Chapter 14
Zaps and Taps: Solar Storms, Electricity and Water Supply Disasters, and Governance

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14.1 Introduction

Electricity distribution for water supply and sewage processing (Wilkinson 2011) (Fig. 14.1) is vulnerable to solar storms. This chapter aims to draw attention to this issue for those involved in water supply risk governance, to motivate more research and action to mitigate the likely catastrophe of an extreme solar storm. The main topics of the chapter are: the solar storm threat including the 'worst case', the vulnerability of power grids and water resources dependent upon electricity, current trends in power grid development in relation to the solar storm threat, mitigation strategies and governance issues, with particular emphasis on cross-border challenges.

14.2 Electricity for Water Management

Energy is needed for water resource management, and most comes from the generation of electricity that is distributed through high voltage power lines. In the USA about 3% of electricity production (4157×10^9 kWh) is for water treatment and disposal of wastewater, about 8% for cooking, cleaning and water heating, and about 1% for pumping and transport of water and wastewater (Novotny 2012). This amounts to about 500×10^9 kWh annually. In six Australian cities, that contain nearly half of the country's population, about 0.2% of the total energy used is for water management (Kenway et al. 2008). Globally there is considerable variability in the amount of electricity used in different parts of the water management system.

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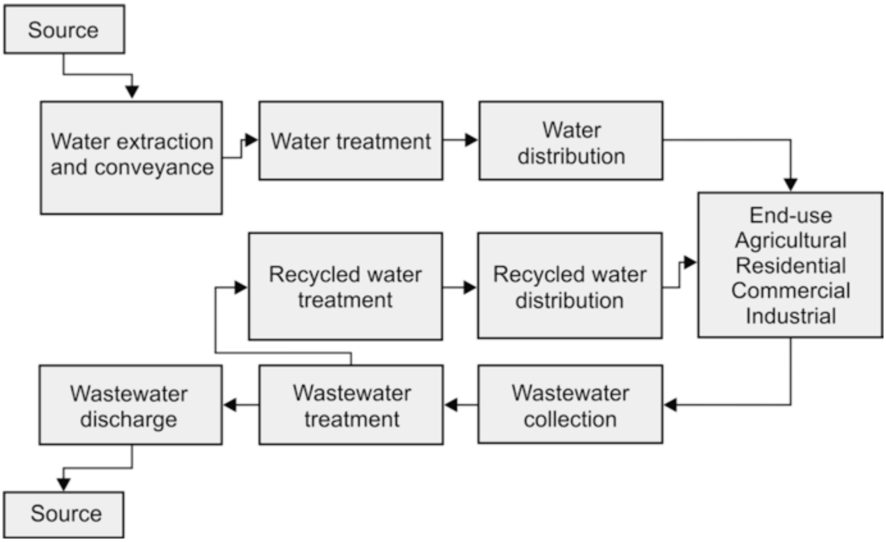

Fig. 14.1 Most of this system is vulnerable to failure of electricity supply

For example, water treatment can be achieved using between 0.03 and 7 kWh m^{-3} (Novotny 2012)—different by a factor of 233. Of the total energy used for water management in Bangkok, 20% is used for drinking water treatment, in contrast with 45% in Tokyo because of different water quality standards (Dhakal et al. 2015). But according to the same authors, 55% of the energy in Tokyo is used for water transport and distribution versus 80% in Bangkok, a share that is even higher in Delhi at 83.5%. From these few examples it is plain that energy is used in different amounts and in different ways depending upon many local factors. Therefore vulnerability to disruption is spatially heterogeneous.

14.3 Solar Storms and Some Examples of Their Impacts

The potential impacts of solar storms are a consequence of the combined effects of the threat, the vulnerability of electricity grids and the dependence of water supply on electricity. There are three components to solar storms: solar flares (SFs) that last for 1–2 h, solar proton events (SPEs) that last for days, and coronal mass ejections (CMEs) that also last for days (Marusek 2007). SFs are magnetically driven explosions on the surface of the Sun that produce electromagnetic radiation in the form of X-rays, extreme ultraviolet (UV) rays, gamma radiation, and radio wave bursts. SFs interfere with satellite communications, radar, and shortwave radio, and also affect the orbits of satellites. M-class SFs cause radio blackouts in the polar regions, while more powerful X-class SFs can trigger worldwide radio blackouts. SPEs consist of high-energy solar cosmic rays that disorient satellites, damage spacecraft electronics including solar panels, irradiate highflying aircraft, produce fading in shortwave radio signals, deplete ozone, and have human health effects (including, in extreme cases, heart attacks). Large SPEs are followed 96% of the time by a CME that is a mass of gas and charged plasma with an embedded magnetic field blasted from the Sun. When a CME reaches Earth it massively disturbs the magnetic field in a geomagnetic storm. Charged particles and electrons in the ionosphere induce powerful electrical currents in the surface of the planet, known as geoelectric-induced currents (GICs), that have spatially variable impacts depending in part on the conductivity of Earth's crust. CMEs cause satellite tracking errors and payload deployment problems, radar errors, radio propagation errors, compass realignments, oil and gas pipeline corrosion and failure, communication landline and equipment damage, electric shocks and fires, and human health impacts. Both SPEs and CMEs will hereafter be referred to as SPEs (Marusek 2007).

In addition to the severe solar storms, there is another space weather phenomenon that deserves attention: sudden impulses. These occur during geomagnetically quiescent periods and are caused by abrupt increases in the solar wind dynamic pressure that increases the northward-directed magnetic field and create GICs that can damage power grids at low latitudes (Carter et al. 2015).

The most readily observed manifestations of geomagnetic storms are aurora, known as the northern and southern lights. They result from the precipitation of charged particles from solar storms into the upper atmosphere. The resulting ionisation and excitation of atmospheric constituents emit light of various colours producing spectacular displays, mostly at high latitudes but also at much lower latitudes during extreme solar storms (Eather 1980).

The 1859 super-magnetic storm, known as the Carrington Event, erupted from Earth's poles to the equator but did not affect electrical supply, as it was not in wide use at the time. It caused telegraph systems to fail, with some machines bursting into flames and telegraph operators rendered unconscious (Clark 2007; Lloyd's 2013). The aurora associated with this event was seen as far south as 18° geomagnetic latitude (corrected for movement of the geomagnetic poles) near Panama, a long way south at about 8.5°geographic latitude (Boteler et al. 1998). With regard to electrical power systems, in 1972 AT&T (American Telephone and Telegraph Corporation) redesigned a trans-Atlantic power cable after a major solar storm stopped telephone communications. Also in the same year a 230,000-volt transformer exploded in British Columbia as a result of a solar storm, and in 1980 a similar failure occurred in Canada at St. James Bay, a replacement for which failed the following year for the same reason (Omatola and Okeme 2012). In 1989 a solar storm induced a geoelectric field that coupled with the Hydro-Québec electric power grid in Canada. The grid collapsed after the protective relays were compromised and about nine million people lost power (Bolduc 2002). Also in 1989, the Salem Pressurized Water Nuclear Reactor in New Jersey was affected when an induced current in the electrical transmission line damaged a step-up transformer (Anon 2014; Lloyd's 2013). During the same event large transformers were damaged in the UK and about 200 significant anomalies occurred in electricity grids across North America, with power interruptions as far south as California (Aon Benfield 2013). In 2003 a large solar storm caused system failure in the Swedish electrical grid by shutting down transformers (National Academy of Sciences 2004; Organisation for Economic Co-operation and Development/International Futures Programme [OECD/IFP] 2011). During the same event damage also occurred to the grid in North America including a capacitor trip and transformer heating, shutting down water and sewage pumps in New York City and spewing millions of gallons of sewage; in Detroit and Cleveland raw sewage polluted drinking water sources (Hines et al. 2009). The same event in South Africa led to 12 transformers being removed from service, a surprise at the time because the largest effects were expected at high latitudes (Lloyd's 2013). But as pointed out by Pulkkinen et al. (2010), geomagnetically induced currents (GICs) are a 'truly global phenomenon' even though the largest magnitudes of GICs are expected at high latitudes. For example, Pulkkinen et al. (2012) suggest that the magnitude of GICs is greater for the 100-year events (i.e. those with an annual probability of 0.01) at geomagnetic latitudes higher than about 40°, although there is enhancement near the geomagnetic equator in the equatorial electrojet. An elecrojet is a band of intense electrical current tens of kilometres above Earth's surface in the ionosphere, near the North and South Poles (the auroral electrojets) and also near the geomagnetic equator (Akasofu 2002; Carter et al. 2015; Lühr et al. 2004).

These examples suggest that in Asia the greatest effect is likely to be in northern China (Liu et al. 2014a), northern Japan and parts of Central Asia, with a smaller effect in Southeast Asia (Malaysia, Thailand, Lao, Cambodia, Vietnam, Indonesia) and India near the geomagnetic equator (Carter et al. 2015; Lühr et al. 2004). The most susceptible areas outside Asia are in Russia, most of Europe including the UK, and most of North America, with impacts in southern Australia, New Zealand and southernmost Africa, and smaller effects near the geomagnetic equator in central Africa and South America (e.g. in Brazil and Uruguay; Barbosa et al. 2015; Caraballo et al. 2013; Carter et al. 2015).

The disruptions to electricity supply described above may seem comparable with the impacts of meteorological storms, floods, earthquakes and heat waves and therefore well within modern society's capability to cope, albeit with some discomfort. An example of a non-solar disruption is provided by the massive power outage in the Midwestern USA in the summer of 2003 that was caused by the shutdown of one generating plant in Ohio: a case of a cascading failure as load was shifted to already overheated power lines that became hotter and shut down (Mitchell 2009). The largest impact of an apparent failure to manage an electrical grid occurred in India when a power outage affected 370 million people in 2012. But management and over-drawing of power may not have been the only cause of the outage. A solar storm is also implicated as the solar proton flux increased just before the outage, causing a trip in the grid (Mukherjee 2015; Mukherjee, personal communication, December Mukherjee 2015); this was possibly the result of enhancement in the equatorial electrojet (cf. Carter et al. 2015).

Perhaps the most disturbing impact of a long power outage is the failure of supply of cooling water for nuclear reactors (Kappenman 2010). Depending upon the magnitude of the impact of a SPE on power grids, hundreds of nuclear power reactors could melt down as their cooling water is depleted. Explosions and breaches of containment vessels would then spread radioactive material into the surrounding areas and further afield if wind speeds are sufficient; this would result in a cascading disaster across borders. The Chernobyl and Fukushima disasters are noteworthy examples of what could happen, but to many more reactors. While this is a realistic possibility, and the blogosphere is full of apocalyptic pronouncements, there appears to have been little serious analysis of the problem.

Society has become used to short-term power outages of a few days, but much longer outages as a consequence of a solar storm are not part of most country's planning (CRO Forum 2011). While researchers have focused on the physics of solar storms and impacts on electricity grids, there is almost no research on the links between electrical failure from solar storms and water supply disturbance. This is possibly because the identification of the 'downstream' cascading impacts of solar storms, including on water supply, requires simulation modeling that entails modeling of the AC power flow through the grid and detailed transformer specifications. Some countries may have undertaken simulations, but the results are not in the public domain. However, it is not difficult to imagine the impact on water supply of a power outage lasting for months, particularly in cities where householders and businesses have little or no water storage capacity. That such a scenario is not fanciful is clear, because even if spare transformers are available it can take weeks to months for transportation and installation (Bartley 2002). The construction of new transformers may take 5–12 months for domestic suppliers and 6–16 months for international suppliers (Corbin 2012; Office of Energy Delivery and Electrical Reliability 2012; United States International Trade Commission 2012). To add to the problem, the construction of new high voltage (HV) or extra high voltage (EHV) transformers requires electricity!

14.4 Threats, Vulnerability and Risk

The threat of solar storms of the intensity of the Carrington Event is real: auroral sightings over the past 2000 years have shown that the Carrington Event was not unique (Lloyd's 2013). An estimate of the probability of such a storm would be a useful input to risk assessment, and has been recommended in many reports on the threat of SPEs (e.g. North American Electrical Reliability Corporation [NERC] 2012). Also, some attention to the 'worst case' threat is provided because it has figured in much of the discussion of risk assessment (e.g. Langbein 2014). But an understanding of the threat will be a long way short of what is required, because the risk is a function of both the threat and the vulnerability of electricity supply and its effect on water supply and treatment.

In what follows the frequency, probability, and possible 'worst cases' of SPEs are considered, along with the factors involved in infrastructure vulnerability and estimates of total risk to electricity availability.

The physics of SPEs is insufficiently understood to estimate frequency from first principles. Therefore empirical methods are required, and scholars have used many different data types and analytical procedures, producing a wide variety of estimates. The 1859 Carrington Event was the largest SPE in at least 450 years according to Shea et al. (2006), and in 155 years according to Lakhina and Tsurutani (2016), with a likely return period of 150 years (an annual probability of 0.007) based on auroral sightings from as early as 480 BCE (Stothers 1979). The Québec event has a return period of 50 years (0.02 annual probability) based on the same information. Using power-law modeling of the Dst distribution (the disturbance storm time that is a measure of the geomagnetic disturbance level globally in units of nanoTesla, nT), Riley (2012) estimated the decadal probability of a Carrington scale event at 12% (an annual probability of 0.0127 assuming that the storms are independent of one another). He got the same result using CME speeds, but a value of only 1.1% using the nitrate in ice cores that has been interpreted to be the result of solar storms, a conclusion doubted by others (for a discussion see Lakhina and Tsurutani 2016). Kataoka (2013) extended Riley's work by using a longer record of magnetometer measurements in Japan, and concluded that the probability of a solar storm of the magnitude of the Carrington Event is 4–6% within the next decade. Love (2012) used the Dst distribution to estimate the decadal probability of a Carrington-scale event at 6%, although he used a Dst value for the event of –1760 nT, a value considered too high by a factor of two (Riley 2012) thereby reducing the probability estimate. Love (2012) calculated the 68.3% confidence limits for his estimate as 0.16–1.4% over the next decade, and the 95.45% confidence limits as 0–23%. Barnard et al. (2011) also used the nitrate record to calculate a rate for a major SEP of 5.2 per century (an annual probability of 0.052) for the period from 1700 to 1970 CE, and only 2.6 per century (0.026 annual probability) for the space era, a decline that may be real or may be the result of low-number statistics.

The longest record used in the analyses summarised above is from nitrate in ice cores, the veracity of which as a record of SPEs is in doubt (see Lakhina and Tsurutani 2016). However, long records are needed for accurate estimates of the probability of rare events. Marusek (2007) used calculated proton fluences (the total fluxes during SPEs) of solar storms >30 MeV cm^{-2} (F_{30}); that is, 30 million electron volts per square centimeter, referred to as F30 from satellite observations, nitrate spikes in ice cores, long records of the cosmogenic radionuclides (see Beer et al. 2012, for an account of these chemicals) ^{10}Be, ^{26}Al, ^{41}Ca, ^{81}Kr in moon rocks, ^{14}C in tree rings, and ^{10}Be in ice cores to conclude that solar storms a million times greater than the Carrington Event are possible on a over a period of a million years (annual probability of 0.000001). The maximum proton fluence based on a power law model of the upper tail of these data is of the order of 10^{16} cm^{-2}, an extreme value that is implausible according to the results of Townsend et al. (2006) who estimated the maximum at 18.8×10^{9} cm^{-2}. This lower value is consistent with the results of analyses by Usoskin and Kovaltsov (2012) and Kovaltsov and Usoskin (2014) that relied on the cosmogenic nuclides ^{10}Be and ^{14}C in terrestrial archives (ice cores and tree rings) and seven cosmogenic nuclides in moon rocks. They found two events during the past 11,400 years, in 780 CE and 1460 CE (an event that has also been ascribed to a supernova explosion rather than an SPE), which they claimed were extreme SPEs. From these data they estimated a conservative upper limit of F_{30} of 5×10^{10} cm^{-2}, with annual occurrence probabilities of extreme SPEs of 10^{-2} to 10^{-4} $year^{-1}$, and perhaps controversially no evidence for a very strong SPE at the time of the Carrington Event. Vasyliunas (2011) adopted a different approach to estimating the maximum possible SPE by using the physical theory embodied in the Dessler-Parker-Sckopke theorem that relates the disturbance magnetic field, created by a SPE, at Earth to the total kinetic energy of plasma in the magnetosphere. The maximum plausible Dst is –2500 nT according to this analysis, about three times the strength of the Carrington Event.

There are large uncertainties attached to all of the estimates of occurrence probability and the possible 'worst cases', and the Carrington Event as an extreme is in doubt. Love (2012) made the following telling statement about these large uncertainties: 'the 10-yr recurrence probability for a Carrington event is somewhere between vanishingly unlikely and surprisingly likely', a conclusion echoed by Lakhina and Tsurutani (2016). And the Carrington Event may not have been particularly severe. Despite the large uncertainties in the peer-reviewed scientific literature, it is noteworthy that Lloyd's (2013), one of the largest insurance companies, is prepared to identify recurrence intervals with error bands but without comment on their accuracy, its printed disclaimers notwithstanding.

The most probable extreme SPE, with an annual probability of 10^{-2}, has been derived from the long records of cosmogenic nuclides. This could be the 'worst case' but details of its likely impact on Earth are not available because the key measures of geoeffectiveness are not available; that is, the magnitude and spatial distribution of GICs. A SPE in 2012, which missed Earth, had a minimum Dst between −1150 and –600 nT, possibly 1.4 times greater than the Carrington Event (Liu et al. 2014b) producing GICs as large or larger than the largest observed GICs, although a parsimonious interpretation is that it was similar to the Carrington Event in strength. If the Carrington Event were to strike Earth today, the estimated cost in the USA alone would be US $2 trillion and a recovery time of 4–10 years (National Research Council 2008) or, with some attention to uncertainty, a cost of between US $0.6 and 2.6 trillion (Lloyd's 2013). The cost of the 2012 SME, had it hit Earth, would have been comparable to the estimate above, causing massive damage to electrical grids, water supplies, and other key facilities, but perhaps not to the extent of sending us back to 'a post apocalyptic Stone Age' as suggested by Anthony (2014) because not all of the planet would have been affected.

Because of the high quality of the data collected during the 2012 event, and the availability of advanced modeling capabilities (Ngwira et al. 2013), Daniel Baker from the University of Colorado observed: 'We would like space weather users, operators of systems, and policy makers (to) adopt this event immediately and do war game scenarios with it' (Byrd 2013). He went further by suggesting that the 2012 event should be adopted as the 'worst case' space weather scenario that should be used in modeling the effects on electricity grids. Even though this is unlikely to have been the worst SME during the past 11,400 years, as seen earlier, it is probably the best-observed extreme event. Baker's suggestion for a 'worst case' is therefore a compromise between the most extreme but poorly known event, and a less extreme but much better known event.

The threat to power grids is not only a function of the frequency and magnitude of SPEs, but also of the orientation of the SPE with respect to Earth; geomagnetic latitude (because GICs are stronger at high latitudes but not insignificant at lower latitudes); ground conductivity that can nonlinearly amplify GICs; and distance from the coast (because seawater is more conductive than rock and soil and the excess current can flow into grounded transformers on nearby land) (Alekseev et al. 2015; Lloyd's 2013; Pulkkinen et al. 2007). Therefore the threat is spatially heterogeneous, and each SPE will produce GICs of different magnitudes in different places. The vulnerability of power grids to GICs is also a function of the characteristics of the grid.

14.5 Vulnerability of Power Grids and Water Supply

Electric power transmission systems have generating plants connected by transmission lines in which voltages are controlled and high voltage is reduced for distribution at substations. Geomagnetic disturbances produce magnetic field variations that drive electric currents in the conducting ground that causes electrical currents (GICs) in conducting structures such as along transmission lines and through transformers into the ground. The magnitude of GICs is modulated by ground conductivity, as already discussed, a quantity that varies within and between countries by a factor of about 10 (International Telecommunications Union 1992) or about a factor of 55 when calculated differently (Alekseev et al. 2015). Damage to power grids by GICs consists of damage to bulk power systems, particularly to HV and EHV transformers, and also the loss of reactive power support (NERC 2012), the power that maintains the reliability of supply. The total vulnerability increases with the length of transmission lines (Lloyd's 2013): it reaches a maximum value in a few hundred kilometres in individual lines but continues to rise over much longer distances if the system length (i.e. all of the transmission lines) is taken into account (Zheng et al. 2014). The topology of the power network produces different GICs at the substations and in the transmission lines, with the largest GIC at the edges of the network and in the middle of individual transmission lines according to the deliberately simplified analysis by Zheng et al. (2014). Transformers can be overheated (but see Vergetis 2016), relays tripped, and/or they can fail completely from voltage instability. A significant loss of reactive power support, along with an increased demand for reactive power, is the largest source of transformer vulnerability. Based on past responses to GICs, transformers with high water and dissolved gas contents, and those nearing the end of their life span, are most vulnerable. Newer designs of transformers are less vulnerable and single-phase transformers are more vulnerable than three-phase transformers. Also the number and electrical resistance of transformers and transmission lines affect the magnitude of a GIC (Vergetis 2016, and references therein).

The ‘perfect storm’ of vulnerability for power grids could of course be produced by the coincidence of an extreme SPE with other sources of power grid failure. Birds, lightning, earthquakes, over-drawing of power, failure of old infrastructure, overheating in heat waves, collapse of transmission lines in ice storms, and instability caused by dead ends in the network (Menck et al. 2014) could coincide with an SPE. Non-SPE failures are planned for, usually using the n–1 criterion: that is, the losses of a single critical component (transformer, transmission line) without causing network overload or unstable operation. But this deterministic criterion is being replaced by a probabilistic approach that takes into account multiple failures (Heylen and Van Hertem 2014), an approach that will be essential for mitigation of the impacts of SPEs. Some countries (e.g. Australia and New Zealand) have already adopted the new approach, and so could be less vulnerable to SPEs depending upon how well they have assessed their vulnerability.

As already noted, reliance on electricity for water supply and treatment is spatially variable with some cities and countries using much more electricity per unit of water than others. Those that use most power for water treatment are most vulnerable to power outages. But if electricity supply is completely switched off by a SPE these differences will be unimportant, unless an adjoining country can still supply water because it has not been badly affected by a SPE (possibly because of differences in ground conductivity and/or the installation of power grid protection), and its electricity use for water supply is low leaving enough to provide water to its neighbour. Neighbours may also be able to supply electricity but not water. But the likelihood of such scenarios will probably depend more upon politics than technology. Other factors may also be important, such as the extent to which gravity flows allow transport of water within and between countries thereby avoiding the need for pumping; the availability of backup diesel generators, although they are likely to be hostage to fuel supply and the need for electricity to refill fuel storage tanks; the availability of alternative power sources such as solar panels and wind turbines that are separate from the grid and protected from SPEs; and the time taken to replace damaged HV and EHV transformers.

14.6 Risk

The current approach to assessing the risk for a power system of a SPE is to combine information in a simulation model of a plausible threat, often a Carrington-scale event (which may be considered similar to the 2012 event), with information about ground conductivity and the grid. Lloyd’s (2013) applied this method to find that the GIC amplitudes in North America were highest in the Midwest of the USA extending into Canada. With information about transformer locations and designs (see Vergetis 2016 for a new view on transformer vulnerability), more detail can be achieved that shows large spatial variations. Storms other than a Carrington-scale event have also been used in simulations. The 2003 ‘Halloween storm’ with a Dst of about –400 nT (Asia Insurance Review 2014) was used by Barbosa et al. (2015) to simulate effects in the low latitude Brazilian transmission lines, showing that events about half as strong as the Carrington Event are potentially damaging.

The North American Electric Reliability Corporation (NERC 2012), Kappenman (2010) and most recently the Institute of Electrical and Electronics Engineers (IEEE 2015) provide detailed accounts of simulation modeling, although they do not take into account network topology and are oriented to the extreme SPEs experienced at high latitudes. Gaunt (2014) makes the case for a systems model that includes space physics, network analysis, transformer engineering, network reliability and decision support, tailored particularly to low latitudes where fewer storms reach damaging levels and awareness of GICs is less well developed. Gaunt has raised the issue of decision support to find the best solutions for a complex system, although he doesn't mention operator error. In the US operator error accounts for 8% of blackouts (Hines et al. 2009), a figure that is likely to rise if space weather forecasts are to be used more to change the operations of power grids.

In addition, the absence of scenario analyses that rigorously include phenomena other than electricity, and water in particular, is a serious limitation on the design of mitigation and governance (OECD/IFP 2011). This absence suggests that solar storms are not well enough understood among government and private sector planners to be included in risk assessments, or they are viewed as having such a low probability that they can be discounted in the face of other risks such as weather and equipment ageing. There is also an issue of incentives for investment in expensive protection devices that may not be needed for a long time.

14.7 Trends in Electricity Grid Development: New Sources of Vulnerability?

In the interests of efficiency, reliability, cost reduction, and the social benefits of providing electricity to more people, cross-border power grid integration has occurred between many countries. NORDPOOL, for example, connects the Nordic Countries to The Baltic States, the UK, and Germany (Glachant and Lévêque 2009) in a region prone to extreme SPEs. Other cross-border grid networks have been established with varying degrees of interconnection, and include the Central American Power market (SIEPAC), the North American power grid, the Greater Mekong Sub-Region (GMS), the Southern African Power Pool (involving 12 nations) and the West African Power Pool (Singh et al. 2015; OECD/IFP 2011). Future potential and limitations of further integration are discussed by Economic Consulting Associates (2010).

In South Asia network links exist between Nepal and India, India and Bhutan, India and Sri Lanka, India and Bangladesh, Pakistan and Iran, and Afghanistan and several Central Asian countries, while an agreement between Pakistan and India is under discussion (Singh et al. 2015). Apart from the reasons given above for network integration, Singh et al. (2015) claim that lessening the role of the State in providing electricity to achieve affordable and reliable electricity is also an objective. But it is not clear if this is an objective of the authors of this World Bank report or an objective of the countries of South Asia. Certainly India has opened its power market to the private sector more than other countries in South Asia. But as we will see below, this trend may need to take account of solar storms.

In Southeast Asia an ambitious plan is underway to link the power grids of all ASEAN countries (Andrews-Speed 2016; ASEAN Power Grid Consultative Committee 2015). Eleven cross-border links already exist, 10 more are in progress and a further 17 are planned. The estimated cost saving from interconnection is US $1873 million in 2009 present value.

Another development that deserves attention is the move to ‘smart grids’ that connect different sources of electricity generation and involve interaction between users and the grid by means of sensors linked through the Internet. The likely benefits of ‘smart grids’ are reduced peak demand, tailored energy use, linkage to renewable sources of power (often a long way from users), automatic rerouting of electricity from disabled network components and routing of power to key facilities such as hospitals and emergency services during disruptions (ASEAN Power Grid Consultative Committee 2015). However ‘smart grids’ appear to enhance the vulnerability to GICs of power systems by extending transmission lines to connect to renewable generating sources and by relying on sensors that are vulnerable to satellite failure from SPEs. Once again, a lack of a comprehensive scenario analysis raises serious doubts about the ability of ‘smart grids’ or any other kind of grid to withstand GICs, although OECD/IFP (2011) notes that the modular components of ‘smart grids’ will be less vulnerable to GICs than large centralised networks.

14.8 Concluding Remarks: Mitigation and Governance

Mitigation can be achieved by planning, engineered hardening, better operational response and reform of governance (OECD/IFP 2011; NERC 2012). Planning might involve all or some of the following: scenario analysis and simulation of the effects on power networks of the 2012 SPE as the best known ‘worst case’; simulations of cascading failures of key facilities and services that rely on electricity, including water resources and sewerage systems; simulations of both national and cross-border networks with sufficient spatial specificity and assessments of social vulnerability for operational purposes; cross-border agreements about how to communicate warnings of impending SPEs and when and how to act; cross-border agreements about the allocation of new or standby transformers in the event of a major loss of this equipment; and insurance against losses, business discontinuity, and the limitations imposed by territorial limitations of insurance (Aon Benfield 2013; Lloyd’s 2013).

The simulations and scenario assessments should include the entire power network in a system dynamics framework along the lines suggested by Gaunt (2014). That is, scenario analysis could be in the form of dynamic systems models rather than large and often unreliable so-called deterministic models (Sterman 2000). They should also make use of modern thinking about how to overcome the vulnerability of networks (e.g. Barabási 2002; Little 2002; Lorenz et al. 2009). Helbing (2013) calls for a major overhaul of risk assessment and management, pointing to the absence in current approaches of coincidences of multiple threats and vulnerabilities (e.g. the 'perfect storm' of a SPE and other failure modes), the absence of feedback loops in analyses, linear rather than nonlinear thinking, downplaying of human errors and negligence in assessments, and insufficient attention to personal and government incentive structures in assessment of risk. He particularly calls for a reversal of the trend to dilution of responsibility in governments and corporations, so that those responsible for a failure are held responsible. But in a complex system with many feedbacks, responsibility can be a slippery concept.

Hardening of infrastructure is clearly necessary but is neither technically feasible nor economically possible for entire power networks, a problem that will be acute in poor countries (OECD/IFP 2011). Therefore, decisions have to be made about which critical facilities will be protected by the installation of neutral blocking devices and transmission line capacitors. Again, national and cross-border agreements will be necessary to ensure maximum protection of hospitals, water distribution and treatment, nuclear power plants, and emergency services. If possible, electricity supply to these critical facilities should not rely on power from neighbouring countries.

Well-executed operational plans and procedures are cheaper than hardening, but cannot fully replace hardening as a mitigation strategy. Operational effectiveness relies upon space weather monitoring (Pulkkinen et al. 2010), warnings (and therefore effective communications), quick and effective reactions to warnings (with sufficient training and flexibility given to operators to enable agile responses in the face of changing circumstances, rather than just following a rulebook); and cross-border coordination of operational plans and procedures. Warnings currently rely upon satellite observations that need to be maintained internationally rather than relying solely upon the USA to provide the hardware (OECD/IFP 2011).

All of these mitigation strategies seem sensible and achievable given sufficient knowledge, motivation, planning, and resources. But they may fail because of the inherent complexity of power networks that include cross-border connections and markets and 'smart grids'. Helbing (2013) argues, for example, that strongly connected networks that have produced highly interdependent systems are too difficult to understand and control top down, and may fail globally if perturbed by a SPE or other threat. Newell et al. (2011) argue that policy is too often designed by taking a narrow compartmentalised view, dominated by one worldview because of the bounded rationality of humans. This can be seen, for example, in the paper by Singh et al. (2015) who adopt a narrow economistic view of the benefits of cross-border power networks without paying attention to other issues. Such an approach almost always leads to policies that have unintended and often disastrous consequences (see Sterman 2000, for some iconic examples). Helbing (2013) goes further to suggest that bottom-up systems are likely to be much more resilient, and mentions the example of 'smart grids' as a solution to large-scale failure of networked power. But even 'smart grids' need high voltage transmission lines and transformers to connect them to part of the generating system, and so will not be entirely immune from SPEs and other sources of transmission line and transformer failure. A scheme analogous to smart electricity grids is the idea of water smart grids (Water Innovations Alliance 2012) that would be localised and optimised by sensors communicating with water and sewerage utilities. But such a scheme would not be entirely safe from SPEs as communications that rely upon satellites could shut down, and power supplies could be disturbed if any part of the local system needed to be connected to the larger grid.

So all power networks are to varying degrees vulnerable to SPEs and GICs, and many if not most water resource and sewerage systems are vulnerable to consequential electricity failure. If, however, reliance is placed entirely on the current trend for market mechanisms (and therefore the private sector) to build and manage new power networks, both within and between countries, the governance perspective may be too narrow to include network hardening and operating procedures to deal with GICs. Moreover, there may be little incentive for the private sector to make the necessary investments. Also, by giving priority to efficiency the opportunity may be lost to have on standby high voltage transformers and backup power systems to build redundancy into networks (see Newell et al. 2011 for examples of these issues in the context of climate change).

Still, localisation and modularisation of both electricity and water supply has many advantages. It will reduce the spatial extent of disruption by any cause, enable quicker recovery, and also reduce the need for difficult agreements between neighbouring states for cross-border network operation during GICs. It may also maximise cooperation between stakeholders because the network density of these small-scale networks is sufficiently small to avoid the erosion of cooperation as network density increases (Helbing 2013), thereby enabling self-organisation and agile responses locally to the threat of a SPE.

Whichever route is taken to rethink and reform governance of power networks, and their dependent functions such as water supply, to take account of SPEs, it is likely that reversing the trend to large centralised networks of the kind being designed and implemented in Asia will be essential, and could be achieved by including 'smart grids'. While this trend is underway in wealthy countries, it needs to be accelerated. Such reforms will require leadership from governments and cooperation by the private sector. It is also strongly recommended that narrow worldviews, such as economic efficiency, be balanced with other considerations by using a system dynamics approach.

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