



CASCADING EFFECTS AND ESCALATIONS IN WIDE AREA POWER FAILURES

A SUMMARY FOR EMERGENCY PLANNERS

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Cover Image: London at night (Source: NASA, WikiCommons). The image was rotated in order to fit the cover.

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Executive summary

This special report is the result of a collaboration between academics and practitioners. *It aims to provide a synthetic overview of the cascading effects caused by wide-area power failures, and to define the recurrent impacts and sources of escalation. It provides a reference for the training and the situational awareness of decision makers and emergency operators.* The format uses bullet points and examples to facilitate reading in conditions of limited availability of time. The following topics have been developed:-

- ✓ A definition of cascading effects.
- ✓ An introduction for of wide area power failures (PF) policies and practices.
- ✓ Illustrative examples.
- ✓ A table listing cascading effects and escalations caused by wide area PF.
- ✓ Resources for training and essential references for further reading.

What are cascading effects?

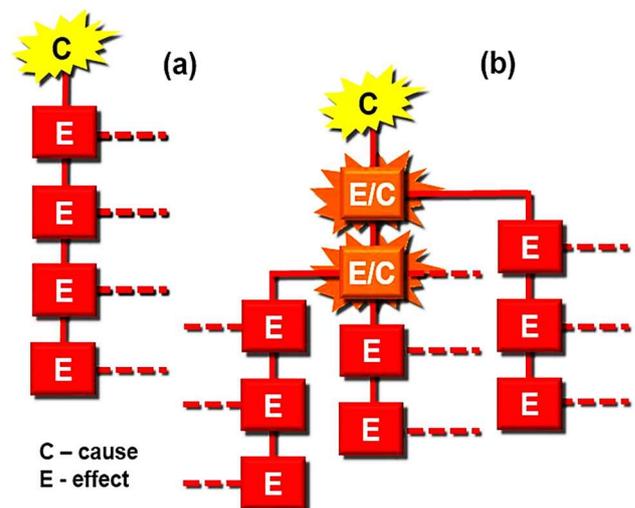
Cascading effects can be defined as:

« The dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events

in human subsystems that result in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes.

Cascading effects are complex and multi-dimensional and evolve constantly over time. They are associated more with the magnitude of vulnerability than with that of hazards. *Low-level hazards can generate broad chain effects if vulnerabilities are widespread in the system or are not addressed properly* in sub-systems.

For these reasons, it is possible to isolate the elements of the chain and see them as individual (subsystem) disasters in their own right. In particular, *cascading effects can interact with the secondary or intangible effects of disasters* » (Pescaroli and Alexander 2015). The figure below illustrates the differences between: (a) linear paths of chain-effects, and (b) complex paths of cascades. In "cascading disasters", secondary emergencies escalate and become the centre of a crisis, challenging the coordination of emergency relief and long-term recovery.



Wide area power failures

Power failures (PFs) can be defined as long term or short-term disruptions of electricity, and they are also known as power outages or “blackouts”. Despite the high reliability of the national grid, the frequency of these events is higher than that which the public might predict. They can be triggered by both natural and man-made external threat, or caused by internal failures and accidents.

It is surprisingly common that natural hazards impacting the built environment cause PFs (Helbing et al. 2006). For example, in 2007, storm Kyrill damaged electricity pylons in different parts of Europe, causing PFs. The figure below shows its effects in the Magdeburg-Ottersleben area of Germany. Only in the first three months of 2013, extreme events, such as flooding, strong winds and earthquakes, triggered 52 power outages in 19 countries, affecting more than one million people (Klinger et al. 2014). At the time of writing, PFs triggered by Hurricane Maria have left millions of customers without electricity in Puerto Rico (see examples).



However, it must be noted that emergency planning cannot concentrate on natural triggers but must consider the existing vulnerabilities of the system. The wide-area blackouts that happened in North America and Europe in 2003 and 2006, respectively, were rooted in technical failures associated with management culture and production pressure. Other intentional man-made drivers, such as cyber and terrorist attacks, have the potential to create widespread PF. This happened in Ukraine in December 2015, when 225,000 customers were affected by a PF triggered in the cyber domain (Campbell 2016).

Implications for emergency planners

Emergency planners should remember that electricity supply is the backbone of all society's functions. It is essential to the delivery of services such as water supply, and it drives individual and collective behaviour. Extended power failures can compromise most services and routine activities, including commuting to work, payments, use of ATMs, cooking and providing drinking water and sanitation. The implications for operational management, contingency planning and business continuity are enormous (Petermann 2011, Hogan 2013). It has been shown that PFs can sometimes require international relief, which could be needed in the form of goods or expertise (Pescaroli and Kelman 2017).

Different elements can influence the likelihood of PFs and their development into cascading crises, including the increased complexity and interdependency of networks, market distribution and ageing infrastructure. Wider attention should be given to the different aspects that determine societal resilience as a whole (Florin and Linkov 2016). Dependency on electricity can influence the vulnerability of society and determine the implications for emergency planning. It is clear that in recent decades the social use of electricity has changed, which has altered the pattern of cascading effects and their impacts in ways that must be considered in both the crisis and the response. For example, the use of the Internet and smart-phones has modified working behaviour, but also the process of information-gathering during a disaster. Independently of the trigger, the escalation paths can be addressed with vulnerability scenarios that consider the technical and societal drivers of PF (Pescaroli and Alexander 2016).



Assessing risk

The implementation of national risk assessments is one of the actions suggested in the Sendai Framework for Disaster Risk Reduction, 2015-2030. The United Nations International Strategy for Disaster Reduction (UNISDR) released a set of guidelines to support this process, and they mention cascading dynamics (UNISDR 2017). However, it must be noted that scenarios and assessments should be grounded in the specificities of the areas considered in the planning process. For example, urban areas with concentrations of high-tech enterprises will have different needs and escalation paths than rural areas, where food production is concentrated. London is an important example, because it is one of the most interconnected cities in the world, with a concentration of businesses that are highly dependent on stable supplies of electricity. Here, a limited power failure of 40 minutes in 2003 affected more than one million people, overburdening the emergency services. The London Risk Register includes the following scenarios based on the UK National Risk Assessment (LR 2017):-

- 1) "Total blackout for up to five days with prolonged disruption for up to 14 days due to loss of the National Grid". Its likelihood is "moderate", but its possible impact is "catastrophic".

Northeast America, August 2003. Fifty million people were left without electricity for up to 48 hours due to the sudden breakdown of one power station which caused the switching out of others (see Figure of the impacted area). Services such as water supply, communications and public transport (including airports) were disrupted. Traffic was affected by the lack of traffic lights, pumping stations were not working, and people were trapped in elevators and subway trains. In the longer term, economic growth was temporarily reduced (Helbing et al. 2006).

Japan, March 2011. The triple disaster in Japan was a complex event with devastating consequences. Although a relatively limited number of lives were lost in the earthquake, many more people were killed by the ensuing tsunami. The tsunami damaged the Fukushima Dai'ichi nuclear reactors, impacting a precarious situation on site that was exacerbated by the damage caused by the earthquake to electricity substations. The National Diet of Japan considered the nuclear accident to be a man-made disaster due to root causes associated with the failure of back-up systems. Overall, the triple disaster left around 4.4 million households without electricity. At least 25 power stations were shut down, and oil refinery capacity fell by 30%. The power failure triggered cascading disruptions in sectors such as rail transportation, communications, manufacturing, water and petrol supplies.

USA, October 2012. Hurricane Sandy affected some densely populated states in

the northeastern USA, and PF lasted from several days to two weeks. In the New York city area, an explosion at a power plant in Manhattan left 600,000 people without electricity. Fires of electrical origin broke out. The official reports highlighted loss of life associated with the joint effect of power outages and cold weather.

UK, December 2013. Severe weather damaged the national electricity distribution network between 22 and 28 December. The electricity supplies were disrupted to approximately one million properties. The service was restored within 24 hours for 876,000 customers, but another 16,000 experienced disruptions for more than 48 hours. This example is used as a reference scenario by the UK National Risk Register (UK Cabinet 2016).

Italy, January 2017. In central Italy, four shallow-focus earthquakes of magnitude $M_w > 5$ occurred, at a time when 150,000 families were without electricity as a result of record snowfall. After one week, 7,000 households in nearly 30 municipalities were still without service and the weather remained cold. This was the longest-lasting blackout in Italy since the end of WWII.

Puerto Rico, September - November 2017 (Ongoing). Hurricane Maria heavily damaged Puerto Rico's grid causing a long - lasting PF. At the time of writing, the disruptions are still ongoing and it has been recognised as the longest blackout in US history.

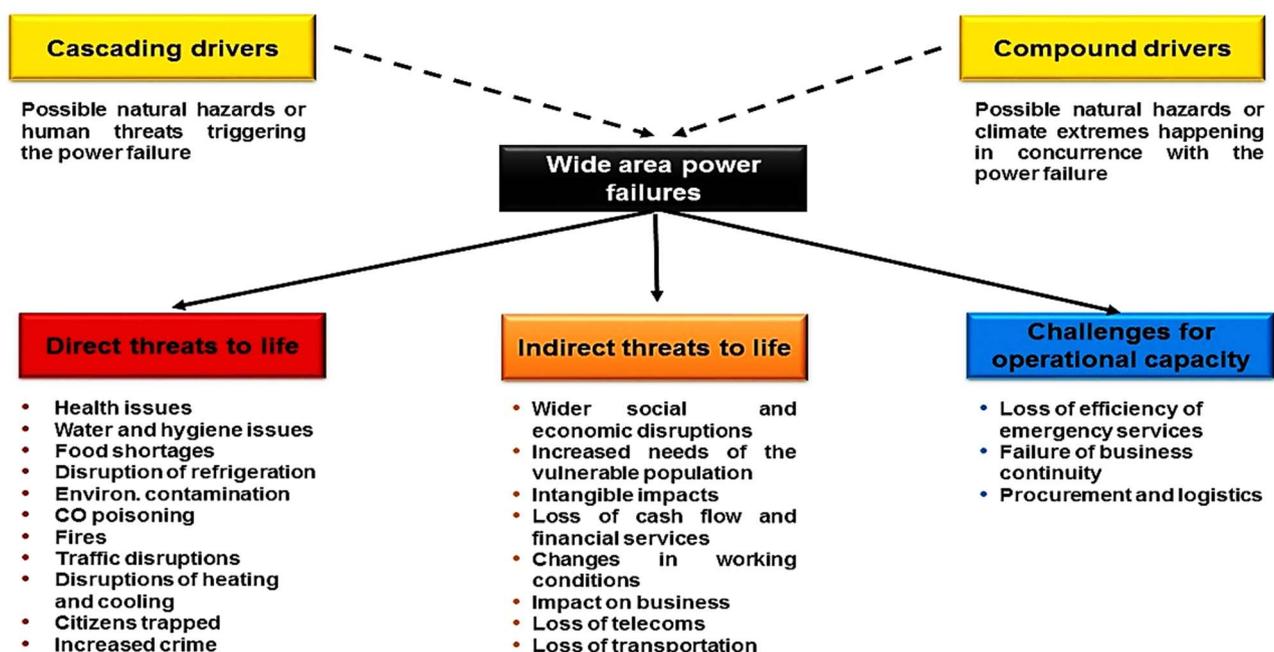
Cascading effects in wide-area power failures

The sectors impacted by wide-area power failures and their cascading effects are summarized in the following figure. In order to provide a synthetic overview of the recurrent paths that have been reported in the literature, each point is described in detail in the table that follows. Please note that this does not pretend to be predictive or fully exhaustive. Its goal is to help emergency managers, emergency planners, and policy makers to have a rapid overview of the common issues that could arise from an extended blackout. It is intended for training and operational purposes only. The impacts, timelines, and escalations are generic, and are derived mostly from experience in the USA and Europe.

The table is divided into four functional categories, as shown below:-

- ✓ Compounding and cascading drivers (yellow), which could be contextual elements that trigger or exacerbate the crisis.
- ✓ Direct threats to life (red), that involve the sectors in which primary action by the emergency services is expected.
- ✓ Indirect threats to life (orange), which can be associated with social and community disruptions that impact the duration of the crisis and undermine the recovery process.
- ✓ Challenges to operational capability (blue), which are those factors that can limit or reduce the emergency response capacity.

Before using this application to build scenarios, please note that a specific operational context can influence the content of this table.



CASCADING EFFECTS AND ESCALATIONS OF WIDE-AREA POWER FAILURES SUMMARY TABLE

	Impacted Sector	Cascading effects and escalations
CASCADING DRIVERS	<i>The power failure itself is triggered by natural hazards or human threats</i>	<p>The wide-area power failure may be caused by particular hazards or threats, such as flooding, storms, heatwaves, ash clouds, geomagnetic storms, terrorism, cyber warfare, etc.</p> <p>This may result in an increased burden on responders and society for the combination with other drivers of crises.</p> <p>Some triggers, such as ice storms, may increase the overall vulnerability of emergency services and utilities.</p> <p>Increased need for timely information, flexibility of response, and resolution of uncertainties.</p>
COMPOUND DRIVERS	<i>Natural hazards or climate extremes that happen in concurrence with the power failure</i>	<p>Compounding risk refers to the risk of concurrence of the wide-area power outage with other hazardous conditions, resulting in a combination of the elements:</p> <p>e.g. heat waves, which can increase wildfires, stressors on the health sector, and importance of refrigeration in food consumption, supply and production,</p> <p>e.g. cold weather and snow, which can be associated to loss of life related to lack of heating, or lower maintenance of the grid.</p>
DIRECT THREATS TO LIFE	<i>Health</i>	<p>An increased number of injuries and fatalities is expected in the short term, both from accidents (e.g. on roads and at home), and from cascading effects of other sectors, such as food toxicity, and vulnerable residents (home oxygen supplies, dialysis, and home nursing). In the medium and long terms, the number is expected to rise even more, for example in nursing homes and where there are newly vulnerable residents (such as patients without medicines).</p> <p>Issues of direct clinical care in hospitals: malfunction of care devices, loss of electronic patient records, and moving patients by stairs instead of in lifts. Evacuation of patients on ventilators may be needed. Major decline in the functionality of the health sector within the first 24h.</p> <p>Reduced efficiency and functionality of hospitals: blood banks, radiology, heating, cooling, cooking and washing. Pharmacies may be left without insulin or vaccines, or have bottlenecks in drug supply.</p> <p>Short and long-term impacts on the production and distribution of medicines (i.e. the supply of pharmaceuticals), some of which could become unavailable in the early phases of the blackout.</p>
	<i>Water shortages and hygiene issues</i>	<p>Lack of potable water due to reduction in supply from water mains, with risk of contamination from different sources. Water may not be capable of being boiled and a scarcity of drinking water may result.</p> <p>Challenges in hygiene: reduced pressure in the water mains, toilets not flushing, difficult to maintain the sewer system. Even when a minimum supply can be guaranteed, booster pumps in high-rise buildings may stop working.</p>
	<i>Disruption of refrigeration</i>	<p>Increased possibility of food poisoning. Increased difficulty of disposing of spoilt food.</p> <p>Challenges for maintaining the food supply to households.</p>

	Impacted Sector	Cascading effects and escalations
DIRECT THREATS TO LIFE	<i>Food shortages</i>	<p>Reduced operational capacity, supermarkets unable to rely on electronic cash machines.</p> <p>Food distribution is heavily affected by transportation disruption: railways (not working), roads (petrol pumps not working), water (e.g. cranes not working in harbours). Bottlenecks expected in a few days.</p> <p>Cooking is not possible or is limited.</p> <p>Increased waste due to disruption of refrigeration.</p> <p>Effects on the food industry with loss of animals and, depending on the season, fruit and vegetables. The disruption of food industry may result in long-term losses.</p>
	<i>Environmental contamination</i>	<p>Possible release of pollutants or contaminants due to the impossibility of storing and disposing of chemicals correctly.</p> <p>Possible leaks triggered by industrial processes.</p> <p>Water contamination: wastewater may escape from pipes (pumps may not have a backup), ships may discharge wastewater into water course due to lack of on-shore services.</p>
	<i>Carbon monoxide poisoning</i>	<p>Unsafe use of generators, cooking with camping stoves.</p> <p>Disruption of ventilation in underground car parks and tunnels.</p>
	<i>Fires</i>	<p>Additional fires in industries due to failure of cooling and control equipment.</p> <p>Increased number of fires in households, due to the use of candles and other unsafe behaviour.</p> <p>Possible reduced capacity of firefighters that allows fires to escalate (see consequences for emergency management).</p>
	<i>Traffic disruption</i>	<p>Traffic lights not working: increased number of accidents, traffic jams, bottlenecks. Possible disruption of tunnels due to reduced lights and ventilation, further increasing bottlenecks.</p>
	<i>Disruption of heating and cooling</i>	<p>The disruption of heating and cooling systems may be associated with loss of life, and increased pressure on health services. The impact is mostly dependent on compounding factors, such as weather conditions (see compounding factors).</p> <p>Industry and research may be heavily affected when controlled ambient conditions are needed: e.g. in laboratories, for livestock in the food industry, in computer data centres – e.g. for financial services, healthcare, government functions, institutional communications (email etc) - see cyber security/loss of telecoms.</p>
	<i>Citizens trapped</i>	<p>Emergency services are called to rescue people trapped in tunnels, lifts and other facilities that have stopped working. The burden may increase with people locked out of or inside houses and in general access devices may malfunction.</p>
	<i>Increased crime and social tensions</i>	<p>Loss of safety and security systems: failure of electric locks and possible issues with CCTV.</p> <p>Possible disorder or riots in jails due to decreased quality of life.</p> <p>Possible episodes of public anger. In case of long-lasting disruptions, increased pressure on scarce resources.</p>

	Impacted Sector	Cascading effects and escalations
INDIRECT THREATS TO LIFE	<i>Wider social and economic disruptions</i>	<p>All aspects of society are affected by wide-area power outages, disrupting the normal functioning of routines and activities. This is likely to increase the burden on emergency services and on politics.</p> <p>The lack of knowledge about which practices are safe to utilise may result in a rise of unsafe behaviour, with pressure on communities, households and individuals.</p> <p>Possible increase in cross-border and transboundary elements.</p> <p>Short- and long-term economic impacts on businesses, households and communities.</p>
	<i>Increased needs of the vulnerable population</i>	<p>Increased need for support of the vulnerable population such as people who are dependent on medical equipment, the elderly, the very young and disabled people.</p> <p>Creation of new vulnerability categories: e.g. stranded passengers and commuters. The closure of public buildings may increase the level of distress.</p>
	<i>Intangible impacts</i>	<p>Despite the need for more studies in this sector, it is likely that there will be an exacerbation of stress levels in line with that experienced in other emergencies, for example, when parents cannot communicate with schools.</p> <p>Adaptive changes of social behaviour can be virtuous, such as mutual aid, or disruptive, such as disputes about scarce resources.</p>
	<i>Loss of cash flow and financial services</i>	<p>Loss of ATM, cash flow, cashless transitions, which effects heavily both distribution and consumption. Where many people use cards, there could be consequences such as the ones that happened during 2015 York flooding. Moreover, the diffusion of automatic cashiers may have decreased the resilience of the distribution system.</p> <p>Disruptions in the financial services makes purchases/payment of invoices not available. Similarly, the administration and management of investments is affected. Despite the resilience of certain critical infrastructures, multilateral trading systems may be disrupted.</p>
	<i>Impact on business, enterprises, research</i>	<p>General deterioration of working conditions where business continuity is ineffective. Health and safety concerns may be raised.</p> <p>Possible limitation of working hours to periods of natural light.</p> <p>High impact associated with the features of just-in-time production.</p> <p>Possible lack of backup for small businesses, possible general lack of mitigation resulting from low levels of perceived risk.</p> <p>Laboratories in universities and high-tech facilities may be heavily disrupted, threatening the results of years of research. Biological, radiological and chemical hazards are possible in some laboratories.</p>
	<i>Loss of transportation</i>	<p>Petrol stations are disrupted, increasing the pressure on public transport and reducing its resilience.</p> <p>Mass transport: underground and surface railways go out of order during the first two hours, airports activate safety procedures and gradually restrict flights. Increased pressure on road transportation may cause a lack of fuel in the short to medium term.</p> <p>The unavailability of all sectors of transportation will affect the logistics of goods and services, and will cause increasing strain on ordinary activities at all levels of government and management.</p>

	Impacted Sector	Cascading effects and escalations
INIRECT THREATS	<i>Loss of telecoms</i>	<p>Loss of telecommunications affects all aspects of ordinary routine, from keeping up business as usual, to allowing family gatherings after work. ICT is nearly 100% reliant on electricity supply.</p> <p>Risk of data losses and disruption of administrative procedures. Consequences both in the short term (loss of operation capacity) and the long term (impact of data losses).</p> <p>Lack of information may increase unsafe behaviour, while the overload of telecoms may be a serious issue.</p>
CHALLENGES FOR OPERATIONAL CAPACITY	<i>Loss of efficiency of emergency services</i>	<p>In general, all the secondary events listed above are likely to increase pressure on the emergency services.</p> <p>Reduction of personnel available to manage and respond to disruption in transportation and communication. Need to add volunteers and retirees.</p> <p>Strain on personnel on duty in the emergency services, hospitals, healthcare, community support. Stress and exhaustion may reduce the effectiveness and efficiency of rescue and crisis management.</p> <p>Challenges of communication may arise <i>within</i> the emergency services, with the government, local communities, and citizens. Similarly, in hospitals problems may arise with both internal and external communications. See Petermann et al. (2011, p. 89) for the estimated duration of ICT (a German example).</p> <p>Loss of effectiveness of firefighting due to reduced pressure in watermains. Possible malfunction of fire alarms.</p> <p>Loss of control in prisons, with challenges to the essential duty to guarantee security.</p> <p>Limitations in access to 999/112: loss of mobile telephony while a smaller request of help (e.g. people trapped in lifters) are likely to increase. Possible overload of landlines, question of how many hours of self-standing capacity are available, and how many households have private telephones. Uncertainties in the modes of communications with the citizens.</p> <p>Possible failure of some critical infrastructure e.g. due to maintenance of generators and contracting procedures. Similarly, it is likely the worsening of working condition in the coordination centres (e.g. reduced ventilation/heating).</p>
	<i>Failure of business continuity</i>	<p>Possible failures in planning in the differentiation between minimum operational capacity and business as usual: focus may be on keeping vital elements going (e.g. data centres), while the absence of lights or power for laptops blocks the work.</p> <p>Possible lack of training for the effective activation of emergency actions, or perhaps plans are outdated.</p> <p>Other challenges are related to procurement: if generators are not already present in a building, contractors may not have working generators available. Shortfall of goods due to competition for the same providers.</p>
	<i>Procurement and logistics</i>	<p>Multiple shortfalls of vital supplies such as: electricity, petrol, food, water supply, hygiene, drugs, and personal communication systems. In the long term, the shortages may impact production and distribution.</p> <p>Even at the national level, resources may not be available, requiring international relief (e.g. EU Civil Protection).</p>

Improving resilience to power failures: a checklist

The awareness of cascading effects described in the previous table is merely the first step for increasing resilience to power failures. These must be incorporated into the practice of preparedness and emergency response. There are some key questions that can be used as a basic guide to dynamic improvements.

- ✓ Are you considering the cascading effects of power failures in your existing emergency planning and business continuity strategies? Are you using any forward-looking tools and wider impact assessment methods?
- ✓ Have you ever conducted an exercise of a scenario of extended power failure? In your area and your organisation, which are the vulnerabilities that are more likely to escalate the cascading effects?
- ✓ Are you aware of CI interdependencies and of which could be the most likely compounding and cascading drivers in your area that could cause the emergency to escalate?
- ✓ Did you conduct any GAP analysis or resilience assessment to consider the real capacity of your organisation to remain operational during an extended power failure? Is it updated and considered a realistic worst- case scenario?

- ✓ Which are the lifelines of supply you may lose in your worst-case scenario? Do you know how to communicate with your colleagues or employees? Are your backup systems available, maintained and operational?
- ✓ Are you considering which could be the most vulnerable categories of citizens in your area? How would you disseminate information to the community and which safety behaviours you would consider a priority to promote?
- ✓ In case of a wide area power failure, which would be the first cascading effects that you would try to mitigate? Which are the organisations you would involve in the process?

Please note that there is no definitive answer to these questions. However, in this scenario, crisis managers may be the first “victims” of the disruption, so it is as well to consider how it could affect your individual capacity to deploy and be operational. The next pages offer a list of possible resources for improving training and planning, and some reading material available in open source.



Resources for training and plans

- ✓ London Resilience developed *ANYTOWN*, a generic and replicable model “to improve the understanding of infrastructure interdependencies by non-experts”. *ANYTOWN* aims to increase information sharing through collaborative scenarios of disruptions that are applied in workshops with local stakeholders. Website: www.londonprepared.gov.uk.
- ✓ The Joint Research Centre of the European Commission created the *Geospatial Risk and Resilience Assessment Platform (GRRASP)* for the analysis of interdependencies and CI disruptions. The platform is online and uses open-source technologies, facilitating the analysis of risk and resilience in networked systems. Website: www.ec.europa.eu/jrc/en/grrasp.
- ✓ The UK Emergency Planning College (EPC) has a list of open access resources that could be used for improving the training levels of organisations. These include the position paper *Decision support tools for risk, emergency, and crisis management: an overview and aide Memoire*. This document provides an intuitive explanation of impact trees and forward-looking tools such as scenarios. The website for this and other resources is: www.epcresilience.com.
- ✓ *Blackout Simulator* is available online for the development of scenarios and understanding of the possible economic damage caused by power failures. After registration, which is free, it can run cost calculations that consider multiple areas and durations of blackouts. Though the assessment may be debatable, it provides an excellent opportunity to gain an idea of the possible impact of disruptions. Website: www.blackout-simulator.com
- ✓ The US National Institute of Standards and Technology released the Community Resilience Planning Guide for Buildings and Infrastructure Systems. It proposes an operational six-step process for understanding the linkages between society and the services provided by CI. Website for download: www.nist.gov.
- ✓ Safe behaviour of individuals and households are important and should be addressed at both the public and private levels. Basic tips on power outage safety, before, during, and after the event, are available on the website of the Red Cross (www.redcross.org), or at: www.ready.gov/power-outages.
- ✓ The website Cipedia.eu provides an overview of official definitions in CIP and resilience, including “blackout”, and “scenario”.
- ✓ Other policy briefs can be downloaded from the website of the International Centre for Infrastructure, www.icif.ac.uk.

Essential references and further reading

The following material is some of the literature considered in the present report. We listed the most relevant papers and reports that are available in open access. For further reading, please contact the authors.

- ✓ Campbell, R. J. (2012). *Weather-Related Power Outages and Electric System Resiliency*. CRS Report for Congress, Washington DC, available at: www.crs.gov.
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New York's skyline during the power outage triggered by Hurricane Sandy in 2012 (Source: Hybirdd, WikiCommons)

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In "Implications for emergency planners": Vernon Chan, *WikiCommons*.

In "Improving resilience": Ilan Kelman, www.ilankelman.org

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