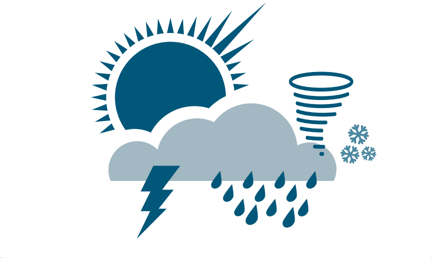
Toolkit for Resilient Cities

Infrastructure, Technology and Urban Planning

A research project carried out by Arup, RPA and Siemens

Content



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Foreword

Across the globe, governments, business and communities are seeing an ever-increasing frequency of extreme weather-related events.These events are playing out against a backdrop of global population growth and urbanization, leading to a complex knot of interrelated pressures. In emerging and established cities alike, these trends are changing the spatial pattern of risk and radically altering perceptions of whether a city is 'safe' or 'well prepared'. Cities have a tremendous challenge to maintain social well-being and economic vitality in the face of these complex, uncertain and constantly changing risks.

City-based residents and businesses depend on the effective and reliable operation of infrastructure systems to deliver energy, mobility, water, sanitation, shelter, information, emergency response and other critical services. Cities need a new way of thinking about how they plan, design, build and manage this essential infrastructure under more challenging conditions. We believe that the principle of resilience offers such a way.

Resilience is the ability of a system to survive and thrive in the face of a complex, uncertain and ever-changing future. It is a way of thinking about both short term cycles and long term trends: minimizing disruptions in the face of shocks and stresses, recovering rapidly when they do occur, and adapting steadily to become better able to thrive as conditions continue to change. A resilience approach offers a proactive and holistic response to risk management and a way for cities to maintain competitiveness in the global forum. It is also a powerful companion to sustainable development thinking.

This report was prepared jointly by Siemens, Arup, and Regional Plan Association (RPA), together with contributions from city managers and experts in urban development and resilience from around the world. The report especially explores the role of technology in enhancing the resilience of cities and their critical infrastructure systems, and the enabling actions that can support a new approach to system design and delivery.

By presenting this research, we hope to stimulate wider discussion about the practise of resilience in relation to infrastructure, and to show how a combination of technology solutions and enabling actions by city and national governments can deliver resilient infrastructure on the ground.

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Summary for Decision Makers

Between 2000 and 2012, natural disasters – including weather, health and seismic events – caused $1.7 trillion (£1.1 trillion) globally in damages. This figure includes direct impacts on infrastructure, communities and the environment, together with reductions in business profitability and economic growth in affected regions.[1]

Resilience is the ability of people, organizations or systems to prepare for, respond, recover from and thrive in the face of hazards. The goal is to ensure the continuity and advancement of economic prosperity, business success, environmental quality and human well-being, despite external threats. In a globalized world, only the most resilient cities will remain economically competitive and attractive for business growth, and capable of adapting to continually changing conditions.

This paper explores how the resilience of critical urban infrastructure systems might be enhanced to prepare cities more effectively for major weather-related hazards[2] and the co-benefits resiliency actions have, e.g. environmental performance, energy efficiency, safety & security etc.

Our research has focused on physical infrastructure relating to energy, transportation, water and buildings. These systems were chosen because they underpin many other essential city operations and services, including sanitation, emergency response, and the delivery of food, fuel and other materials. Our research considers proven technology solutions applicable to emerging and established cities, and the enabling actions required from policy makers, utility providers and other city stakeholders to facilitate delivery.

Creating Resilient Systems

The creation of resilient infrastructure systems may require large scale changes to the way infrastructure is planned, designed, managed and maintained. In many cases, advanced technology and instrumentation can facilitate the development of systems with greater ability to withstand and respond to sudden impacts. Resilient technologies for energy, transportation, water and building systems share common attributes, which are largely underpinned by advanced IT and communication services.

Robustness of new and existing infrastructure

Resilient infrastructure networks must incorporate components that will continue to function in an ever-changing environment. All equipment must be capable of handling stronger winds, more intense rainfall, higher temperatures, and other impacts. This implies improved specifications for new system components (including water and heat resistance) and the use of sensitivity analysis during system planning and design to take account of more extreme operating conditions. Revised asset management regimes are also required to ensure maintenance of acceptable performance. At the network level, utility managers may consider optimizing the location of new or redeveloped infrastructure to reduce exposure to hazards, including undergrounding or elevation of essential equipment.

Decentralized resource supplies and distribution networks

Energy, transportation and water infrastructure can be designed to operate both as part of a large system and to serve a more localized community independently of the wider network. This relies on multiple connected microgrids that can either operate together or individually. During a major hazard event, microgrids can buffer local service users from impacts elsewhere. IT is the key enabler allowing service providers to switch operations from microgrids to integrated networks and vice versa. Besides contributing to resilience, local solutions can also improve the efficiency of water and energy supplies by reducing distribution losses.

Enhanced monitoring and controls

System monitoring and control is underpinned by increased application of IT networks and IT-enabled equipment (such as field devices and sensors), either embedded in new infrastructure or retrofitted into existing assets. Improved monitoring and control capabilities for all infrastructure can enhance resilience by providing detailed and rapid information to utility managers and city leaders regarding operating conditions and performance. This has the potential to minimize feedback loops and response times, enabling diversion of resources to priority areas while limiting the overall loss of system function. Furthermore, the proliferation of IT-based equipment across infrastructure networks leads to greater connectivity between systems. With greater ability to share information, performance can be optimized across all city network domains.

Creating Resilient Cities

Technologies alone cannot make urban infrastructure resilient. They will not be adopted without an appropriate climate for the required investments, and their potential benefit will not be secured unless system operators are equipped to use and act upon the information and controls that technologies can provide. Changing social, political and economic conventions is as fundamental to the success of city resilience initiatives as is upgrading physical assets. Implementation of technology solutions often requires a broader ‘enabling’ toolkit, which includes changes to urban planning, policy and regulation; governance; knowledge development; and financing models. No single piece of this toolkit can deliver resilience on its own but a number of actions must be taken.

Urban planning and land use policies can direct development in ways that protect people and structures from harm

Every city has its own planning constraints related to topography, historic patterns of growth, land ownership or tenure, and land values. Well entrenched planning ‘norms’ can deter proactive change and impede progressive adjustments to changing external conditions. Nevertheless, effective planning and land use policies can reduce the loss of life and property in the event of a disaster. Buffers, building codes, easements, transfers of development rights, and no-build and no-rebuild zones can aid in this goal. Inadequate or poorly performing infrastructure may not be easily adapted to meet resilience criteria, while the lack of space may inhibit relocation or renewal of at-risk assets.

Resilience practices should be adopted in policies, planning and construction across all city districts, to ensure that resilience of the whole city is increased and not enhanced in one community at the expense of another.

Governance should take a whole system approach to city management

Governance needs to take a whole system approach, taking advantage of the interdependency between sectors through greater coordination and communication. Collaborative planning should be normal behavior, not just a crisis response strategy. Decision making should extend across disciplines and progress should be monitored using shared metrics.

Collaboration is important throughout disaster preparation, relief, recovery and rebuilding. Different parts of the process require different skills and expert knowledge, which can only be gained through an interdisciplinary approach.

Improved knowledge and capacity can help city stakeholders plan for and recover from emergency situations.


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There can be an information gap at many levels in city decision making from the top level of government down to individual households. Knowledge and the capacity to act influence the types of infrastructure that a city is willing or able to adopt. A strong understanding of a city's dependence on systems, the interdependencies between systems, regional convergence and coupling is needed to optimize the selection of new technologies and equipment

Data can be used to provide a sound evidence base for decision making. Hazard preparation and response can be inhibited by a lack of data and information about at-risk assets Where data exists, it is often sector focused and not widely available to decision makers who need it. Furthermore, misinterpretation of data is common and can mean it is not utilized effectively. Lack of sound evidence can undermine public confidence in governance organizations.

Cities should create a data clearinghouse to help identify and monitor structures, systems and places that are exposed to hazards. The clearinghouse should be supplied with data from all key sectors and the community.

Appropriate financing mechanisms are needed to support investments in resilient infrastructure

City resilience strategies require sustainable financing, both for capital and operational investment. This can be a particular challenge under limited city budgets, especially in low income countries.

Investments should be appraised against longer timescales to match the lifecycle of most infrastructure assets. This would ensure that the full scope of short term costs and long term benefits are taken into account in investment decisions. City budget allocations should prioritize investments that amass the most benefits over the long term, based on both present and anticipated future conditions. Where possible, resilience criteria should also be integrated within normal city maintenance and upgrade routines, thereby entirely avoiding the need to justify unusual project investments.

Where upfront capital is required, innovative financing mechanisms may be needed to support resilience investments, including new economic incentives and revenue sources, such as grants, taxes and fees that help build redundancy, flexibility and reduce consumption.

New York City: increasing the resilience of the electricity grid

The city of New York is an international icon, offering an attractive environment for businesses and residents. The city has established a strong identity as a global enterprise hub; a center of commerce, highly connected to trade and industry throughout the world.

But with great strength, comes great vulnerability. During just a few hours in October 2012, Superstorm Sandy brought winds of up to 85mph (38 m/s) and a peak storm surge of 9 feet (2.7 meters), which occurred on top of a 5 foot (1.5 meter) high tide. The storm caused widespread loss of power to residents and businesses across the metropolitan region, and rapidly focused New York City on some very basic needs.

We undertook a high level review of the vulnerabilities in the New York City electrical grid and the steps that could be taken to mitigate risk. Impacts of four types of natural hazards (drought, heat wave, wind and flood) on the generation, transmission and distribution of electricity where explored, in order to extrapolate how.

From the analysis of the threats to the grid, we developed a range of investment options.

Making equipment more robust

In the short term, technologies that promote robustness will be essential. Protection measures include flood-proofing and waterproofing substations and installing submersible equipment, undergrounding critical overhead lines, adding hydrophobic coatings on overhead lines, and installing fuse-saving technologies.

Expanding demand reduction programs to reduce peak demand and network congestion

Demand response programs are typically voluntary programs with incentives that are initiated by the utility contacting the customer but there are greater opportunities with advanced metering infrastructure (AMI) and Energy Management Systems (EMS) at the building level for automated demand response through the internet.

Developing a smart grid for greater flexibility and responsiveness

In the medium term, investing in AMI will provide detailed, real time information to help manage the large and dynamic power grid. Smart meters communicate with a wide range of user control systems, and securely and reliably communicate performance information, price signals and customer information to the utility.

Distributed automation of the systems will integrate smart technologies and provide a monitoring and control function to allow for system performance optimization. Intelligent feeders and relays, voltage/Voltage Ampere Reactive (VAR[3]) controls, and automated switches are essential to enable this function.

In the long term, investments such as increased deployment of distributed generation, Automated Demand Management (ADM) – which connects buildings to the grid and reduces grid load by automatically powering down non-critical appliances – and vehicle-to-grid (V2G) technologies will all make the grid more resilient by increasing the diversity of supply, creating system capacity at times of peak demand, and enabling flexible means of energy storage.

Economic benefits for New York City

An economic analysis was developed to demonstrate the business case for investing in technologies that enhance resilience and help to manage risk by improving robustness, redundancy, responsiveness, flexibility and diversity to the grid, while also increasing capacity and efficiency in normal times.

Our analysis projected a cost of $350 to $450 million (£225-290 million) every three years, based on the damages caused by recent events and their projected frequency in the future.[4]

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If this scenario prevails, the city and the tax/rate payers will pay up to $3 billion over 20 years just to repair the damage (in red in graph labeled as 'no action').

The simplest course of action to avoid these costs is to increase infrastructure robustness. Flood and wind protection measures for critical assets can be implemented relatively quickly (within three years on an accelerated schedule) with a cost in the range of $400 million (£258 million). Implementing these measures should reduce the cost of repair and response in the next 20 years by approximately $2 billion (£1.3 billion) (in blue in graph labeled as 'partial investment').

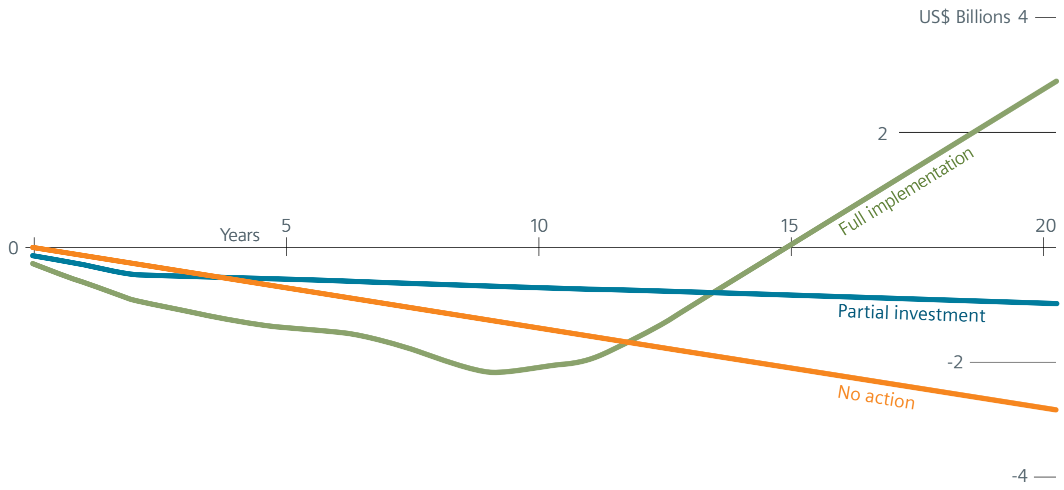
However, the robustness investments provide only a defensive solution which can at best reduce losses. Meanwhile, full investment in protection together with smarter infrastructure solutions will not only reduce the impact of future events event, but will also provide long term added benefits to the city, its residents and its businesses. On an ambitious 12-year investment program, city agencies and utilities will need to spend approximately $3 billion (£1.9 billion) to introduce an effective system of smart technologies.

This is a significant cost, but these investments should lead to:

- Fewer outages and increased reliability for the utility and the customer
- Decreased transmission and distribution losses, with consequent system cost reductions
- Reduced need for additional generation capacity due to improved system energy efficiency
- Reduced disruption to priority energy consumers, including medical and emergency services, businesses and industry
- Reduction of greenhouse gas emissions and other pollutants
- The continued ability of the city to maintain its global competitiveness.

The financial value of these benefits may reach $4 billion (£2.6 billion) (in green in graph labeled as 'Full Investment').

Economic analysis of future scenarios for New York City electrical grid



1 Why Resilience?

Introduction

Between 2000 and 2012, natural disasters – including weather, health and seismic events – caused $1.7 trillion (£1.1 trillion) in damages related to direct impacts on infrastructure, communities and the environment, together with reductions in business profitability and economic growth in affected regions.[5]

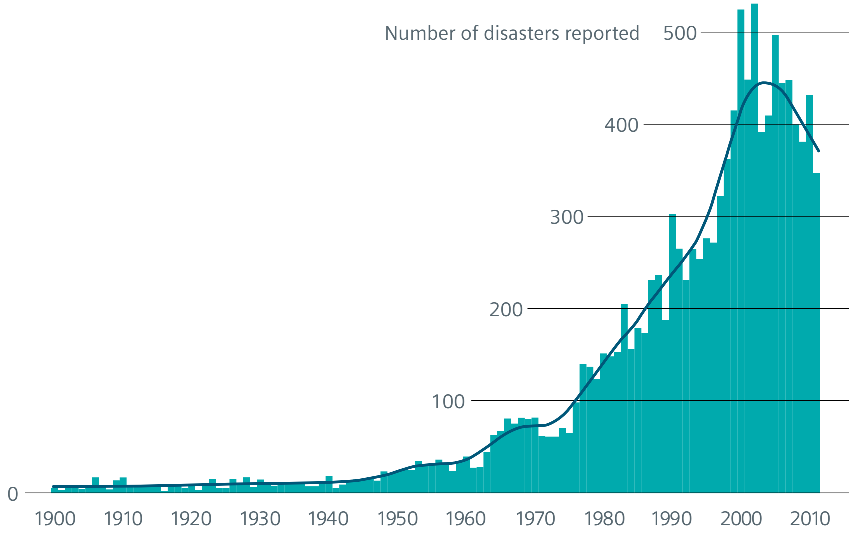
This paper explores how the resilience of critical urban infrastructure systems might be enhanced to prepare cities more effectively for major weather-related hazards.[6] Our research has focused on the physical infrastructure relating to energy, transportation, water and buildings. These systems were chosen because they underpin many other essential city operations and services, including sanitation, emergency response, and the delivery of food, fuel and other materials. The report considers proven technology solutions applicable to emerging and established cities, and the enabling actions required from policy makers, utility providers and other city stakeholders to facilitate delivery.

> The Moore, Oklahoma, tornado was the most powerful in a series of 76 tornados that hit 10 US states between May 18 and May 20, 2013, causing an estimated $2 to $5 billion in insured losses (£1.3 to 3.2 billion), according to Equecat, an insurance modeling company.[9]

Why must cities be resilient?

Rapid population growth, large scale environmental change and a globalized economy make today's world one of increasing complexity, uncertainty and continuous transformation. Directly and indirectly, these factors give rise to the growing frequency, magnitude and geographic range of major hazards.

Hazards include man-made and natural events, both long term stresses and sudden shocks. This paper focuses on the weather-related hazards that occur at local, regional, national and international scales. Recent examples range from the devastating tornado that killed 24 people, injured 377, and left a 17 mile trail of destruction in Moore, Oklahoma in May 2013[7]; to the chronic floods that submerged 50 per cent of Manila, Philippines, in August 2012, affecting nearly 2 million people, including 49 fatalities.[8]



Frequency of reported natural disasters, 1900-2011 (source: EM-DAT)

In cities, the challenges are especially acute. People, infrastructure and economic activity amass in urban areas, concentrating high value in often exposed locations. Cities require complex infrastructure networks to serve patterns of demand and supply. They operate as a 'system of systems', where the provision of any single service depends on the

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City infrastructure failure can have global impacts

In 2011, prolonged flooding in northern and central Thailand affected 13 million people and caused damage estimated at over $45 billion (£29.4 billion).[12] The flooding affected thousands of factories in Bangkok, causing manufacturing to come to a halt. The impact spread around the world, as supply chains responded to the shortage of essential components manufactured in Thailand. Many sectors were affected, such as transportation equipment, electronics, pulp and paper, and rubber products. Product prices increased around the world, including an uplift of 10% in the average price of computer hard drives.[13]

As a result of the floods, Thailand's growth projections for 2011 were revised from 4.1 per cent to 2.6 per cent,[14] and many businesses expressed doubts about the security of future investment in Thailand.[15] Following the floods, the Thai government approved a plan for infrastructure and water management improvements worth $11.1 billion (£7.3 billion), with the objective to restore investor confidence and prevent a repeat event of this scale.[16]

successful operation of many others. Managed intelligently and under normal conditions, these interdependencies contribute to effective operations, efficiency and economies of scale.

However, interdependency also makes each system vulnerable to failure as impacts can cascade from one system to another, blurring the lines between cause and effect and compromising targeted preparation and response. Compounding the challenge, infrastructure in many developing cities fails to keep pace with rapid rates of expansion, while in developed cities infrastructure often suffers from under-investment and poor maintenance. In both cases, these conditions put cities close to a tipping point of disaster from hazard events.

More than half of the global population are now urban dwellers, living in cities where economic opportunities are greater but where the local environment, concentration of people and increased reliance on complex systems amplify the potential impact of any event. Eight of the ten largest cities by population are sited in coastal areas[10], exposed to sea level rise, saltwater intrusion, flash floods, river flooding and coastal surges.

As urban populations grow, many cities are expanding into higher risk areas.

A higher concentration of people in hazard zones inevitably means increased human exposure to risk, and a growing pressure on critical city infrastructure that supports not just local, but national and global economies. Today, cities generate more than 80 per cent of global Gross Domestic Product (GDP).[11]

Cities have always faced these risks, but in a time of rapid change – including a changing climate – cities need to plan for and manage risks differently from before, in a way that includes strategies to deal with complexity and uncertainty. This approach is at the heart of resilience planning.[17]

More than half the urban area of Ho Chi Minh City, Viet Nam, is located on a delta raised less than one meter above sea level.

What is resilience?

Resilience | The capacity of people, organizations and systems to prepare for, respond, recover from and thrive in the face of hazards, and to adjust to continual change. Resilient systems share certain qualities such as redundancy, flexibility and responsiveness.

Hazard | A sudden event or gradual change, which can lead to impacts on a place or people.

Exposure | People and things located in a place that could be affected by a hazard.

Vulnerability | The propensity for a hazard to affect the wellbeing of a person, community or organization.

Risk | The impact that occurs, whose severity depends on how the above factors interact.

Key terms related to risk and resilience [21]

Traditional disaster risk management considers the likely frequency and magnitude of a hazard, the probability that the hazard will affect a given place or population, and the vulnerability of that population to loss or damage. By evaluating these elements, targeted risk management strategies seek to avoid, mitigate, accept or transfer known risks.

In practice, we have little control over the pattern, timing or scale of many environmental hazards. Human exposure and vulnerability to hazard events are influenced by decisions about what, where and how to develop cities, but in reality a city's ability to influence underlying economic and demographic forces is limited. Added to this, there is growing acknowledgement that many risks are unknown or uncertain, and cannot be managed using any single targeted approach. Therefore, since risk avoidance will never be completely achievable, cities must look for other ways to reduce or mitigate known and unknown risks in an integrated way.

The solution can be found in resilience thinking. A resilience approach employs proactive strategies for risk reduction and continual adjustment to change across the urban system, from water and energy planning through to community preparedness and governance.

Poor resilience is bad for business, and bad for communities

$3.3 billion (£2.1 billion) is the estimated economic loss to the city of Jakarta, Indonesia, when infrastructure was damaged and trade was halted by severe flooding in January, 2013.[18]

$19 billion (£12.2 billion) was the total cost to New York City in damages and lost economic activity due to Superstorm Sandy in October, 2012. As sea level rises and more property becomes exposed to coastal flooding, forecasts suggest that a storm like Superstorm Sandy could cost around $90 billion (£58.3 billion) by mid-century.[19]

100,000 residents permanently relocated from Louisiana to Texas in the year following Hurricane Katrina (2005). The population of Louisiana fell by 5%, and the city of New Orleans lost 50% of its population immediately following the storm. Seven years later, the city remained at around 80% of its pre-Katrina population.[20]

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Resilience, and/or Sustainability?

Resilience and sustainability are not mutually exclusive but should be seen as powerful companions to shape both the future planning and daily management of cities.

Sustainability represents the end goal that forward-thinking cities are pursuing: to secure a good quality of life for all people, today and in the future, through strong and prosperous communities, a vibrant and resource efficient economy, and stewardship of both local and global environmental assets.

Resilience works within the context of long-term sustainability objectives but specifically embraces the turbulence of daily life. Resilience is about learning to live with the spectrum of risks that exist at the interface between people, the economy and the environment, and maintaining an acceptable stability or equilibrium in spite of continuously changing circumstances. Resilience also addresses the interdependencies between systems and minimizes unforeseen 'gaps' in risk management.

At times, a resilience approach may appear contrary to accepted definitions of sustainability. For example, while sustainability may encourage leaner, more efficient operations in the interests of resource conservation, resilience promotes greater redundancy in city infrastructure to provide back-up during a crisis. Such tensions can be an important signal that short term efficiency gains may not in fact be the right pathway to long term sustainability.

Therefore, system planning and design should seek to measure performance against both resilience and sustainability indicators. Many of the technologies presented in this paper demonstrate the possibility of achieving both simultaneously.


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London

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How does resilience apply to cities and infrastructure?

City stakeholders and service providers can take positive steps to influence a city’s resilience, whether as sector-based investments in infrastructure and technology, or cross-sector policy making and coordination.

Previous research on urban resilience has highlighted key characteristics that can be observed in resilient systems across scales and types.[22] From this literature, together with expert interviews, we have identified the following five characteristics that form a useful framework to guide resilience thinking in design and decision making.

These characteristics can be used to assess a variety of options for action, with the most effective pathways in any city being influenced by the local climatic, economic, demographic and political context. While the most resilient systems are likely to demonstrate all five characteristics, some strategies may strengthen one characteristic instead of another, and cities should select strategies based on cost, effectiveness and suitability for the anticipated risks. For example, coordination can be a lower cost and more rapidly deliverable strategy for less prosperous cities than major investments in redundancy or robustness.

Robustness Robust infrastructure is able to withstand the impacts of hazard events without significant damage or loss of function.

Redundancy Redundant systems have spare or latent capacity (or the ability to manage loads), which can absorb sudden surges in demand or partial loss of supply. Back-up equipment may be used to enable continuity of service in the event of infrastructure failure.

Diversity and flexibility Diversity and flexibility in infrastructure systems mean that services may be supplied via a number of pathways, using distributed resources and multifunctional equipment. If one pathway fails, another can be used to achieve the same service.

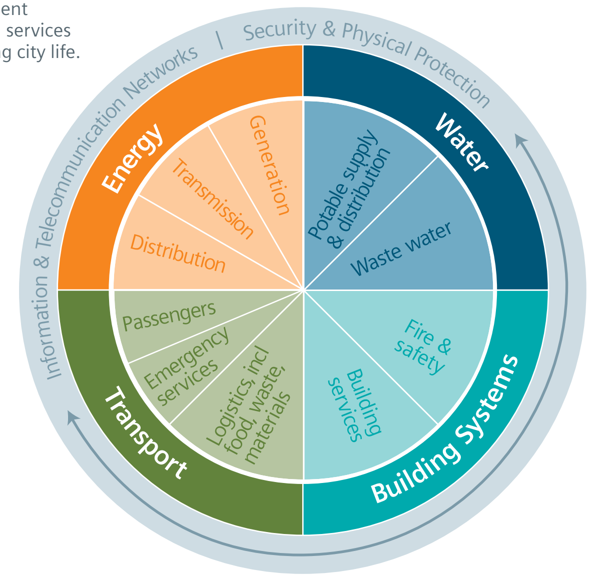
Responsiveness Responsive infrastructure systems incorporate automated monitoring, short feedback loops and controls at multiple points, enabling transparency of performance data and rapid adjustment to maintain functionality.

Coordination Coordination between systems means that knowledge is shared, planning is collaborative and strategic, and responses are integrated for mutual benefit.

2 Creating Resilient Systems

Energy, mobility (including movement of goods and people), water and buildings are central to life in the 21st century. In cities, these services are delivered by physical infrastructure, which can be broadly understood to include buildings, plant and equipment, civil structures, pipelines, cables, roads, railways, landscapes, waterways and natural areas.

In this section, we consider some of the weather-related risks to these assets and the information, communication and technology solutions that can enhance efficiency and resilience in specific system components.



Interdependent systems and services underpinning city life.

Technical Attributes of Resilient Infrastructure

Some common technical attributes can be observed in the architecture of resilient infrastructure systems across sectors, which are clearly demonstrated by the technologies presented here.

Decentralized resource supplies and distribution networks

Energy, transportation and water infrastructure can be designed to operate both as part of a large system and to serve a more localized community independently of the wider network. This relies on multiple connected microgrids that can either operate together or individually. During a major hazard event, microgrids can buffer local service users from impacts elsewhere. IT is the key enabler allowing service providers to switch operations from microgrids to integrated networks and vice versa. Besides contributing to resilience, local solutions can also improve the efficiency of water and energy supplies by reducing distribution losses.

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Energy

Energy is fundamental for life in cities. Stable energy supplies are essential for water and wastewater treatment and distribution; train, tram and metro networks; communications; medical and emergency services; lighting, heating, ventilation and security. If the energy supply fails, the impacts for business and communities can be serious, or even fatal.

The energy supply in cities comprises a number of sources and modes, including electricity from centralized power plants (most cities), gas and oil for heating, cooking and local power generation (many cities), and heat networks and solid fuels in some. Decentralized and renewable energy systems are gaining momentum. The solutions presented here focus primarily on resilience in the electricity supply.

During Superstorm Sandy the loss of power at New York University's Langone Medical Center resulted in the evacuation of over 200 patients, some of whom were critically ill.[23] A further 725 patients were evacuated from the nearby Bellevue Hospital Center.[24]

The grid electricity system includes three primary activities: generation, transmission, and distribution and supply. Electricity is transmitted from the power generation station at high voltage to a substation, where voltage is stepped down, or converted, for distribution to consumers. The high voltage is required to reduce losses during transmission.

Some components of the energy supply system are highly exposed to severe weather events. Long-distance transmission lines can be downed in high winds and open air substations damaged by heavy rains or tidal surges. If centralized grid infrastructure is affected, millions of customers may lose power.

The shift towards decentralized, automated and remotely controlled ('smart') energy systems presents opportunities simultaneously to improve energy efficiency, to adopt cleaner sources of power, and to increase the resilience of energy supplies by minimizing single points of system failure and increasing diversity, flexibility and responsiveness in the system. The following examples offer benefits to individual parts of the system.

The Grid Electricity System

Microgrid infrastructure protects neighborhoods from power failure

Micrograms are small, independent electricity or heat grids that distribute locally generated energy to nearby customers. They can operate as part of the central grid, or when necessary they may operate independently for an extended period of time. This provides protection for consumers against shocks to the wider energy network, and helps to maintain service in local areas. This decentralized design offers increased reliability and enables greater diversity of energy supplies from local sources to the grid. In the event of a major catastrophe at a centralized plant or in the transmission network, microgrids could channel energy to critical services, such as hospitals and other emergency services.

The advantages of microgrids were evident during Superstorm Sandy at Co-Op City – a housing development in the Bronx, NYC. The trigeneration system at Co-Op City incorporates a 40MW steam turbine, which generates power, heat and cooling. A microgrid serves 14,000 apartments in 35 towers. During the storm, the microgrid continued to provide electricity, heat, hot water and air conditioning for 60,000 residents, while neighboring areas sat in darkness. The upfront investment for this microgrid paid back after just five years, aided by the sale of surplus power back to the grid.

Remote monitoring and control enables rapid response to system failure

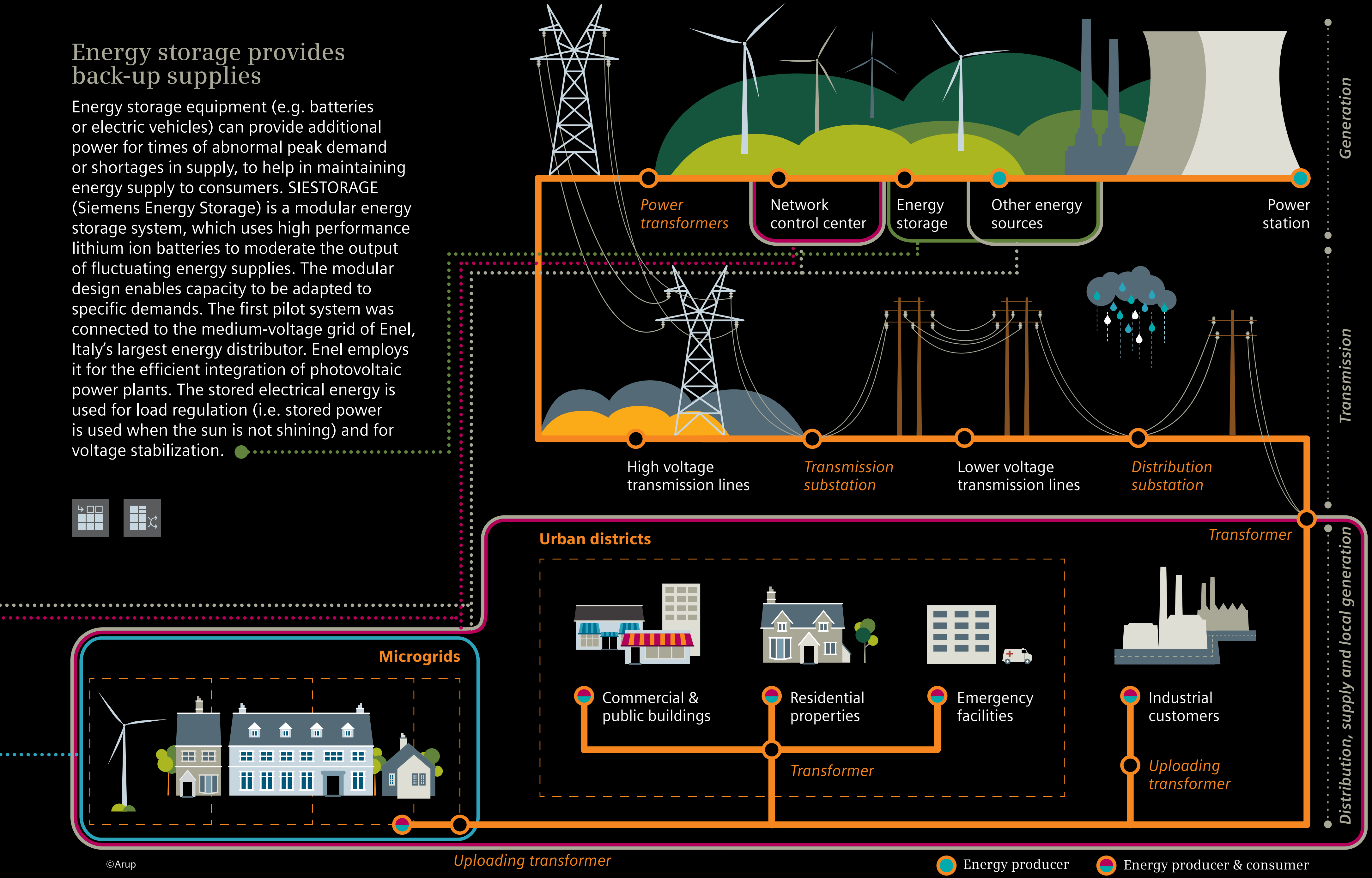
India's economic growth has led to demand for electricity greatly exceeding supply. The country experiences daily power outages and faces a growing risk of major power cuts.[25] Back-up diesel generators are used to create redundancy and make up shortfalls in supply. This is an expensive solution, but contributes to severe air pollution in cities.[26] Additional production capacity and modernization of power distribution networks is crucial. Supervisory control and data acquisition (SCADA) technology is now being installed, offering the potential to cut power losses in distribution networks by up to 15%.[27] Two way, real time communications give grid operators far greater network oversight and control, enabling rapid identification of and response to faults. This will help to reduce the need for local generators, offering economic and health benefits.

Flexible integration of decentralized energy improves efficiency and resilience

The 'virtual power plant' is a flexible system in which small-scale, distributed energy sources are pooled and operated as a single power installation. In Munich, Germany, this system has brought together 8MW in distributed cogenerating stations, together with 12MW in renewable hydroelectric and wind power plants. A Distributed Energy Management System allows these decentralized generation facilities to be operated as a single system, or independently to serve local networks as required. The system helps to regulate variable supplies of power from individual renewable sources and promotes more efficient use of decentralized energy. Flexibility and diversity of supply help to avoid supply disruptions.[28]

Energy storage provides back-up supplies

Energy storage equipment (e.g. batteries or electric vehicles) can provide additional power for times of abnormal peak demand or shortages in supply, to help in maintaining energy supply to consumers. SIESTORAGE (Siemens Energy Storage) is a modular energy storage system, which uses high performance lithium ion batteries to moderate the output of fluctuating energy supplies. The modular design enables capacity to be adapted to specific demands. The first pilot system was connected to the medium-voltage grid of Enel, Italy's largest energy distributor. Enel employs it for the efficient integration of photovoltaic power plants. The stored electrical energy is used for load regulation (i.e. stored power is used when the sun is not shining) and for voltage stabilization.



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The Transportation Network

Transportation

The transportation network is a highly diverse system, composed of fixed assets (roads, railways, bridges, ports) and moving parts (trains, buses, cars, boats and bicycles). Both the fixed infrastructure and the moving vehicles must be operational to enable the network to function. In times of disaster, either one of these components could be affected. For example, due to the flooding of roads or rails, the loss of power or fuel for vehicles, or reduced availability of transit operator personnel.

Mobility underpins social and economic activity. If transportation networks are compromised, evacuation during a hazard event may be hindered and emergency services may be unable to reach affected areas. After the event, the delivery of food, fuel and other goods will be affected due to disruption in logistics. All of these things affect the health and safety of citizens and their ability to return quickly to their normal patterns of life and work. Even if business premises remain undamaged, the businesses themselves may be unable to operate if employees cannot get to work. The direct risks to transportation networks therefore indirectly threaten the entire city system, with cascading impacts for the domestic and international economy.

In most cities, transportation networks have an operational advantage over other critical systems, due to the diversity provided by multi-modal services and systems. Most city transportation systems comprise a variety of mode and pathway options, such that if one option is damaged another can be used instead. This could be viewed as built-in diversity and flexibility. Nevertheless, travelers and freight tend to depend on a familiar route, and widespread havoc can be wrought by a single point of failure. Add to this the reliance of transportation services on stable energy and fuel supplies, and you have a highly sensitive and relatively easily disrupted system.

Sustainable travel is being promoted in many cities through initiatives that improve safety and environmental quality for pedestrians, cyclists and public transit users. These objectives help to diversify the range of travel options in cities, providing energy and cost savings while adding viable alternative routes that can be adopted during unexpected system outages. Successful navigation is facilitated by integrated travel information, which enables passengers to plan intermodal travel in real time via internet and mobile smart devices. The following solutions can offer specific benefits to components of the system.

> In October 2012 Superstorm Sandy forced a two day closure of the New York Stock Exchange, largely due to the shutting of roads, bridges and mass transit services which inhibited staff travel. Trading was delayed throughout the US and overseas.[29]

Secondary power supplies ensure continuity of services

Normally, the London Underground operates using grid supplied electricity. However, the network is backed up by a separate power supply at Greenwich Power Station, which generates power specifically for the Underground. This back-up supply enables trains to function through catastrophes that could disrupt grid functionality.

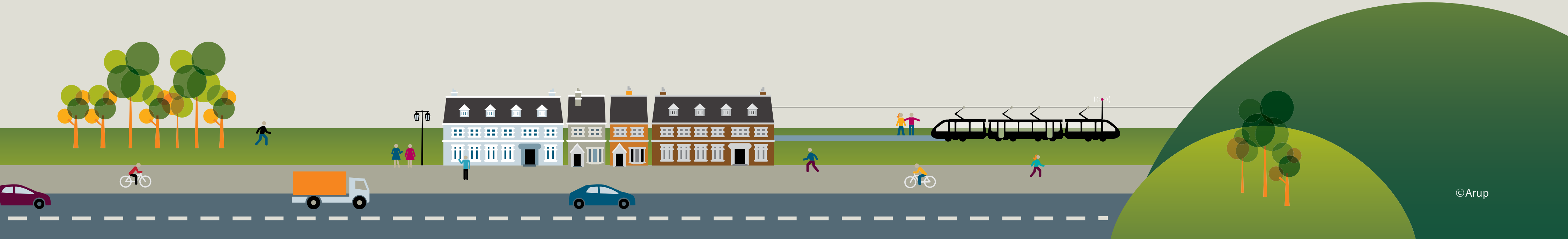
Transportation systems may also respond to the power needs of other urban services. During severe weather, rail services are often suspended or reduced for safety reasons. During down time, power to railroads could be diverted via local networks to provide back-up energy supply for more critical facilities, such as hospitals and evacuation centers. Since railroads often have an independent power supply separate from the grid, this solution ensures power availability even in the event of wider grid failure.

Sensitive network controls increase carrying capacity

Communications-based rail signaling systems can increase passenger capacity on the rail network and improve operating efficiency by reducing the time between successive trains. Conventional signaling systems detect trains in fixed sections (or 'blocks') of the track and protect the whole block from entry by other vehicles. This limits the minimum time between trains and restricts total passenger capacity. In communications-based ('moving block') systems, trains continuously communicate their exact position. This information is relayed to other trains automatically, to adjust their speed while maintaining safety. This allows reduced distance between trains and increased capacity on the network. The San Francisco Municipal Railway (Muni) increased the capacity of light rail infrastructure from 23-26 trains per hour under a fixed block signaling system, to 50 vehicles per hour using communications-based technology. The retrofit successfully created additional capacity for peak travel periods.[30]

Real time system monitoring and communications enable rapid recovery

In times of crisis, coordination of transportation is essential. Co-location of system operators can enable instantaneous shared decision making for active transport management, resulting in enhanced passenger service with fewer disruptions. This was proven by the Transport Coordination Center (TCC), which was introduced temporarily for the 2012 London Olympic Games. The TCC located event delivery partners and transportation organizations at a single control room to coordinate operations. The TCC could track incidents on the network using advanced surveillance and communications, and service times and vehicle capacity were managed according to real time changes in competition schedules. On a single event at Bank Station passenger time savings due to the TCC were estimated to be equivalent to $133.000 (£85.000).[31]



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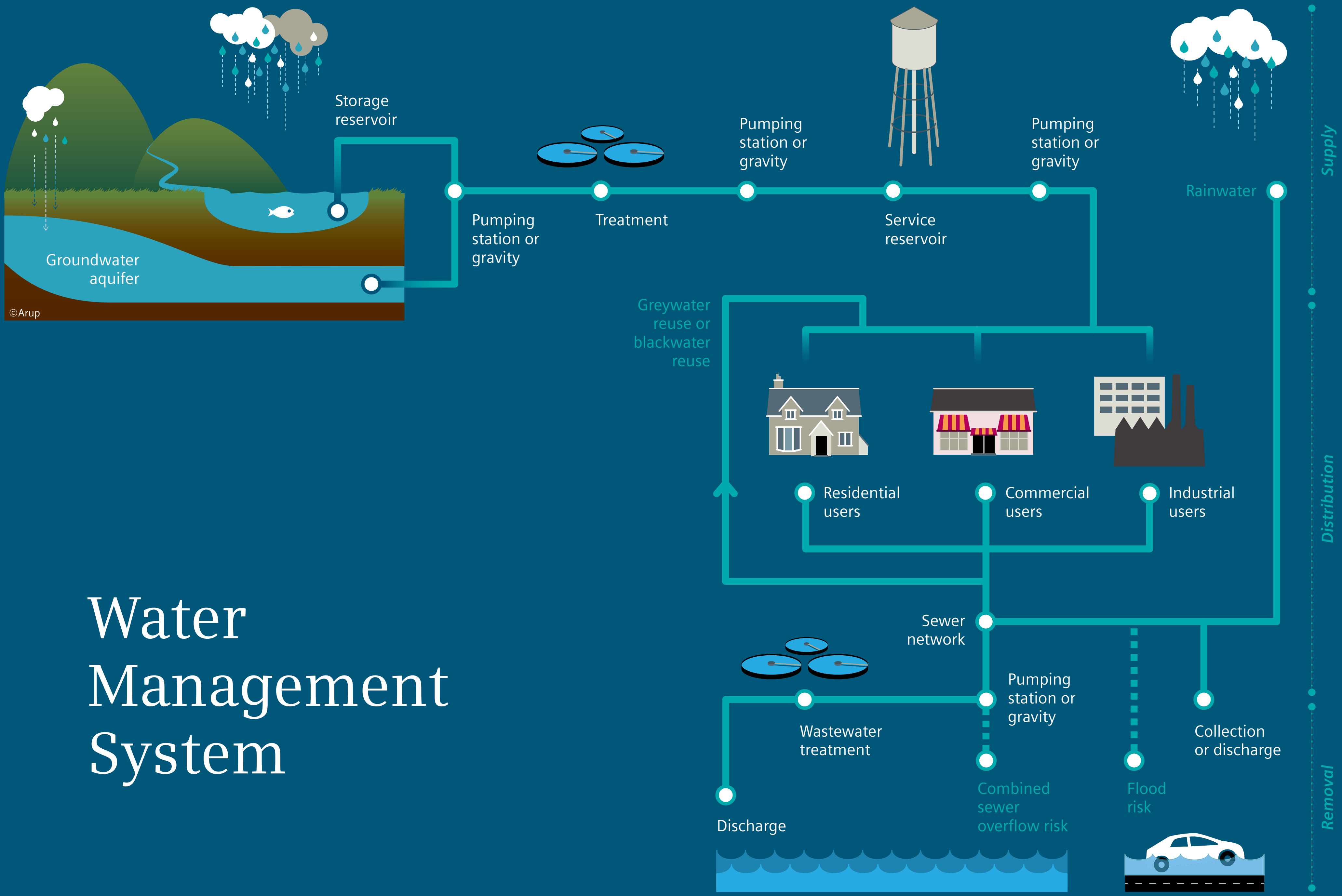
Automated system controls facilitate traffic flows

Vehicle-to-Infrastructure communications have been developed as a pilot project in Harris County (Houston metropolitan area), Texas, in response to the chaotic evacuation of the county during Hurricane Ike (2008). The project equipped 400 intersections in Harris County with a simple control system that dynamically alters the timing of traffic lights based on an algorithm, which estimates the number of vehicles approaching an intersection using Bluetooth signals from smartphones inside vehicles. Data is aggregated and mapped, enabling drivers to access real time information about the volume of traffic on the roads, and to select their evacuation route based on the shortest travel time. The upgraded traffic lights can also detect signals from emergency vehicles, and turn green to facilitate rapid response.

Continuous asset monitoring avoids damage to fixed infrastructure

The new two mile (three kilometer) suspension bridge between Istanbul and Izmir, Turkey, will be fitted with a state-of-the-art traffic control system, monitoring technology, communication and camera equipment, which is designed to guide traffic management and monitor the stability of the bridge. Any damage or deformation to the structure or its components will be detected and reported at an early stage, enabling rapid corrective action to avoid risks to road users. A Supervisory Control and Data Acquisition (SCADA) system will be used for monitoring and control, with data directed to an integrated operations center.[32]

Water Management System



Storage reservoir

Groundwater aquifer

©Arup

Pumping station or gravity

Treatment

Pumping station or gravity

Service reservoir

Pumping station or gravity

Rainwater

Supply

Greywater reuse or blackwater reuse

Residential users

Commercial users

Industrial users

Distribution

Sewer network

Pumping station or gravity

Wastewater treatment

Collection or discharge

Discharge

Combined sewer overflow risk

Flood risk

Removal

Water

Water management in cities includes a number of critical and interrelated services:

- Collection, treatment and distribution of drinking water
- Removal, treatment and disposal or reuse of wastewater
- Removal, treatment and disposal or reuse of rainwater (stormwater)
- Protection of people and critical facilities from flooding.

Each of these services relies on specific, separate physical assets, which may include storage tanks, conveyance pipes, pumping stations and treatment facilities. Natural and designed landforms, such as slopes, waterways, swales and detention ponds (so-called green and blue infrastructure), also play a major part in directing, filtering and dispersing flows of storm and flood water. Flood defenses such as levees, wetlands, dunes and sea walls also feature in these systems.

In many cities, drinking water distribution has been designed with very high redundancy. With security of supply a main driver for the industry, equipment at pumping stations and storage facilities has historically included additional capacity and back-up equipment to protect against failure. However, this redundancy often does not extend to distribution pipelines. If a pipe bursts or cracks under pressure, water supply to whole neighborhoods may be cut off.

In some cities, the pumping and treatment of water is highly vulnerable to disturbances in the energy network. Health and safety risks arise if drinking water cannot be supplied, or wastewater and stormwater cannot be removed. Contamination of stormwater is a particular concern in cities with combined sewer infrastructure, where wastewater can easily overflow and cause widespread environmental damage as it drains through overloaded systems and into water supplies.

Even before the 2010 earthquake and hurricane in Haiti, millions of Haitians had no reliable water supply. Many of the underground pipes that did exist were ruptured by the earthquake, making access to drinking water a daily struggle. Shortly after the earthquake, water supplies became contaminated with cholera originating from a leaky wastewater system. The ensuing epidemic caused 8,000 deaths (compared with an estimated 300,000 in the earthquake itself), and the sickening of over 600,000 more. These events highlighted the risks associated with failure of water and wastewater infrastructure.[33]

Sustainable design criteria promote improved resilience by encouraging water conservation to maintain availability, use of green infrastructure to remove and treat stormwater, and decentralized water sources such as rainwater collection and grey water reuse. These strategies help to diversify water management systems and reduce the burden on existing infrastructure, while reducing reliance on vulnerable energy sources. Like energy and transportation networks, water systems are also becoming smarter, enabling a higher degree of monitoring and control over water management. The following examples demonstrate the role that technology can play in resilient water systems.

water supplies contaminated with cholera causing sickening of over

600,000

Decentralized wastewater treatment manages wastewater flexibly

The Food Chain Reactor (FCR) solution for urban wastewater management combines conventional treatment methods with biological treatment provided by the roots of 2,000-3,000 plant species, thereby treating water to high quality standards. This is a decentralized approach, which manages wastewater on a neighborhood scale using small, odor free facilities. The decentralized approach helps to avoid the risk of sewer overflows and burst pipes during severe weather. The FCR uses advanced automation to ensure reliable and efficient treatment of wastewater, while handling extreme variations in quantity and quality. A single facility may treat between 264,000 and 53 million gallons (1,000 and 200,000 m^3) per day. The FCR reduces greenhouse gas emissions and lowers operational costs by more than 30% compared with conventional wastewater plant. In Shenzhen, China, an FCR manages wastewater for a city centre industrial park of 17,000 people.[34]

Redundant infrastructure provides alternative pathways for water supply and removal

In the event of drinking water supply outages, it may be possible to compensate for partial system failures without relying on an alternative water source. Redundant pipe connections and strategically placed valves make it possible to isolate damaged pipes and minimize the area of lost service. New York City and Cleveland, USA, both rely on system redundancy for their emergency water supply plan, while Seattle has means for establishing temporary connections between pressure zones to bypass damaged areas. An adequate number of operable valves is essential for isolating affected parts of the system and circumventing sources of pressure loss. Treated water storage may make it possible to maintain service for a certain period of time while treatment plants are repaired.[35]

Automated leak detection alerts asset managers about water losses

Leak detection sensors alert utilities to faults and failures along distribution pipelines or in water storage facilities, enabling rapid action to reduce loss of vital drinking water supplies. Mumbai, India, is delivering a large scale smart water project, aimed at using existing water resources more efficiently to bring water to more residents. Before the project, broken pipes were thought to be causing leaks that reduced the city's water supply by 50%, with around 150 million gallons (700 million liters) of water leaked from the system each day. Smart water meters have now been installed to enable water balance to be calculated on an ongoing basis to inform leak detection. The meters can be read remotely, enabling the Municipal Corporation of Greater Mumbai to identify and locate leaks. Since the project commenced, it is estimated that the volume of water losses have been reduced by 50%. By avoiding leaks, sensors also help to avoid risks of local flooding.[36]

Automation and remote controls improve reliability of drinking water distribution

The growing population of the São Paulo metropolitan region in Brazil requires an ever increasing supply of water. The water utility, Sabesp, has introduced a new Water Supply Operation Control System (Nova SCOA) to manage critical pressure points in the water supply network and ensure effective communication with the population in the event of water shortages. Through Nova SCOA, Sabesp supervises, controls, plans and manages drinking water conveyance between treatment stations and regional reservoirs for the entire region of 19 million inhabitants. This control is achieved using data from 180 remote monitoring stations. The system constantly measures pressure in the pipes and monitors water consumption on a neighborhood by neighborhood basis throughout the region. Digital water management equipment also collects data such as outdoor temperatures, which can be used to make water consumption forecasts. Smart applications allow the whole distribution network to be visualized and remotely controlled, allowing Sabesp's daily operation plans to be adjusted according to demand, which helps to avoid the risk of water shortages and increase operating efficiency by pumping water only when it is needed.[37]

Continuous asset monitoring avoids risks from infrastructure failure

Engineered flood defenses are highly effective in designed-for flood events, but the impact of peak flood levels can be severely worsened if dams fail. By embedding a comprehensive system of sensors in the walls of defenses, flood management operators can continuously monitor the behavior of the structures, to enable real time reporting on the status of the structure, and triggering alarms in the event of damage or failure. Sensors measure parameters such as water and air pressure, expansion, and differences in humidity and temperature inside and outside the defense. Weak points can be identified for targeted maintenance. The system also allows management of critical points where floods may begin, and calculation of flood expansion to support evacuation plans. Information feeds into decision support systems that allow city managers to make informed decisions during an emergency. Trials of this technology are underway as part of the EU Urban Flood project at the Livedijk in the Netherlands.[38]

Building Systems

Buildings provide essential shelter and structure while shaping the culture and physical character of the city. They are central to any discussion of infrastructure resilience, since they house the infrastructure required to bring energy and water to consumers, and provide the destination points for most transportation systems. If a disaster razes buildings to the ground, our requirements of other city systems will change substantially.

Technology is just one element in a strategy for resilient buildings; fundamentally, the siting and design of buildings dictate their level of exposure and vulnerability to hazards. Nevertheless, in emergency situations where buildings remain safe, structurally sound and where energy supply is maintained, technology can help to maintain occupant comfort and distribute information about emergency response.

Data centers have become a particularly critical component of a city's building stock. Data centers facilitate the information flows that support business and city operations and public communications; in their absence, smart technologies would not be possible and media channels would be limited. Individual data centers may serve customers who are located internationally, meaning that their ability to withstand hazard events is vital not only for the host city, but for communities around the world. To minimize large scale disruption in IT services, safe, resilient and energy efficient data centers are essential. This implies the need for a high level of security, robust design and reliable power supplies, among other things.

The following technology solutions can help to support the resilience of building systems, and ensure their ongoing functionality through short term weather events.

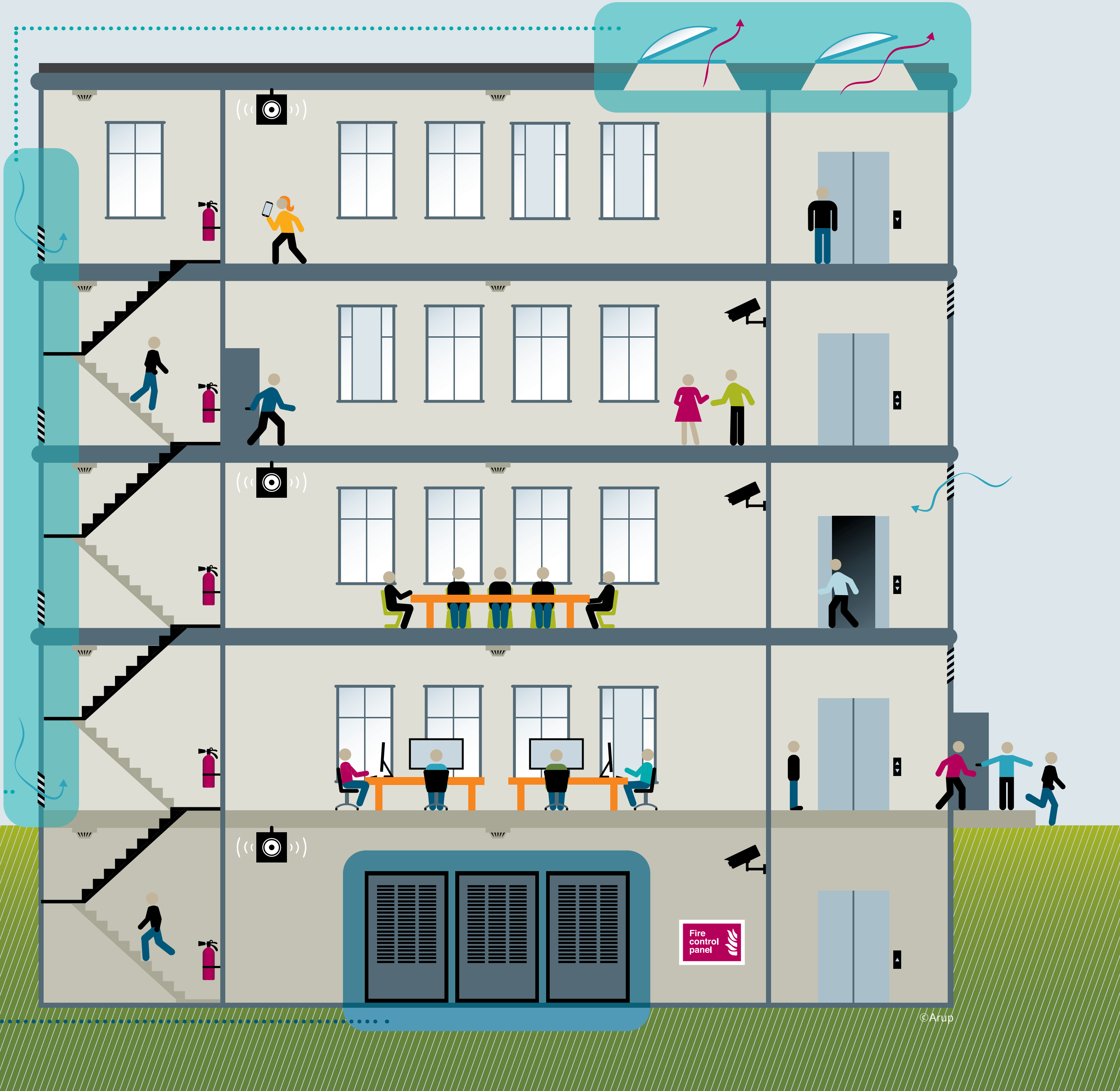
In 2012, a fire at a data center building in Calgary, Canada, caused the failure of city services and delayed hundreds of surgeries at local hospitals. The fire was caused by the explosion of a transformer in the building, which triggered the building's sprinkler systems and brought down both the primary and back-up systems housed on the site. More than 20,000 business and household clients lost cable, telephone and internet services. The outage affected emergency services, provincial property and vehicle information databases, and a medical computer network for Alberta Health Services. Banking services, ATMs and debit terminals were also affected throughout the city.[39]

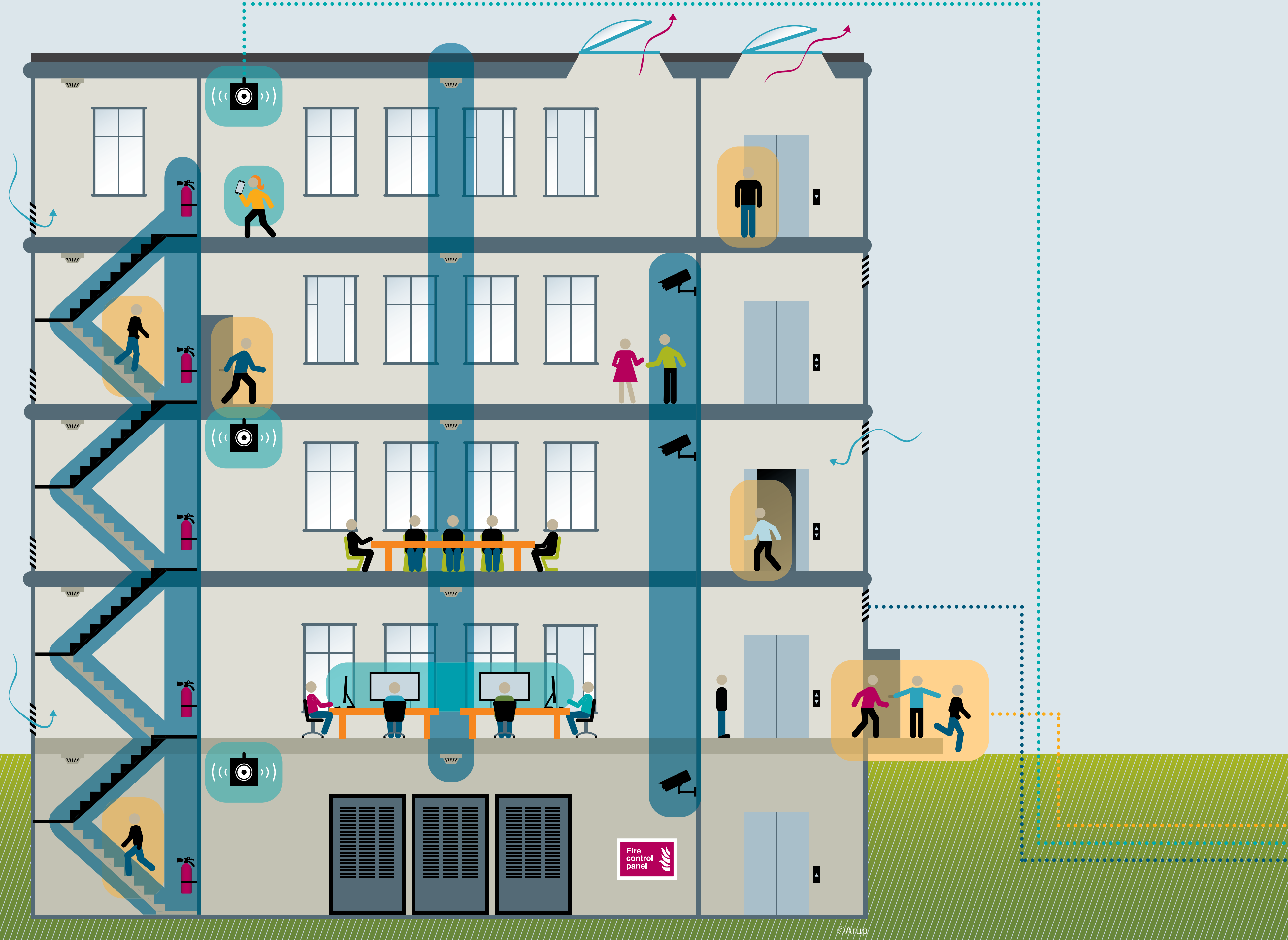
Responsive building management systems maintain occupant health and comfort

Building Management Systems can be calibrated to work in response to local microclimates and maintain occupant comfort. The California Academy of Sciences in San Francisco takes advantage of natural air currents in the surrounding Golden Gate Park to regulate the indoor temperature. Windows and skylights are designed to open and close automatically, controlled by an automated ventilation system. As heat rises through the building during the day, the skylights will open to allow hot air out from the top of the building, while louvers below draw in cool air at the lower floors. This provides an energy efficient and cooling flow of air during hot weather that can operate independently without the need for conventional energy intensive air conditioning systems and chemical coolants.

Holistic system design secures information flows and communications

The Safe Host SA data center in Geneva, Switzerland, incorporates a range of data center infrastructure services that promote service reliability and data security. Built-in solutions protect against power supply interruptions, security and fire safety threats, and ensure that servers operate at the correct temperature to protect customer data from changes in environmental conditions. Features of the data center include a central management system, over 800 smoke detectors, fire control panels, nitrogen based extinguishing solutions and video surveillance at all major entrances.




Fire control panel

3D simulation of human behavior enables advanced evacuation planning

The behavior of building occupants during an emergency can be modeled prior to an event, using advanced 3D simulation software. The software enables movement through a building or space to be forecast up to ten times faster than real time with relative accuracy, including places where blockages may occur. Using this information, evacuation strategies may be planned and communicated to building users to ensure a rapid flow of people to safety. This tool improves human preparedness, coordination and response. With a faster than real time reaction, this technology also helps to gain valuable time in a situation where every second counts. The approach has been implemented with a number of high rise buildings, including 1 Canada Square at Canary Wharf, which until 2012 was the tallest building in London. The software can even model people flows at the city block level, thereby assisting evacuation far beyond the walls of a single building.

Building Mass Notification Systems coordinate human reactions to hazards

Mass Notification Systems (MNS) deliver targeted messages to advise building occupants during a crisis. Messages are disseminated through multiple redundant channels, including voice systems, LED signage and local area networks. The system can contact people en masse inside and outside of the building, and directly via personal devices such as cell phones. Systems inform occupants about what action they should take, therefore coordinating movement to facilitate safe and efficient response. At Medicine Hat College in Alberta, Canada, the MNS comprises 192 strategically zoned indoor speakers, together with four giant voice speakers outside. There are connections to response team cell phones, employee PCs, and two command-and-control centers. The system was designed around the College's existing Emergency Response Plan, and allows targeted alerts via a user friendly digital interface. Typical risk scenarios are pre-recorded to allow easy activation and effective messaging during a crisis.[40]

Sophisticated fire safety systems enable rapid isolation of incidents and evacuation of occupants

Taipei 101, a 101 story tower in Taiwan, sees 40,000 people pass through its doors each day. Fire prevention and emergency reaction plans have been paramount since the start of construction in 2000. The building houses very early warning fire detection systems, smoke detection and expulsion systems and automated fire extinguishing systems, which are coordinated via a central disaster prevention center. Infrared detectors and cameras are installed to detect fire anywhere in the building. Taipei 101 is also equipped with state-of-the-art emergency elevators that travel from ground level to the 90th floor in 50 seconds, allowing emergency personnel to reach a disaster in the fastest possible time. Air pressure in the emergency staircases is automatically controlled to minimize smoke intrusion, allowing people to evacuate from lower levels. Emergency shelters are distributed throughout the building to provide temporary shelter for escaping personnel. These advanced emergency systems offer a 'layered' approach to fire safety and ensure rapid response in the event of a disaster. A similar approach has been employed at London's iconic new skyscraper, The Shard, which now stands as the tallest building in Western Europe.[41]

3 Creating Resilient Cities

Technologies alone cannot make urban infrastructure resilient. Their adoption will not occur in the first place without an appropriate climate for the required investments, and their potential benefit will not be secured unless system operators are equipped to use and act upon the information and controls that technologies can provide. Changing social, political and economic conventions is as fundamental to the success of city resilience initiatives as is upgrading physical assets. This section focuses on four aspects of city governance and operations that, our research indicates, together provide the critical 'enabling framework' for investment and action to achieve greater infrastructure resilience.

Urban planning, policy and design

Urban planning and land use policies can direct development in ways that protect people and structures from harm.

Every city has its own planning constraints related to topography, historic patterns of growth, land ownership or tenure, and land values. As an example, high land values and growing populations in many cities precipitate development in every square inch of the urban area, regardless of risk. In many countries, undeveloped spaces are frequently used for informal settlements, leading to high density with little awareness of potential danger. Inadequate or poorly performing infrastructure may not be easily adapted to meet resilience criteria, while the lack of space may inhibit relocation or renewal of at-risk assets.

Effective planning and land use policies can reduce the loss of life and property in the event of a disaster. However, entrenched planning 'norms' can also deter proactive change and progressive adjustments to changing external conditions. Buffers, building codes, easements, transfers of development rights, and no-build and no-rebuild zones can aid in this goal. For instance, city plots may have to be strategically reprioritized and managed to allow set-aside of at-risk sites – such as those along rivers and coastlines – for 'green' or 'water friendly' uses like parks and gardens. Brownfield sites in existing cities may be leveraged to provide spaces suitable for emergency evacuation, public assembly and temporary housing. Judicious use of land acquisition and assembly powers can also support such initiatives. Resilience practices should be adopted in planning and construction across all city districts, to ensure that resilience of the whole city is increased and not enhanced in one community at the expense of another.

Integrated policies for infrastructure upgrades will build resilience across sectors.

At present, there are concurrent and sometimes competing policies in land management, environmental protection, hazard mitigation, building design and infrastructure planning. This has resulted in a mix of directives and incentives that in some

56% higher prices are commanded by waterfront properties in the UK, compared with equivalent properties located inland. Some waterfront real estate achieves premiums of up to 300%.[42]

circumstances have pulled urban strategy in opposing directions. Failures can occur when policies undermine one another.

Policies and programs may need to be updated to promote resilience. Cities must clearly signal their goals and ensure consistency in their messaging. In some cases, individual city policies have acted against resilient outcomes or have proved too easily influenced to achieve their priorities for urban development.

Policies must be mutually supportive across sectors, pushing towards common objectives of resilience and long term sustainability. Development of cohesive policy proposals requires improved communication and shared decision making across sectors, leveraging the interdependencies between city systems and reflecting them within policy and regulations.

Updates to planning and local development policies must be considered in tandem with necessary infrastructure improvements to enable change to be delivered cost effectively as part of scheduled regeneration and development projects. Planners and designers should be encouraged to prepare sensitivity analyses, mitigation and response plans for known hazards, to ensure that planned developments are prepared for events of varying magnitude. Cities must integrate planning for future demand with plans to retire assets that are redundant or beyond repair, and those that are increasingly vulnerable to risks. Adapting older cities to meet new risks will take time. Without a comprehensive understanding of the potential risks, cities can miss critical opportunities for investing in resilience.

Urban design can balance the preservation of local identity with city risk mitigation.

Compromises must be reached between the need to preserve existing urban character, and the need to protect the city from future hazards. For example, policies that promote a retreat from waterfronts or installation of new physical protection for cities may affect local identity. Where at-risk buildings must be raised above historic flood levels, concern is voiced about the loss of street activity and retail viability. Resolving these conflicts implies innovations in urban design, which offer added value over standard approaches. Deliberative planning is essential to help cities secure the support of residents while achieving multiple goals: sustainability, liveability, economic prosperity and resilience.

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Amendments to urban design conventions can protect infrastructure and services from failure

The NYC Building Resiliency Task Force was convened at the request of Mayor Michael R. Bloomberg following Superstorm Sandy, with a mission to identify measures that would protect buildings against the effects of extreme weather and facilitate recovery after an event, addressing both new construction and building retrofits.[43] Recommendations were released in June, 2013, offering options for a strengthened Building Code and Zoning Resolution to ensure future construction meets standards for resilience. Focusing on commercial premises, multiresidential buildings and homes, it also proposes measures that would establish back-up power if primary networks fail, protect water supplies and stabilize interior temperatures if residents need to shelter in place.[44]

Policies and design standards promote resilient system architecture

Electrical equipment, such as transformers and circuit breakers, are vulnerable to temperature extremes, which can lead to power outages. In the UK, design standards are in place to provide common rules for the design and erection of electrical power installations, to provide safety and proper functioning for the intended use. Since 2010, the standards have specified a temperature range within which component parts of the electricity network should be designed to operate. For example, outdoor components should function at ambient air temperatures between -13 and 104°F (-25 and 40°C). Recorded extreme UK temperatures fall within this range, therefore components designed to this standard should continue operating during periods of extreme weather in the UK. The standard also requires that critical circuits have two levels of redundancy, such that the service will remain operational in the event of minor faults.[45]

Incentives can facilitate action and investments towards resilience goals.

Cities must provide the right incentives to drive decision making that is consistent with resilience goals. Many of the technologies and solutions outlined in this paper will require widespread IT infrastructure and access to data. Where cities already have mature infrastructure networks in place, actions will focus on renewal and retrofit to overlay smart components on to those existing legacy systems. For developing cities where basic infrastructure systems are not yet built across the whole metropolis, the objective should be to plan ‘smart ready’ buildings and systems today and to create the conduits and rights of way for future installation of the smart systems that will connect them.

Governance

Governance should take a whole system approach to city management.

Most city services are both governed and operated by sector-based and single-purpose departments and agencies. These governance models are ubiquitous and generally effective because they provide for clear delineation of responsibilities within definable service parameters. However, the inability of such structures to deal with cross-sectoral issues is evident, for instance, each time a below-street utility repair is made the week following street resurfacing work.

A strictly vertical governance model cannot achieve the kind of intra- and inter-organizational coordination needed for resilience because no department or agency has a mandate to deal with the cross-system effects of decisions or to maximize potential cross-sector benefits. The disconnect between agencies is amplified in cities where public services are delivered through long term contracts with private sector organizations, meaning that city governments do not have direct powers to change the way systems operate in the short term.[46]

Hat Yai

©Wikimedia

By empowering local stakeholders, resilience plans benefit from community knowledge

Hat Yai, the main commercial hub in the south of Thailand, experienced two disastrous floods between the years 2000 and 2010. Despite the government's $116 million (£76.2 million) investment in major flood mitigation infrastructure following the 2000 event, the 2010 floods caused even more damage. Taking matters into their own hands, a group of residents, municipal officials, government officials, non-government organizations and the business sector came together to conduct a city vulnerability assessment, prioritize community needs and develop a strategy for resilience. The group was coordinated by the Asian Cities Climate Change Resilience Network (ACCCRN), funded by the Rockefeller Foundation. Working at the grassroots level and with the urban poor living in flood prone areas, they identified village-specific plans and priority actions to take in the event of a flood. The group has also established a website to provide public access to real time flood monitoring information at strategic locations in Hat Yai. They have launched the Hat Yai City Climate Change Resilience Learning Center to address inadequate coordination between relevant authorities and sectors, by sharing knowledge on flood-related issues. This bottom-up approach seeks to strengthen the capacity of communities, business and government actors, while formal policy development and integrated city planning remain the domain of the municipality.[49]

Governance needs to take a whole system approach, taking advantage of the interdependency between sectors through greater coordination and communication. Collaborative planning should be normal behavior, not just a crisis response strategy. Decision making should extend across disciplines and progress should be monitored using shared metrics.

Collaboration is important throughout disaster preparation, relief, recovery and rebuilding. Different parts of the process require different skills and expert knowledge, which can only be gained through an interdisciplinary approach.

Governance structures can enable a rapid, accurate, decentralized emergency response.

In many cases, urban governance is a centralized, top down process, in which directives are issued in a command-and-control manner. In risk and disaster management situations, a single authority is necessary for clear and effective decision making, and yet these same structures often struggle to distribute vital and locally appropriate information and assistance to the grassroots level. As city governments direct their attention to large scale infrastructure challenges and urgent threats to public health and safety in the aftermath of an event, community leadership and self-governance can aid resilience by organizing local relief and supporting neighbors' short term coping and longer term recovery decisions.

Local decision makers and community leaders should be empowered to deliver community support and immediate organization in communities. Multi-stakeholder governance structures should be coordinated in advance to ensure their preparedness and capacity for effective response. The power of grassroots leadership was evident in parts of New York following Superstorm Sandy[47] and in Chicago during a heatwave in 2011.[48]

Knowledge and capacity

Improved knowledge and capacity can help city stakeholders plan for and recover from emergency situations.

There is an information gap at many levels in city decision making from the top level of government down to individual households. Since disasters are sporadic and often unpredictable, disaster management capability – such as dedicated personnel and training across organizations – can erode as time passes since the last event. Consequently, institutional knowledge can be inadequate and, when an event occurs, rapid and coordinated action is inhibited.

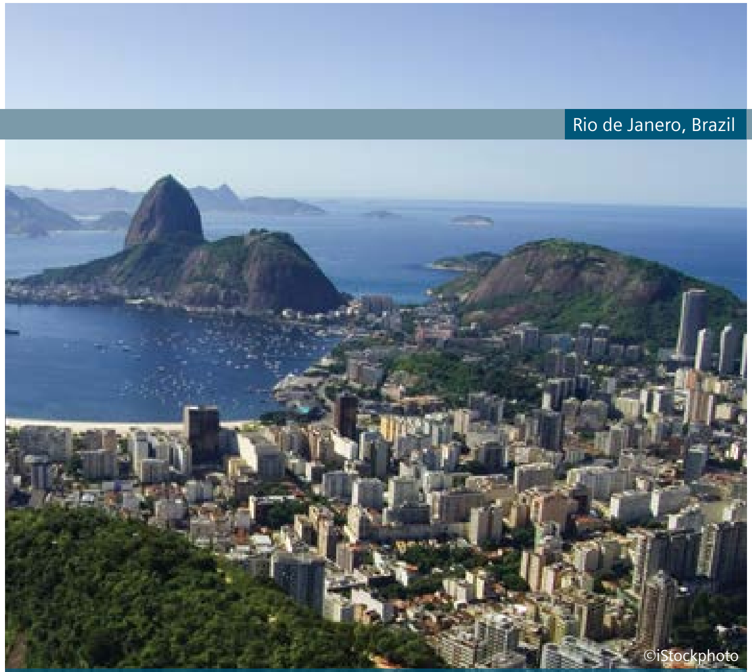
Knowledge and the capacity to act also influence the types of infrastructure that a city is willing or able to adopt. A strong understanding of a city's dependence on systems, the interdependencies between systems, regional convergence and coupling is needed to optimize the selection of new technologies and equipment. Any new infrastructure must be appropriate to the local skill base, and must be operable and maintainable by local people.

A strategy should be in place before a disaster occurs, which supports targeted knowledge development and communications. Knowledge is fundamental to ensure that individuals, communities, businesses, government and other groups are prepared for sudden events. Appropriate information should be channeled to specific audiences and neighborhoods before a crisis occurs. During an event, communications must be instructive, frequent, clear and accurate, within the constraints of communication systems available at the time.

Data can be used to provide a sound evidence

Hazard preparation and response can be inhibited by a lack of data and information about at-risk assets. Where data exists, it is often sector focused and not widely available to decision makers who need it. Furthermore, misinterpretation of data is common and can mean it is not utilized effectively. Lack of sound evidence can undermine public confidence in governance organizations.

Cities should create a data clearinghouse to help identify and monitor structures, systems and places that are exposed to hazards. The clearinghouse should be supplied with data from all key sectors and the community. Effective communication channels should be set up to distribute data back to those who need it. Multiple stakeholders should be trained to analyze available information, interpret automatic system alerts, understand trends, and apply this understanding to inform policy and support decision making. Smart technologies are a positive step towards improving data availability, but their function must be understood by those who can benefit from them.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Inter-agency collaboration promotes connected, rapid response

Rio de Janeiro City Hall launched its Operations Center in December 2010, providing a single center for the integration of real time information from across the city. Real time weather, traffic and emergency services data is gathered in a single location, allowing decisions to be based on the best available data. Through analysis of the data, operators are able to anticipate natural disasters and alert affected communities, while taking instant action to reduce their impact. Thirty municipal and state departments are represented at the center, plus utility and transportation providers. The center operates 24 hours a day, receiving images from more than 800 City Hall cameras, the police and other agencies. Using weather radar that blankets a 250km (155 miles) area around the city, weather and flood forecasters can predict emergencies up to two days in advance.[50]

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Early warning systems provide advanced knowledge of emerging risks

Surat is the most flood prone city in the state of Gujarat, India, with particularly high vulnerability among industries and low income households. In 2006, water from a nearby dam release inundated 75% of the city's area, costing several billions of dollars. Working with the Asian Cities Climate Change Resilience Network, Surat Municipal Corporation has developed an integrated meteorological, hydrological and reservoir modeling system to improve reservoir operations for future flood mitigation. A near real time end-to-end early warning system is also in place to advise the city administration to take action in case of extreme precipitation. The project is also building community capacity for disaster response, with potential to set up a database of vulnerable people and an asset bank to be managed by the community. This initiative addresses the issue of flooding in a multi-scalar and multi-institutional way, understanding the upstream causes of flooding beyond the administrative boundary of the city.[51]

Financing investments

Appropriate financing mechanisms are needed to support investments in resilient infrastructure.

City resilience strategies require sustainable financing, both for capital and operational investment. This can be a particular challenge under limited city budgets, especially in low income countries. In recent decades, funding for infrastructure has diminished in many established cities, while developing cities rely on minimal budgets to finance infrastructure improvements upfront. The selection of technologies and other investments must be appropriate to local economic conditions, financial arrangements and investment capacity. In cities with small and finite capital resources, a focus on community capacity, future proofing and open source infrastructure solutions may be a more acceptable response.

Where upfront capital is required, innovative financing mechanisms may be needed to support resilience investments, including new economic incentives and revenue sources, such as grants, taxes and fees that help build redundancy, flexibility and reduce consumption.

For example:

- Public-private partnerships can offer stability for new investments, and are a justifiable approach for investments that offer the benefit of security for future business
- Concessions allow public agencies to lease infrastructure to private companies with the agreement that the private company will own, operate, and maintain the asset to meet specified performance objectives.
- City assets can be converted into working capital. For example, with careful siting and design, inner city substations could be moved underground, allowing the air rights to be sold to real estate developers with profits used to fund substation improvements
- Market mechanisms offer an efficient way to advance objectives without significant upfront investments. For example, utility providers may offer variable service levels to customers with differing risk profiles, using the additional funding to finance network improvements.

Partnerships can work together to access new sources of finance

In 2012, C40 Chair Mayor Michael R. Bloomberg announced the launch of a C40 city-led network focusing on Sustainable Infrastructure Finance. Led by the city of Chicago, the network has been established to help cities work together to create, evaluate and replicate financing structures for improved mass transit, alternative power generation, and other projects relevant to urban resilience planning, low carbon cities and sustainability. The network initially focused on sharing the experiences of cities that have leveraged public and private investments, including Chicago’s Green Infrastructure Trust and Melbourne’s Sustainable Melbourne Fund. The network is also working with private financial institutions, multilateral development banks and other investment experts to broker access to existing funds and shape city-focused financial mechanisms for the future. Other activities will include sharing template legal and financing documents and developing partnerships with global accounting firms to procure pro bono assistance.[52]

Project appraisal procedures should be adapted to consider the lifecycle benefits of infrastructure investments.

In many cities, the barrier to action may not be the absolute lack of finance, but rather a lack of ability or incentive to measure and capture the holistic, long term value that a proposed investment could deliver. All resilience investments are made in anticipation of a future event that may or may not occur in the short term, although the probability of a particular event occurring will increase as time horizons are extended. With an uncertain return on investment and many competing investment priorities, resilience can be difficult to justify through conventional project appraisal methodologies.

Investments should be appraised against longer timescales to match the lifecycle of most infrastructure assets. This would ensure that the full scope of short term costs and long term benefits are taken into account in investment decisions. City budget allocations should prioritize investments that amass the most benefits over the long term, based on both present and anticipated future conditions. Where possible, resilience criteria should also be integrated within normal city maintenance and upgrade routines, thereby entirely avoiding the need to justify unusual project investments.


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Market based solutions enable resilience without major capital investment

The Energy Network Operations Center (EnerNOC) is a market based mechanism to facilitate demand response in the absence of smart technologies. EnerNOC helps commercial, institutional and industrial organizations primarily in North America but also in other regions to use energy more intelligently, reduce costs, and generate cashflow. EnerNOC utilizes a web-based application to communicate with consumers to reduce non-essential energy use during periods of high grid demand, or low supply. During these periods, utilities and grid operators call on EnerNOC to ask consumers to reduce their power use or switch to their on-site generation capacity. The grid is stabilized, and consumers are paid for the energy they don’t use. Consumers are also paid year round for being part of the program. This solution offers benefits in terms of energy efficiency, cost savings, resilience and greenhouse gas emissions reduction.[53]

4 Case Study: New York City Electrical Grid

Scope

So far, this paper has surveyed a wide spectrum of ideas for building resilience in multiple urban infrastructure systems around the globe. In this section, we report on a focused case study carried out for the electrical grid of New York City and its metropolitan area.

The case study presents a high level review of the vulnerabilities in the electrical grid and the steps that could be taken to mitigate risk. We investigate the impacts of four types of natural hazards (drought, heat wave, wind and flood) on the generation, transmission and distribution of electricity, in order to extrapolate how New York City can ensure continuous electricity supply during a range of such extreme events. We propose a series of actions and investments that will contribute to advancing the resilience of the electrical grid and, in turn, the city.

Context

The city of New York is an international icon, offering an attractive environment for businesses and residents. The city has established a strong identity as a global enterprise hub; a center of commerce, highly connected to trade and industry throughout the world.

But with great strength, comes great vulnerability. During just a few hours in October 2012, Superstorm Sandy brought winds of up to 85mph (38 m/s) and a peak storm surge of 9 feet (2.7 meters), which occurred on top of a 5 foot (1.5 meter) high tide. The storm caused widespread loss of power to residents and businesses across the metropolitan region, and rapidly focused New York City on some very basic needs. It is estimated Superstorm Sandy caused more than $50 billion in overall damage to the greater New York area.

Apart from the short term impact on people and businesses, there is potentially a long term impact of increasing hazard frequency on the city’s ability to attract and retain the scale of inward business investment that defines New York City. If business disruption becomes a regular event, and if quality of life cannot be assured, what kind of city will New York become? Action must be taken to ensure the resilience of critical infrastructure that supports city life.

Hazards and risks review

New York City has a long history of environmental events, ranging from floods and hurricanes to heat waves and drought. Our understanding of risk is based on historical data; the frequency and intensity of past events is used to estimate potential hazards of the future. However, recent events indicate that this understanding may no longer be accurate. Superstorm Sandy and Tropical Storms Lee and Irene occurred in consecutive years, and took a tremendous toll on the northeast region. New hazards are also arising; tornados, which are historically infrequent, have hit New York City each year since 2010.

In the past three years alone, New York City and the surrounding metropolitan area have endured an unprecedented variety and number of severe weather events, with substantial costs incurred due to direct damages and consequential disruptions. The variety of hazards experienced by the region affects all aspects of the electricity grid, from substation flooding to wind and ice damage of overhead lines. Looking ahead, climate scientists project that these events will increase in frequency and severity, leading to greater direct and indirect impacts such as increases in peak demand that strain generation facilities as summer temperatures trend upwards and the region's population grows.[55]

Frequency of Hazard Occurrence in New York City[54]

	Flooding	Drought	Heat Wave	Wind Events
Past Events (1970-2000)	1 in 100 years	1 in 100 years	2 per year	1 in 3 years
Projected Events due to climate change	1 in 15 years	Unclear	8 per year	Increased frequency

Effect of recent hazards on the New York City electrical grid

	2010		2011	2012
Event	Tornado	Blizzard	Heat Wave	Superstorm Sandy
Hazard	125 mph (56 m/s) winds	60 mph (27 m/s) gusts, 20 inches (51cm) of snow	104°F (52°C) temperature	14ft (4.3m) storm surge, 8 mph (3 m/s) gusts
Cost/Damage	Damage and outages – 45,000 customers affected	Outages and loss of subway service	Outages – 139,000 customers affected	Over $40 million (£26 million) in damages to the electricity grid

Options for making the grid more resilient

Understanding the current risks and resilience of New York's electricity infrastructure is vital to developing a plan for the area's future. Due to the complexity of electrical infrastructure, solutions for resilience will need to address all of the city's current assets with the appropriate level of action. There is no single technology or investment that can respond to every threat. Multiple, targeted investments combined with enabling actions are necessary to protect and maintain the grid.

Electricity assets can be categorized into substation equipment, transmission and distribution infrastructure, and generation facilities. Con Edison is New York City's primary utility provider, and serves approximately 3.3 million electricity customers in New York City alone. It owns 61 substations within the city, approximately 18 of which are in flood zones. The area's transmission and distribution infrastructure includes 2,200 primary feeders consisting of 94,000 miles (151,300 kilometers) of underground cable and 34,000 miles (54,700 kilometers) of overhead lines.

Each asset is vulnerable to a particular range of risks and requires specific solutions to withstand future shocks and stresses. However, assets must be addressed collectively to provide resilience throughout the system. Additionally, a number of non-energy systems are affected by impacts to the grid – including water distribution and transportation – and must be accounted for when determining a response to sudden events. An understanding of these interdependencies is necessary to achieve comprehensive and cost-effective strategies for resilience.

Potential environmental hazards that could affect the NYC metro electricity grid

Hazards		
Tidal surges	High winds	Heat waves
Flash floods	Blizzards	Drought


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Despite the well-known reliability of Con Edison's systems, Superstorm Sandy caused extensive damage to New York City's electricity grid. One of the most visible effects of the storm was the failure of Con Edison's 13th Street substation. On the evening of October 29, 2012 water from the storm surge began to inundate the city's low-lying areas. The substation, located in a designated flood zone, had been designed to withstand a peak water level of 12.5 feet (3.8 meters). However, this design standard was not enough to withstand the 14 foot peak brought by Sandy.[56] Sea water inundated circuits and blew the transformer, leaving lower Manhattan in darkness. The explosion resulted in outages for nearly 250,000 customers,[57] and forced the evacuation of critical facilities. Several other neighborhoods were disconnected as a precaution, due to concern for potential equipment damages and load constraints. Hundreds of thousands of customers were left without power over the next six days.

$1 billion (£646 million) is the cost to New York City of a day without power.[58]

Potential resilience investment options

From the analysis of the threats to the grid, we developed a range of investment options.

Making equipment more robust

In the short term, technologies that promote robustness will be essential. For example, gas insulated switchgear is contained in a sealed vessel to provide a degree of waterproofing. Since it requires considerably less space than conventional switchgear, it may also allow electrical equipment to be located on higher floors or even below ground. Additional protection measures include flood-proofing and waterproofing substations and installing submersible equipment, undergrounding critical overhead lines, adding hydrophobic coatings on overhead lines, and installing fuse-saving technologies.

Expanding demand reduction programs to reduce peak demand and network congestion

Demand reduction and energy efficiency in infrastructure and buildings must also continue. The Distribution Load Relief Program and the Commercial System Relief Program are two demand response programs available to businesses. The CoolNYC program allows residential customers to wirelessly control their window air conditioners. The New York Independent System Operators (NYISO) provides several demand response programs to industrial and commercial consumers.

Demand response programs are typically voluntary programs with incentives that are initiated by the utility contacting the customer but there are greater opportunities with advanced metering infrastructure (AMI) and Energy Management Systems (EMS) at the building level for automated demand response through the internet.

Developing a smart grid for greater flexibility and responsiveness

In the medium term, investing in AMI will provide detailed, real time information to help manage the large and dynamic power grid. Smart meters communicate with a wide range of user control systems, and securely and reliably communicate performance information, price signals and customer information to the utility. This information allows utility providers to monitor system performance and take rapid action where required.

Distributed automation of the systems will integrate smart technologies and provide a monitoring and control function to allow for system performance optimization. Intelligent feeders and relays, voltage/Voltage Ampere Reactive (VAR[59]) controls, and automated switches are essential to enable this function. Many of these technologies are currently in pilot stages across the metropolitan region; however there is a number of enabling factors required for these technologies to be deployed at scale (discussed below).

In the long term, investments such as increased deployment of distributed generation, Automated Demand Management (ADM) – which connects buildings to the grid and reduces grid load by automatically powering down non-critical appliances – and vehicle-to-grid (V2G) technologies will all make the grid more resilient by increasing the diversity of supply, creating system capacity at times of peak demand, and enabling flexible means of energy storage.

Contribution of potential investments to advancing resilience characteristics

Robustness	Gas insulated switchgear Flood proofing and water proofing Undergrounding Hydrophobic coatings Fuse saving technologies Voltage/VAR controls
Redundancy	Battery storage Vehicle-to-grid Demand reduction and energy efficiency
Diversity and flexibility	Distributed generation Intelligent feeders and relays Automated switches Battery storage Vehicle-to-grid
Responsiveness	Advanced Metering Infrastructure (AMI) including smart meters Automated Demand Management Intelligent feeders and relays Automated switches
Coordination	Advanced Metering Infrastructure (AMI) Geographic Information Systems (GIS)

Economic analysis

An economic analysis was developed to demonstrate the business case for investing in technologies that enhance resilience and help to manage risk by improving robustness, redundancy, responsiveness, flexibility and diversity to the grid, while also increasing capacity and efficiency in normal times.

Recent events have changed our understanding of our risk profile, and show that investments in resilience can be worthwhile.

When an event occurs, the city – and therefore the tax/rate payer – must pay to respond and repair the damage. Our analysis projected a cost of $350 to $450 million (£225-290 million) every three years, based on the damages caused by recent events and their projected frequency in the future.[60] If this scenario prevails, the city and the tax/rate payers will pay up to $3 billion over 20 years just to repair the damage (in red in graph labeled as ‘no action’).

The simplest course of action to avoid these costs is to increase infrastructure robustness. Flood and wind protection measures for critical assets can be implemented relatively quickly (within three years on an accelerated schedule) with a cost in the range of $400 million (£258 million). Implementing these measures should reduce the cost of repair and

> *We can do nothing and expose ourselves to an increasing frequency of Sandy-like storms that do more and more damage, or we can abandon the waterfront. Or, we can make the investments necessary to build a stronger, more resilient New York – investments that will pay for themselves many times over in the years to come.*
>
> Mayor Michael R. Bloomberg, speaking in New York City, June 11, 2013[61]

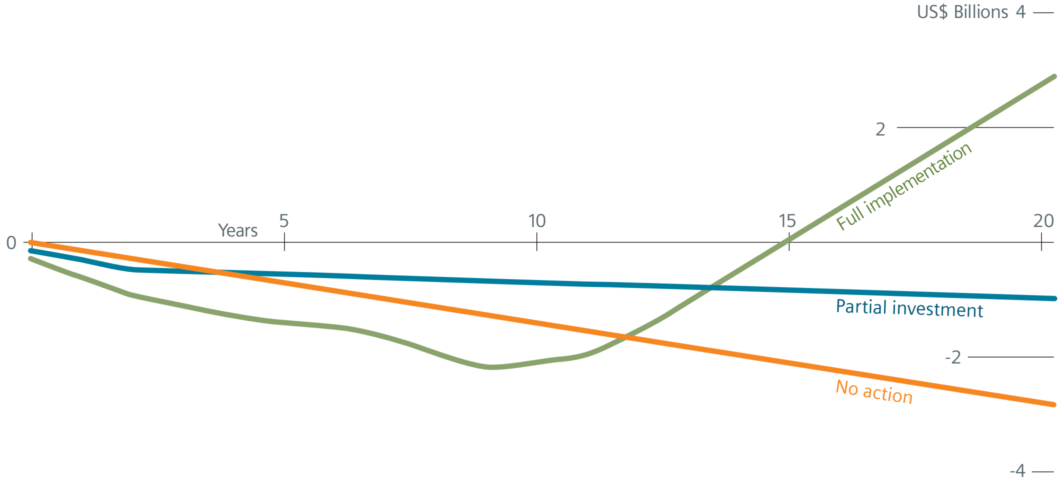
response in the next 20 years by approximately $2 billion (£1.3 billion) (in blue in graph labeled as ‘partial investment’).

However, the robustness investments provide only a defensive solution which can at best reduce losses. Meanwhile, full investment in protection together with smarter infrastructure solutions will not only reduce the impact of future events event, but will also provide long term added benefits to the city, its residents and its businesses. On an ambitious 12-year investment program, city agencies and utilities will need to spend approximately $3 billion (£1.9 billion) to introduce an effective system of smart technologies. This is a significant cost, but these investments should lead to:

- Fewer outages and increased reliability for the utility and the customer
- Decreased transmission and distribution losses, with consequent system cost reductions
- Reduced need for additional generation capacity due to improved system energy efficiency
- Reduced disruption to priority energy consumers, including medical and emergency services, businesses and industry
- Reduction of greenhouse gas emissions and other pollutants
- The continued ability of the city to maintain its global competitiveness.

The financial value of these benefits may reach $4 billion (£2.6 billion) (in green in graph labeled as ‘Full Investment’).

Economic analysis of future scenarios for New York City electrical grid (the methodology is presented in full in Appendix 2).



In this model, investment costs and benefits have not been attributed to different parties, but instead reflect the costs and benefits to the whole system. In practice, they are likely to accrue asymmetrically to stakeholders including the federal government, the city, utilities, ratepayers, private business and individual consumers. A key next step for this case study, or for another city investigating its own resilience opportunities, would be to map the “investors” or “contributors” and the “beneficiaries” across the system, leading to the development of planning, regulatory and market mechanisms to capture the value created by resilience benefits from the beneficiaries.

Enabling actions to support resilience investments

As discussed in Chapter 3, the recommended technologies need a package of enabling actions to support their widespread deployment. Policy and regulation will need to keep pace with new technologies. New York City has a progressive government, which has taken action in recent years to further the goals of sustainability and efficiency, with a growing focus on resilience since Superstorm Sandy. Nevertheless, there are further changes that can facilitate a large scale shift towards greater resilience.

Existing city regulations prevent non-utilities from operating power lines to serve microgrid customers. Other regulations stop utilities from owning energy generation facilities. Currently, such regulations are inhibiting the adoption of local energy generation and supply networks. These regulations need to be reconsidered.[62]

The cost of real estate in New York City and the complex nature of the existing grid[63] inhibit the optimal siting of infrastructure technologies. Integrated planning solutions are necessary, which incorporate power supplies as part of the design by, for example, undergrounding power lines in new developments and planning for cogeneration. Building and zoning codes should be modified to prevent the location of critical infrastructure in exposed areas. In addition, more pilot project opportunities should be promoted to trial and demonstrate smart technologies, especially in areas with high electricity demand.

Ownership and operating structures for new infrastructure must be better defined and understood, including local energy generation, storage and vehicle-to-grid (V2G) technologies. This would remove uncertainty surrounding responsibilities for payment, maintenance and management, with greater clarity attracting more frequent adoption.

The location of critical infrastructure is fundamental. This information should be known by utilities, and shared with planners and engineers. Utilities should map out their assets using Geographic Information Systems (GIS), because a map-based database is widely understood and well suited to track assets, identify exposed infrastructure and monitor the status of dispersed equipment.

It will also be essential to communicate the benefits of proposed infrastructure improvements and service changes (such as real time pricing) to communities and businesses to ensure widespread understanding about the benefits new systems will bring. Furthermore, utilities and technology companies must ensure that the reasons for neighborhood construction projects are widely understood in terms of long term safety, security and reduced risk exposure.

The level of investment necessary for these infrastructure renewals will not be possible without government involvement. It is the responsibility of state, local and federal entities to establish a legislative and regulatory environment, and flexible protocols that supports resilience planning. Governments also have greater access to financing, and can effectively communicate with the public and business to coordinate interests.

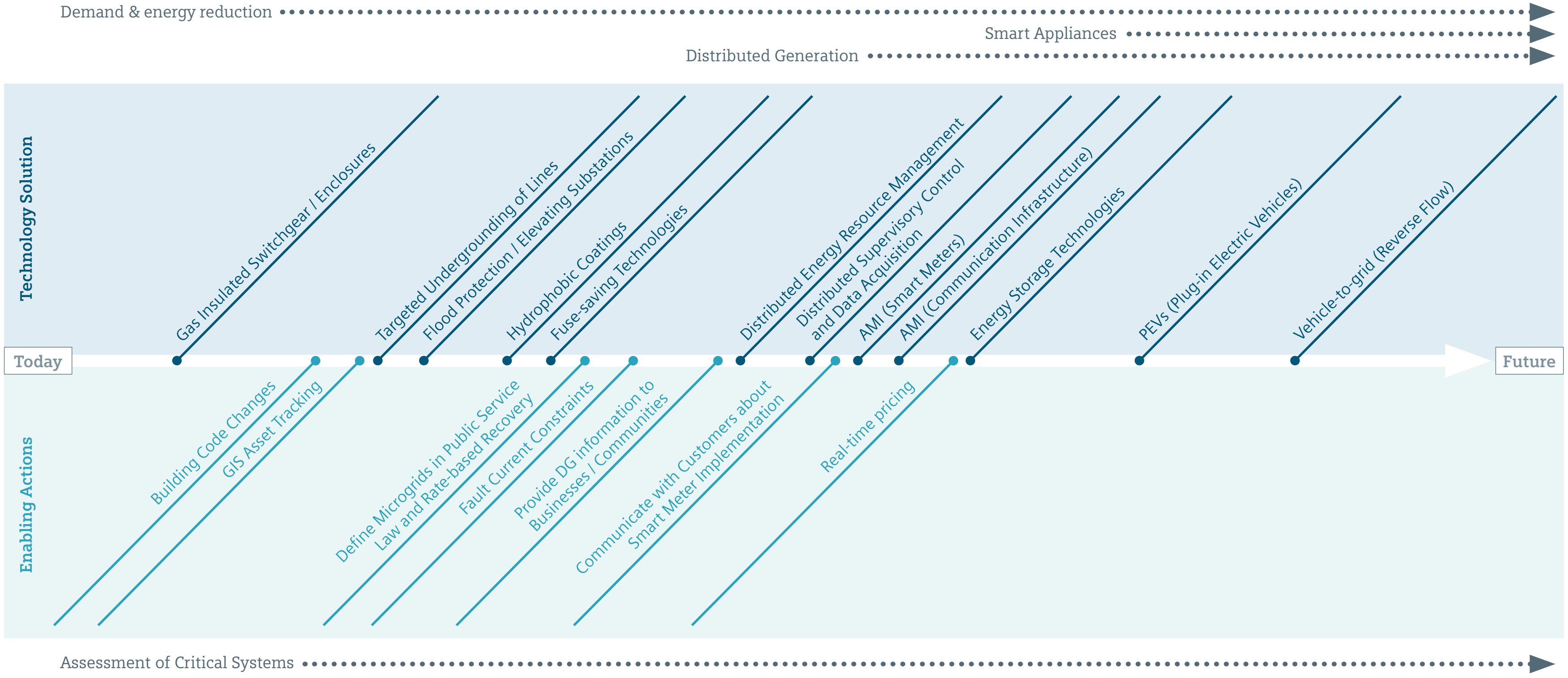
> *We don’t know for certain that we’ll ever see another storm as strong as Sandy and we all hope we don’t. But we must prepare for that possibility – and others. Heat waves, drought, and sea level rise will also pose significant challenges in the years ahead.*
>
> Mayor Michael R. Bloomberg, speaking in New York City, June 11, 2013.

Road map for grid resilience

We have evaluated the potential future risks for the New York region and identified short, medium and long term technology investments to help prepare the area's electricity grid for future disasters.

Additionally, we have examined the enabling actions that would aid the implementation of these technology solutions (summarized below). The actions listed here are not unique to New York – they are appropriate within the context of any city, regardless of infrastructure age or scale of operation.

Responses and effects of asset and system level impacts



Appendix 1: Resilience Performance Indicators

The table below shows a sample of indicators which have been designed to help cities and infrastructure system managers measure the resilience of their systems. Indicators such as these are an essential part of operationalizing resilience.

Robustness	Average age of critical transportation, electricity, gas and water infrastructure versus originally estimated useful life (years). Material damage to infrastructure per year due to environmental effects ($).	Aging infrastructure is more vulnerable to failure due to hazard impacts. Higher costs of material damage imply a greater risk of failure under hazard impacts.
Redundancy	Proportion of commercial / residential / institutional buildings served by own energy generation (%). Total improvement in city-wide energy/water efficiency over past 5 years (%). Total volume of potable water lost from distribution channels per year (gallons).	Greater uptake of local energy supply systems implies increased protection against shocks in the wider electrical grid. Efficiencies help to increase system capacity. Higher losses from the water system imply lower system capacity to serve the city during times of abnormal high demand.
Diversity and flexibility	Proportion of electric feeders and communication network lines in loop versus radial configuration (%). Proportion of base load able to be served by distributed energy systems (%) (Note: this is different from building level back-up). Proportion of commercial/residential/institutional buildings served by own energy generation (%). Proportion of commercial/residential/institutional buildings served by local energy networks (microgrids) (%). ‘Wargaming’ of emergency transportation/evacuation and shelter/displaced persons plans (frequency of review).	Loops can tolerate a fault in one or more locations and route power/information in the opposite direction. Greater uptake of local energy supply systems implies increased protection against shocks in the wider electrical grid. Plans in place to utilize all modes of transportation to move people and first responders throughout the metropolitan area and to shelter, and feed those displaced.

Responsiveness	Average speed of emergency response to an event (minutes). Proportion of city households with access to data networks (%). Number of events and inquiries handled (quantity). Proportion of city households with access to data networks (%).	Fast response times contribute to enhanced resilience. Prevalence of data networks indicates greater potential for real time data monitoring, and encouraging rapid communications across sectors. Ability to handle a large number of events and inquiries implies a responsive and engaged city administration. Prevalence of data networks indicates greater potential for real time data monitoring, and encouraging rapid communications across sectors.
Coordination	Number of city government policies jointly 'owned' by two or more agencies. Proportion of civic organizations or community groups formally engaged in disaster preparedness or recovery activities (%).	Inter-agency ownership of city policies implies greater collaboration and shared decision making. Engagement of civic groups indicates greater dissemination of knowledge throughout the community, and improved coordination of disaster response on the ground.

Appendix 2:

Introduction

The economic analysis demonstrates a high level business case for investing in technologies that provide not just robustness (such as flood protection) but also those that can provide redundancy, responsiveness, flexibility and diversity to the grid. The high level costs are based on costs from the utilities such as Consolidated Edison and studies by respected organizations. The Electric Power Research Institute (EPRI) study, Estimating the Costs and Benefits of the Smart Grid (2011), was a primary resource from which national smart grid data on costs and benefits for the United States has been down-scaled for the New York City scenario.

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New York City Economic Analysis

Scenarios

‘No action’ scenario

The ‘no action’ scenario assumes the following conditions:

- Seven major events occur in a 20 year period, each causing damages equivalent to $400 million (£262 million). This is modelled as an annual damage figure of $140 million (£91.8 million) over the 20 year period.
- All spending is purely repair and restoration to the current function and service. No proactive investments are made to increase protection of critical electrical assets or otherwise upgrade infrastructure.

‘Partial investment’ scenario (flood protection and undergrounding)

In the ‘partial investment’ scenario, the frequency and scale of events is the same as for the ‘no action’ scenario, however the following additional investments are made to increase the protection of the grid from future damage:

- $414.5 million (£271.9 million) is invested for implementation of flood protection measures and undergrounding of critical infrastructure components (i.e. substation flood protection and waterproofing, submersible substation equipment, undergrounding critical power lines).

This investment is assumed to reduce the total damages of all events by 80% over the ‘no action’ scenario, resulting in total damage costs of $560 million (£367 million), or $28 million (£18 million) per year over 20 years.

‘Full investment’ scenario (flood protection and undergrounding, plus smart grid investment)

The ‘full investment’ scenario assumes the same frequency and scale of events as above, with the following investments made to protect the grid and increase its redundancy, responsiveness, flexibility and diversity:

- The same protection investments ($414.5 million) are made as in the ‘partial investment’ scenario.
- An additional $2.4 billion (£1.6 billion) is invested in smart grid equipment, as follows
- Automatic Metering Infrastructure (AMI) – smart metering
- AMI communication infrastructure
- Direct load control
- Distribution automation
- Intelligent feeder reclosers and relays (head-end)
- Intelligent recloser equipment (mid-point)
- Voltage/VAR control on feeders
- Remotely controlled switches
- Power electronics

These investments are assumed to occur on an accelerated schedule of up to 12 years for full implementation. Individual Smart Grid components were assigned separate implementation periods based on the technology used, on installation time and role in the overall Smart Grid infrastructure.

Smart grid benefits are articulated in terms of the following attributes, which will accrue over time to a number of parties. This table describes benefits to the utility and the consumer only, together with the total value to these two parties.

Attribute	Utility benefits (power delivery)	Consumer benefits	Benefit contribution (%)
Cost of energy (total cost to deliver electricity to customers, including capital costs, operations & maintenance costs, & the cost of line losses on the system)	Operations & maintenance costs Capital cost of assets Transmission & distribution losses	End user energy efficiency Capital cost for end user infrastructure Operations & maintenance cost for end user infrastructure Cost of control/management	25%
Capacity	Increased power flow New infrastructure Demand responsive load	Improved power factor Lower end user infrastructure cost through economies of scale & system streamlining Enhanced opportunity for growth	21%
Security	Enhanced security Self healing grid for quick recovery	Enhanced security & ability to continue conducting business & everyday functions	10%
Quality	Improve power quality & enhance equipment operating window	Improve power quality & enhance equipment operating window	4%

Attribute	Utility benefits (power delivery)	Consumer benefits	Benefit contribution (%)
Reliability & availability	Reduce frequency & duration of outages	Enhanced security Self healing grid for quick recovery Availability of power	22%
Environment	Electric & Magnetic Field management Reduction in SF6 (sulphur hexafluoride) emissions Reduction in clean-up costs Reduction in power plant emissions	Improved aesthetic value Reduced electric & magnetic field Industrial ecology	14%
Safety	Safer work environment for utility employees	Safer environment for end-use electrical facilities and	1%
Quality of life (integrated access to multiple services, including electricity, internet, telephone, cable & natural gas)	Value added electric related services	Comfort Convenience Accessibility	5%

Source: EPRI (2004) Power Delivery System of the Future: A Preliminary Estimate of Costs and Benefits and EPRI (2011) Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid. EPRI, Palo Alto CA Report.

Limitations

The NYC case was necessarily simplified from reality to generate a clear set of results within the scope of the analysis we were able to carry out.

For instance:

- The assumptions on hazard event impacts are smoothed out to an annual damage figure.
- The investment expenditure is modeled over a challenging timescale and the implementation could take longer, due to regulatory and planning barriers that would need to be addressed to implement some of the technologies.
- Investment costs and benefits are not attributed to different parties within the model, whereas in reality they fall asymmetrically to a variety of parties, including the federal government, the city, the rate payer, private business, and utilities.
- Likewise, the costs for responding and repairing are reflected as costs to the city as a whole, but realistically these costs would be incurred by multiple parties and much of it through insurance/reinsurance.

The figures used in the calculations should be viewed as broad approximations of a plausible future scenario. They therefore provide a useful illustration of the potential benefits to NYC from grid investments, but not a universal principle that will be true in all possible scenarios.

Finally, the costs of the above technology investments are likely to decrease over time as economies of scale and maturity of the market is achieved.

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