the distribution network. The DAS enables remote monitoring and control of the distribution line switchgears based on communication technology. Fault monitoring, fault location and isolation, backup circuit switch-on, and other tasks can be completed automatically in a preset sequence with faster operation rate, contributing to shorter power interruptions. Real-time control of DAS also allows automated power management, which offers a load-shedding algorithm and optimized system operation with multiple power sources during emergency events.

Figure 4: System Structural Enhancements Adopting Grid Partitioning Design



Source: Author.

Box 2: New Distribution Network Based on Grid Partitioning Design Adopted by Power Utility in the People's Republic of China

In 2012, Beijing's urban power distribution network was dominated by radial links, with few interconnections for backups. The lack of mutual support between the power distribution areas contributed to prolonged power outages. At that time, the average interruption hours of customer (AIHC) was 57 minutes.

To enhance the efficiency of the distribution system, including its operation and maintenance, power utilities of Beijing started to plan for the upgradation of Beijing's distribution network based on grid partitioning design (GPD). The objective is a smart, reliable, and green distribution network. First, the whole distribution area was divided into 44,000 network modules according to location and customer category (i.e., residential, industrial, or commercial). Referring to factors such as load density, administrative level, and functional positioning, the network modules are banded together to form 566 power supply regions. According to the importance of the load, these regions were assigned one of five service priority categories: A+, A, B, C, and D, where A+ is the highest priority consumer.

The utility carried detailed research and design according to load predictions result for each supply modules, with 44 categories of customers, a total of 3,262 typical loads selected for forecasting study, and both historical data and future development taken into account. The distribution automation system was also installed.

In 2020, Beijing Electric Power Company sold 105.75 billion kilowatt-hours per year of electricity and served 8.9875 million customers. Its distribution automation has achieved a coverage rate of 100%. Once a fault occurs in the district power distribution network, it can "self-heal" intelligently. The entire process does not require manual intervention but is automatically completed by the control system. With a maximum load of 24.57 gigawatts, the power supply reliability rate has reached 99.995%; in the core area of the city, it has exceeded 99.9999% with an average annual outage time of 21 seconds.[a]

Shenzhen Power Supply Company (SPSC) began to pilot its network renovation in Luohu District in 2009. The district was divided into 132 network modules according to the load category, location, and urban layout. Network modules became the basic unit for managing equipment and customers. After the pilot, the network structure is clearer, reducing the complexity of switching and shortening the recovery time. The average power outage time of users in this area was reduced to 21 minutes.

SPSC scaled up the GPD in other districts in the following years; hence, the grid structure, supply capacity, and utilization rate of facilities were significantly improved. Shenzhen City's transferable distribution line rate reached 96.44% in 2020, with AIHC at 24.6 minutes.

The graph presents the average quarterly household power outage time in Luohu District, Shenzhen, for 2011–2012. The table shows a comparison of the distribution network performance before and after the GPD network design renovation.

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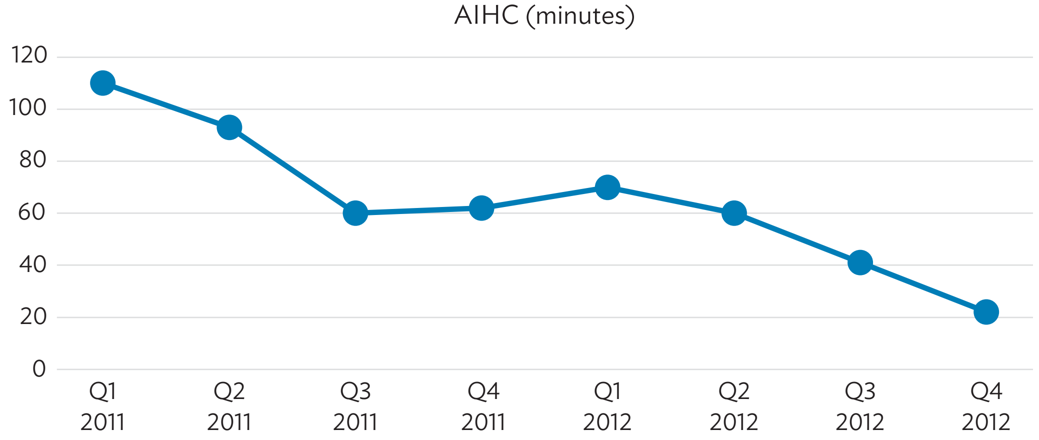
[a] D. Min and Z. Yi. 2014. Grid Partitioning Design: The New Coordinate for the Development of the Capital Distribution Network, PRC. *State Grid News*. p. 128.

continued on next page

Box 2 *continued*

Average Household Power Outage Time in Luohu District, Shenzhen, 2011–2012



AIHC = average interruption hours of customer, Q = quarter.

Source: J. Li et al. 2015. Research on a Grid-Based Optimal Planning Method for Urban Distribution System. *Southern Energy Construction*. 2 (3). pp. 38–42.

Comparison Between Before and After Implementation of New Distribution Network Design in Luohu District, Shenzhen

Evaluation Index	Before	After
Transferable distribution line	67%	94%
Interstation line connection	42%	95%
Average line load rate	38%	45%
Number of heavy-load lines	35	2

Source: J. Li et al. 2015. Research on a Grid-Based Optimal Planning Method for Urban Distribution System. *Southern Energy Construction*. 2 (3). pp. 38–42.

Source: Compiled by the authors.

C. Building Hardware and Software Endurance for Facilities

The basic resilience of a distribution network is the ability to withstand various physical damages. Towers, poles, and overhead lines are vulnerable as they are exposed to the external environment. The dominant cause of large-scale power outages is collapse of poles and towers, or broken lines. The restoration process of these facilities is labor- and time-intensive.

Reinforcement methods can start from planning. In areas prone to natural hazards, utilities should use stronger equipment such as concrete poles, aerial insulation line, indoor gas insulated substations, and underground cables (Box 3), or build protection facilities for the equipment such as elevated construction and other flood-prevention measures.

Box 3: Converting Overhead Distribution Lines to Cables for Bengaluru Power Distribution Network

Bangalore (also called Bengaluru), India has a population of more than 10 million (as of 2017) and is the fourth most populous city in India. Since 2015, with Bangalore's economic growth averaging approximately 6.8% per year, power demand has increased at an average annual rate of 10%.

Bangalore experiences frequent thunderstorms that occasionally result in power outages and flooding. The overhead distribution system is unsafe, particularly in urban areas. The distribution lines are prone to coming into contact with trees, animals, and human beings, which can cause power failures and fires as well as serious and fatal accidents. Utility poles on sidewalks create obstacles for pedestrians. During disasters brought about by natural hazards, snapped lines and broken poles can lead to accidents, destabilize electricity supply and information network systems, and block emergency transportation roads and evacuation routes. The average annual number of outage duration in 2019 was 112.0 hours per customer, and the annual number of power interruptions was 15.3 times.

To address these problems, the Asian Development Bank (ADB) provided loan financing for a Smart Energy Efficient Power Distribution Project to convert 7,200 kilometers of overhead distribution lines to underground cables, with 2,800 kilometers of optical fiber cables, and install 1,700 automated ring main units adapted with a Distribution Automation System (DAS).

Adopting underground cables prevents electricity theft and minimizes electricity outages from natural hazards and interference with overhead distribution lines by foreign objects. The DAS enables automatic continuity of power flow to healthy sections of the distribution system, efficiently isolating the failed sections until further repair work—without having to dispatch staff to the field.

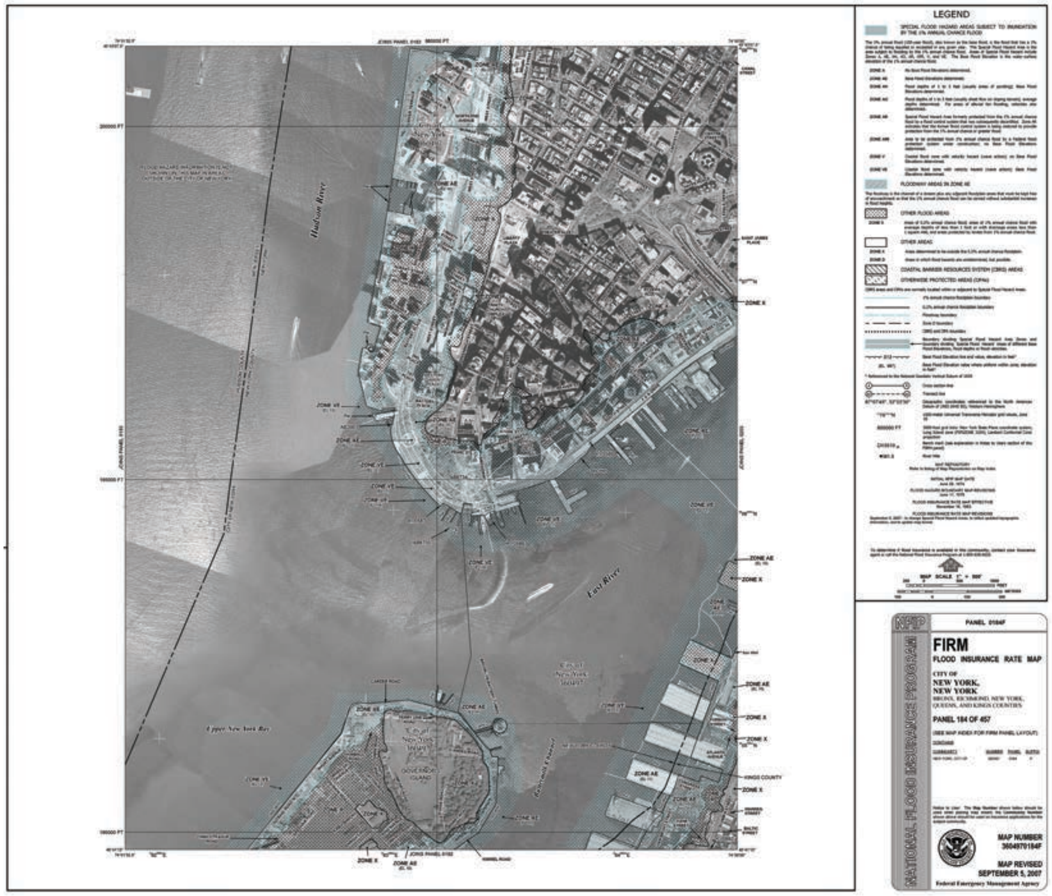
Optical fiber will be installed in parallel with the power cables. Fiber communication can be utilized for a smart metering system, DAS, and any other devices that contribute to making the distribution grid more reliable, flexible, responsive, and smart. Surplus capacity of the optical fiber network will be leased to private telecommunications companies. This will help create better and faster internet communications, which will help support work-from-home and online schooling arrangements during and after the coronavirus disease (COVID-19) pandemic.

The total project cost was estimated at $277.3 million. ADB provided an innovative financing package with a $100 million sovereign loan and $90 million nonsovereign loan. The project is financially and economically viable (details on weighted average cost of capital, financial internal rate of return, and economic internal rate of return are redacted from the publicly disclosed board documents).

Source: Asian Development Bank. India: Bengaluru Smart Energy Efficient Power Distribution Project. https://www.adb.org/projects/53192-001/main.

For existing equipment, inspections, assessment, and functional checks on the working environment before the reinforcement design are essential. For prioritizing investments, selective reinforcement is more cost-effective than wholesale redesign and reconstruction. In many countries, maps of common disasters such as strong wind and floods have been drawn (Figure 5); the vulnerable power equipment within these areas needs to be assessed and strengthened first.

Figure 5: The Federal Emergency Management Agency Flood Map Service Center



Source: Federal Emergency Management Agency (FEMA) of the United States Department of Homeland Security. FEMA Flood Map Service Center. https://msc.fema.gov/portal/home.

Failure of each electrical equipment would cause different impacts of scale and extend to the distribution system. Through the vulnerability analysis, the weak links of the system and the areas that are prone to cascading failures can be found, which can effectively improve the resilience of the entire power distribution system.

In the face of the high-impact and low-frequency (HILF) threat, the N-1 rule for power systems reliability is no longer effective. For some risks, the degree, time, and place of damage cannot be anticipated. The assessment and enhancement can be carried out with a focus on critical loads, including transportation, fire protection, rescue and police stations, hospitals, water plants, signal base stations, shelters, lighting and heating equipment, and other lifeline facilities.

Critical load-based resilience enhancement. Some loads in the power system are directly related to the daily supply for people's lives. Resilience investment should be given priority to where it is most needed. Aiming to provide uninterrupted electricity for critical loads, utilities should consider and take the following steps:

- Identify and enhance the key transmission lines and high-voltage substations that supply power to critical loads;
- Ensure at least one back-up connection for critical loads—the connections shall be strengthened and carefully monitored;
- Connect to or build distributed power sources near critical loads as a back-up supply in case of grid outage; and
- Include end-users' back-up generators, other distributed energy (e.g., rooftop solar), energy storage, or other resources as a supplement.

With this method, by 2021, China Southern Power Grid (CSG) has assessed and built an uninterrupted power grid for all the critical loads in 66 cities and guarantees the supply to the maximum possible extent under extreme conditions (CSG 2021).

Daily maintenance is another important aspect. Routine inspections and regular seasonal inspections can help detect risks in advance. The inspection objective includes not only the transformers, lines, and poles, but also the surrounding vegetation, buildings and other infrastructures, fire risk in densely populated areas, etc. Public consultations and trainings for electricity safety are also necessary.

Cyberattacks and digital resilience. Digitalization can bring many benefits, but it can also make energy systems more vulnerable to cyberattacks (IEA 2017). The rapid development and application of information and communication technology in power systems can improve the system's perception ability but can expose the power distribution system to information attacks. As more information attacks take place in both developed and developing nations (Doan 2021), cybersecurity has become an important part of resilience.

Power system control centers utilize supervisory control and data acquisition (SCADA) to collect, monitor, and control the operating status of the entire system, transmitting data to advanced application software in the energy management system, such as topology analysis, status estimation, bad data identification and correction, and predictive accident analysis. Results obtained from the analysis are used for dispatching decision-making.

With the deepening integration of cyber-physical systems, the fragility of SCADA systems has gained more and more attention. The SCADA system often becomes the starting link of a network attack, which is generally called "SCADA hacking." There are many types of network attack methods that can be used to attack SCADA systems, and false data injection attacks (FDIAs) are one of them. By injecting false data into metering devices distributed in the power grid, FDIA causes the status estimation result to shift from the nonattack state and successfully evades the bad data detection mechanism to achieve the purpose of affecting the operation and control of the power system. Another common cyber threat is the denial-of-service attack that prohibits the transmission of measurement or control signals by occupying communication resources and causing the deterioration of system performance.

Cyberattacks on a few countries in 2016–2020 (Doan 2021) seem to have expanded to various means with strong destructive intent. There are many studies, but there are no silver bullets for defense against such attacks (Bird 2018). The hackers had a deep understanding of the target and a comprehensive knowledge of the energy industry. It is highly likely for hackers to implement more destructive attacks in the future. Awareness of this risk should be raised first among all the stakeholders. The defense measures shall start from the system design with security configuration, keeping firewall and software updated, and incorporating security protocol in daily operations. Preparation for extreme scenarios shall always be necessary.

D. Emergency Response and Recovery

Adjusting system operation status according to the risk forecast information before its arrival can minimize the scale of power outages and maintain continuous power supply to critical loads. This is a preventive measure as the load control and dispatching plan can be formulated and tested in advance. However, when a disaster strikes, it is difficult for the control center to obtain detailed information about the damage in time and take remedial measures. Therefore, the response is determined by the network structure and its running state before the strike. If the distribution network can maximize the protection for critical loads and others that survive, it will help speed up the recovery.

System restoration includes the operation and control method in which, during or after a natural hazard, the distribution network gradually restores the power for critical loads and brings the grid back to a normal state. At this point, the control center may be able to obtain sufficient damage information and take recovery measures such as load transfer and backup equipment.

E. Emergency Management Plan

Posthazard event clearing and power restoration are challenging, which require massive efforts, coordination, and cooperation among departments and individuals of utilities. To ensure an effective and coordinated response for frequent hazards, power utilities must prepare emergency management plans (EMPs) to establish a unified state of readiness and guidelines for standardized and swift actions (Box 4). The EMP is supported by knowledge of previous disasters and stipulates the response measures in different disaster scenarios. When a disaster occurs, utilities can adopt applicable protocol for operations and logistics. The EMP also enables cooperation with transportation, meteorology, telecom, and other government departments for efficient resource allocation and for accelerating postdisaster recovery.

Generally, utility-level emergency plans are event-based action plans, guided by national-level EMPs—e.g., the Crisis and Disaster Management Plan for the Power Sector, 2017 issued by the Ministry of Power, Government of India (MOP 2017). Utility emergency plan specifies in detail the specific organization and measures before, during, and after the occurrence of one or several disasters (PG&E 2019). The EMP would include the classification of an event, severity appraisal, advanced planning and preparation, major critical loads and prioritization, logistic support, inventory, and other definitions of necessary measures to be considered in all aspects of power restoration by each department within the utility.

An information-based management platform for engineers, resources, and backup supplies can realize the expedient and efficient deployment for recovery, such as showing the location of the outage or damage; knowing availability of crews and resources; dispatching contingency generators or mobile energy storage vehicles for critical loads; and scheduling personnel, vehicles, and spare equipment on site. Information technology would support real-time decision-making, update and share the progress of restoration, and provide all staff with timely situational updates. After the disaster, the data of the entire process can be recorded, and the operating teams can assess the damage, evaluate, learn, and make continuous improvement of responses by communicating the findings.

Box 4: Building Power Resilience in Belize

Belize is a coastal country in the Caribbean Sea with frequent hurricanes and tropical storms. Hurricane Dean in 2007 struck Belize and caused a near countrywide blackout, and Hurricane Richard in 2010 affected more than 35,000 customers (over 45% of the utilities' total customer base); yet, the two events only caused about $0.5 million in infrastructure losses.

Supported by the World Bank, a comprehensive study was conducted on building the country's energy system resilience against extreme weather events. The resilience strengthening program of Belize was designed focusing on both the physical power system and the capacity of the utility from five perspectives: (i) segmentation of the transmission network, (ii) strengthening of transmission network structure, (iii) improvement of vegetation management, (iv) strengthening of distribution system infrastructure, and (v) emergency response and recovery planning.

Among these five perspectives, emergency response and recovery plans were developed to improve the speed and quality of response to emergency situations and for more efficient and effective recovery. The response and recovery capabilities will be further enhanced through upgrades of the communication system and improvements of the management of utility and/or client interaction during emergencies, including the implementation of an outage management system and the piloting of the Advanced Metering Infrastructure.

Source: M. S. Jayawardena, B. G. Serna, and J. J. Han. 2016. *The Power System in the Eye of the Storm: The Call for Energy Resilience and Climate Adaptation in Belize*. Washington, DC: World Bank. http://hdl.handle.net/10986/25104.

IV. RENEWABLE ENERGY AND MICROGRID

In the coming years, the power distribution network systems will face many new challenges and become increasingly important. On the supply side, rooftop solar photovoltaics and other distributed power sources will require the distribution network system to absorb intermittent power output more effectively. On the consumption side, new industries, electric vehicles, clean heating, and cooking with electric energy, etc. will continue to drive up the demand for electricity, requiring the distribution network systems to sustain sufficient capacity and high-reliability power.

In terms of grid operation, energy storage technology and energy storage facilities, including electric vehicle batteries, need to interact with the distribution network, while demand-side response and virtual power plants can facilitate more flexible operations by integration into the distribution network system.[2] Figure 6 illustrates the grid morphology, which is common in most ADB DMCs. Figure 7 illustrates the conceptual morphology of urban microgrids, which can operate in "island" mode. Investing in distribution systems is one of the most important aspects to secure the urban energy supply.

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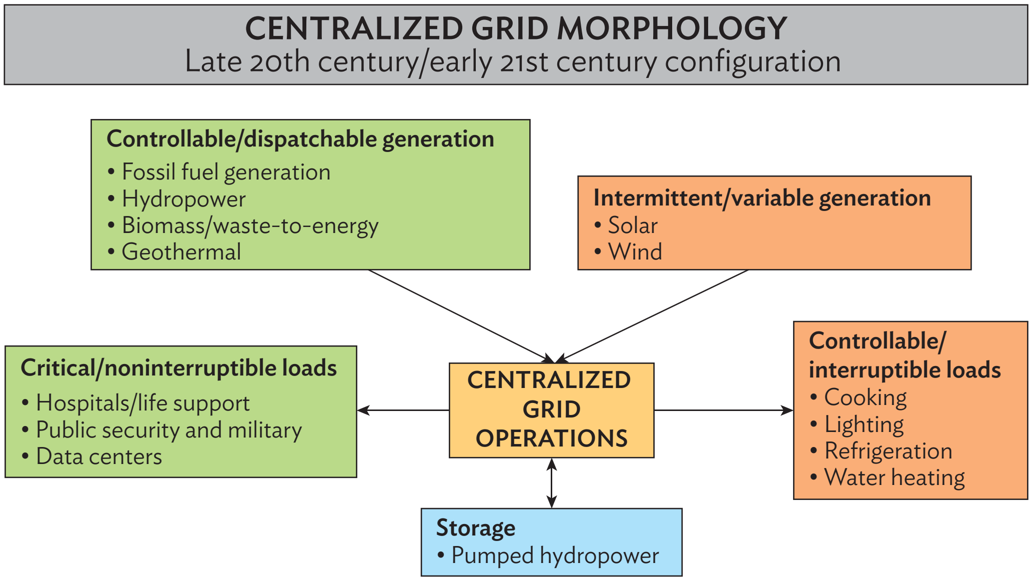
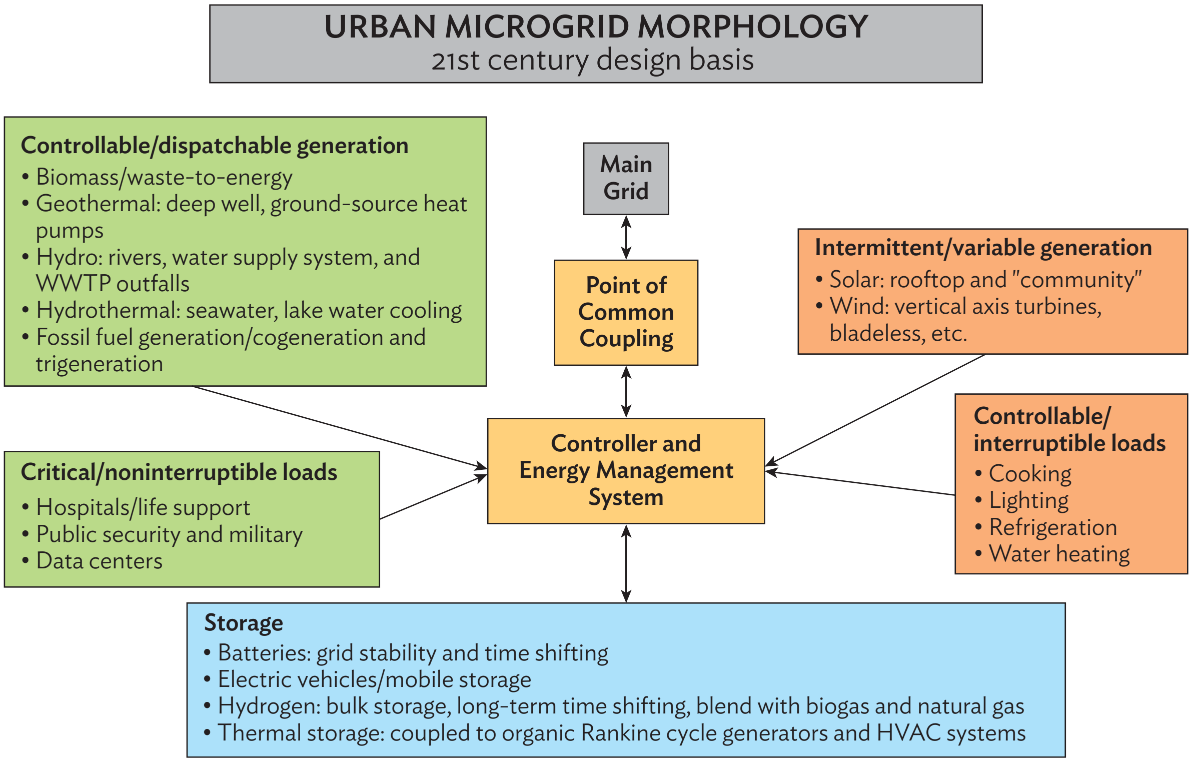
[2] A virtual power plant (VPP) is one of the important smart grid technologies. It integrates distributed clean energy, controllable load, and energy storage system installed in the power distribution network through the energy management system. VPP acts as a special power plant to participate in power market, which can make full use of distributed energy.

Figure 6: A Typical Electricity Grid



Source: P. Wijayatunga. 2021. Presentation Notes for Online Webinar: Building Resilience of the Power System in the Low-Carbon Transition, Season 2. *ADB Virtual Dialogues on Resilient Infrastructure Webinar Series.* https://adb.eventsair.com/virtual-dialogues-on-resilient-infrastructure/season-2

Figure 7: Conceptual Design of Urban Microgrid



HVAC = heating, ventilation, and air conditioning; WWTP = wastewater treatment plant.

Source: P. Wijayatunga. 2021. Presentation Notes for Online Webinar: Building Resilience of the Power System in the Low-Carbon Transition, Season 2. *ADB Virtual Dialogues on Resilient Infrastructure Webinar Series*. https://adb.eventsair.com/virtual-dialogues-on-resilient-infrastructure/season-2

A. Solar and Wind for Power System Resilience

In general, power generation from photovoltaics and wind has both positive and negative effects on the resilience of the power system. Considering the diversified power generation mix, renewable energy can be an effective support for improving resilience. Distributed renewable energy (DRE) helps reduce the vulnerability of the power system to HILF events as it will not be restricted by fuel transportation like a traditional generation nor restricted by geography and climatic conditions like hydropower.

The main challenge of renewable energy power generation is intermittency and fluctuation, which impact voltage and frequency in the grid. These issues can be addressed through on-grid energy storage (e.g., high-power batteries) and more sophisticated weather forecasting to predict solar and wind outputs. In hot climates, solar photovoltaic output will follow daily electricity demand, which is dominated by air-conditioning load, and may provide some system stability during the afternoon peak demand period. For future power distribution system planning, both DRE and climate projection should be considered as a factor.

Impact of intermittency and fluctuation of large-scale renewables. Electricity generated from wind turbine and photovoltaic fluctuates due to variations in wind strength and the intensity of insolation. Progressively higher renewable energy penetration can cause problems such as overcapacity of conductor, frequency deviation, harmonics, voltage fluctuations, and flicker. When there is unintentional islanding with wind and photovoltaic as primary power sources, the voltage and frequency cannot be regulated by grid network. When power supply and demand are unbalanced, power voltage and frequency will fluctuate, which can seriously affect the safety of the equipment and complicate black start ability with an adverse effect on system recovery.

Measures to develop or enhance the positive effects of renewable energy on power resilience and better response to various threats include the following:

- The renewable energy generation forecasting tools and methods shall be adopted. An accurate real-time generation prediction with demand-side management will effectively offset the power fluctuation.
- Adjustable and dispatchable generation, such as energy storage systems, pumped storage, or distributed small capacity gas turbine, shall be planned and installed with fast control and protection system.
- Large capacity renewable energy shall be carefully evaluated from the grid point of view before the connection. The capacity of related distribution lines and substations shall be verified and strengthened if required.
- The site for the construction of renewable energy shall be carefully selected considering the impact of HILF events, based on findings of a detailed location-specific climate and disaster risk assessment.

Distributed small wind or solar systems. The distributed energy resource (DER) or DRE system has many advantages, making it popular in recent years. For example, the United States has installed more than 2 million rooftop solars or solar home systems (SHS) up to 2020 (EERE 2020). In 2017, ADB also approved a loan for Sri Lanka to build about 6,400 rooftop solar generation project (ADB 2017). These systems generally include photovoltaic panels, battery, and control systems, which are simple, flexible, and easy to install. The generation output is generally stable and reliable, with low operation and maintenance costs. When the grid is disrupted by a storm, the SHS will serve as a backup source. Individual end users also enjoy the benefit of both energy resilience and lower monthly electricity bills.

The fluctuation of surplus power produced by the SHS can be regulated by household batteries or electric vehicles. In this way, multiple SHS can effectively improve the power supply in a small area in an emergency.

Nevertheless, not all power utilities or distribution systems support SHS or allow the back feed. Barriers to promoting SHS may be because of both technical and financial aspects. The distribution system was not initially designed to accommodate the reverse flow of power; it is difficult to recover the cost of renovating the distribution network for SHS.

Burning concerns about electrochemical energy storage. Electrochemical energy storage can secure renewable energy generation in a stable and controllable fashion and provide electricity during periods of low production. Driven by demand, megawatt (MW)-scale battery storage is becoming a common feature of urban power grids. However, fire incidents of on-grid battery infrastructure (Energy Iceberg 2021) reveal another risk factor amid a safety probe. The reasons may include the thermal stability of battery cells, leakage, overvoltage, and overcurrent; they may also be related to poor quality installations, faulty operations, missing protection, and lack of overall control systems (Hering 2019a and 2019b). Large-scale battery deployments require the industry stakeholders to incorporate lessons learned and update safety codes and standards.

B. Improving Distribution Network Resilience by Microgrid

Unlike the traditional distribution network, microgrids are controllable entities with some flexible power components (such as distributed power-generation units, photovoltaics, and wind turbines), circuit breakers, and control units for the local network (Figure 7). Energy supply and consumption are more flexible and self-sufficient within the microgrid service area, which can reduce the vulnerability of power supply from centralized generation and long-distance transmission. This feature is particularly pivotal for power system restoration after extreme weather events (Kwasinski et al. 2012).

In addition, due to the uncertainty of the time and location of threat and its uneven impact on the power system, connecting microgrids to the distribution network can significantly improve the network resilience as destruction of the entire microgrid would be highly unlikely. As an independent power source, one microgrid can support other critical loads in the nearby area in case of emergency, thus reducing losses.

A microgrid is a flexible and controllable unit in the distribution network. Through energy management systems, the output of distributed generation can be accommodated. Coupled with demand-side management and energy storage, the impact of renewable energy fluctuations can be mitigated while achieving a high penetration rate.

The value of microgrid in improving the resilience of the power system has been widely recognized. Governments and enterprises are studying technology, regulations, and cost–benefit analysis; some have started piloting microgrid projects (Irie et al. 2013).

Community microgrids. With the community as a unit, investment can be feasible for installing energy storage or building microgrid facilities (Weng, Maitra, and Roark 2018). This allows the community to be isolated from the centralized grid network and operate as an autonomous microgrid when disaster strikes. Many cases have reflected the stability and resilience of the microgrid system.

In New York Co-op City, one of the largest residential communities in the United States, a microgrid was built to save energy costs by producing electricity locally and ensuring reliable supply in extreme weather conditions. The core equipment of this project is a combined heat and power plant that refers to the cogeneration of electricity and thermal energy (heating and cooling) from natural gas. The total installed capacity is 40 MW, which can meet the peak demand of 24 MW of electricity load for all 60,000 residents, with a periodic surplus of 16 MW that can be sold to the power grid (Pentland 2012). In October 2012, Hurricane Sandy caused extensive power outages, while the microgrid in Co-op City continued to supply power to all its residents.

The Great East Japan earthquake and tsunami in 2011 stimulated microgrids development around the country, helping Japan meet its energy needs and build resilience (Lempriere 2018). From the ruins caused by the tsunami, Higashi Matsushima was rebuilt in 2016 with decentralized microgrids to supply power to 70 houses and 15 apartment buildings. This project consists of 460 kilowatts (kW) of solar generation, 480 kilowatt-hours of battery storage, and 500 kW biodiesel generators for backup. The microgrid is designed with the capacity to supply the whole area for hours when the main grid suffers power losses. In case of emergencies such as an earthquake, the energy supply will support the critical load for days to ensure that the hospital services and basic life needs are met.

The Satjelia Island community microgrid project is another example, located in the coastal area of India where many cyclones occur, and its main power grid often gets affected. To mitigate the frequent power outages, six community solar microgrids of 10 kW each catering to about 600 families were built (Basu 2020). The community solar microgrid project provided reliable and clean energy for vital community facilities and assets within the area and continued to supply energy to communities in case of an emergency.

Microgrid clusters for resilience. The capacity of a single microgrid, such as the Satjelia Island community microgrid, is generally small at around 10 megavolt amperes. However, multiple microgrids can be interconnected and operated jointly as clusters with higher capacities. When an individual microgrid is off or its energy storage cannot supply all loads, surrounding microgrids can complement, share the capacity, and provide a backup to their neighboring grid; therefore, urban distribution network resilience can be further improved. This strategy helps reduce investment and enhances distribution system adaptability to unforeseen failure events (Wu and Guan 2013).

Electricity coupled with other forms of energy such as gas, heating, and cooling can constitute an urban multienergy system, improving the overall urban energy resilience through complementarity. In 2015, ADB provided financing for the PRC's Qingdao Smart Low-Carbon District Energy Project, which included natural gas, solar, thermal, geothermal, and waste heat recovered from industrial plants to power its district heating, cooling, and power production and distribution systems (ADB 2015). With multiple sources of electricity, heating, and cooling, the low-carbon transition of Qingdao's energy system also achieved a high level of energy resilience. The total project cost was estimated to be $263.6 million. ADB provided $130 million in sovereign financing. The project is financially viable with a financial internal rate of return of 10.35% versus a weighted average cost of capital of 2.92%. The project is economically viable, with an economic internal rate of return (EIRR) of 16.81%; considering the environmental benefits, the EIRR reached 16.98%.

Multienergy systems complement each other when well-designed (e.g., Qingdao's system), while some systems can collapse without adequate reinforcement. A key factor in the February 2021 power system outage in Texas was the failure of the natural gas transmission system to maintain supply to gas-fired power plants, causing a cascading failure of generation plants, which negatively impacted millions of consumers (Pickrell 2021).

V. INSURANCE PRODUCTS AND POLICY FOR RESILIENCE

As indicated earlier, investments in urban power system resilience are in effect insurance policies against catastrophic events that result in billions of dollars being lost in economic output. It is possible to assess the cost-effectiveness of resilience measures, such as the Qingdao low-carbon energy project discussed earlier. This points to a relatively simple proposition: is it possible to engage the private sector insurance industry in grid resilience and commercialize a broader spectrum of investments in climate change resilience? As climate change increases the likelihood of HILF events, the insurance industry will respond by raising prices for insurance policies (the extent to which this is already occurring is beyond the scope of this report). In some cases, public sector funds may be directed toward subsidizing the price impact to insured parties—e.g., governments may subsidize the cost of insurance for port facilities subject to sea level rise and more frequent storm surge events. A first step would be to adopt weather index insurance policies for grid resilience insurance, with payouts based on specific event thresholds (e.g., Category 5 hurricane, or storm events above a 100-year moving average). Weather index insurance has been applied in the agriculture sector and coral reef rehabilitation, and it could be readily adapted to energy infrastructure.[3]

There are other examples of insurance products, which may be of value for infrastructure resilience. For example, under some types of life insurance policies, the recurring payments are invested so that the value of the policy grows and the policy holder receives return payments on a predictable basis. This type of policy is win-win for the insurance company and the insured party. A variation on the nontraditional life insurance policy could be developed for power system "build back better" programs. For example, a power utility would make regular payments to the insurance company for a weather index-based type of policy. In years when there is no payout triggered, the insurance policy would provide a rebate to the utility for investments in system resilience, which could include physical hardening as well as emergency response planning.

ADB could assist DMCs in developing new insurance policies as climate resilience finance instruments. Some concessional funding might be needed to initiate such a program—e.g., for technical assistance to develop a pilot program, with the insurance industry coming in as a cofinancing partner for ensuing investment operations. A modest amount of grant funding could be leveraged, and with the right policy design, private sector insurance company participation should be a more readily accessible option than climate finance from multilateral sources.

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[3] In India, weather index-based insurance is available for farmers on many crops, covering risk against adverse weather conditions such as floods, droughts, high or low temperatures, and cyclones since 2003. A weather-based crop-insurance product was also introduced in the Philippines to make farming more climate-change resilient. A coral reef insurance was developed in the Mexican state of Quintana Roo in 2018, which will support the conservation and restoration of the reef and the economic resilience of the region.

VI. CONCLUSION AND WAY FORWARD

The COVID-19 pandemic is an ongoing test of the resilience of urban public service systems as communities strive to build back better. Although cyber threats and changes in demand patterns have brought huge challenges to the energy industry, the power industry is, for the most part, maintaining reliable supplies, demonstrating the resilience to the crisis and the importance of continued investment in system resilience.

Moving forward, a collective effort is needed to ensure that the technology and measures can be implemented. Private sector participation is necessary as they can support with comprehensive ideas and solutions including technology, knowledge, finance, and policy making. One of the most promising areas for innovation is partnering with the insurance industry. Insurance can effectively disperse and transfer losses from risks and disasters, reduce and prevent the adverse effects of risks on funds, and has become an important method to deal with the risks. The insurance industry has developed a series of innovative insurance products and services to counteract and disperse climate risks. For example, catastrophe insurance supports postdisaster compensation and reconstruction, and Corporate Risk Solutions for the power and utilities industry (Munich RE 2021). The insurance industry also actively cooperates with scientific research institutions, governments, and nongovernment organizations to support and carry out the identification, research, and management of climate change and related risks.

This paper explained the fundamental principles on how to improve urban distribution systems resilience through technical and management means. Energy utilities in ADB DMCs are advised to proactively plan and prepare for known and unknown risks on the path to achieving energy access for all. Examples show that low-carbon energy solutions can also be reliable and resilient, particularly through the elimination of fuel supply chain risks. Digitalization will play a pivotal role for creating better awareness, monitoring, preventive maintenance, and improvements in urban power system efficiency. The projects financed by ADB in Bangalore, India; Sri Lanka; and Qingdao, PRC clearly demonstrate that investments in power system resilience are financially and economically attractive, and that there is potential scope for greater private sector investment in resilience initiatives.

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Making Urban Power Distribution Systems Climate-Resilient

This ADB South Asia working paper proposes a framework for mainstreaming gender equality and social inclusion (GESI) in energy system planning, establishes a methodology for measuring and comparing community and energy system resilience to extreme weather events, and clarifies how the proposed project design framework can be piloted in Bangladesh. The main contribution of this project design framework and methodology for a GESI-integrated resilient community energy system is its consideration of the technical and social aspects of energy resilience. It proposes to track sociodemographic indicators as key measures of power system performance. The study further proposes a risk-based approach to planning energy systems that would enhance community resilience to extreme weather events.

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