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An Insurance Perspective on U.S. Electric Grid Disruption Costs

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Large yet infrequent disruptions of electrical power can impact tens of millions of people in a single event, triggering significant economic damages, portions of which are insured. Small and frequent events are also significant in the aggregate. This article explores the role that insurance claims data can play in better defining the broader economic impacts of grid disruptions in the U.S. context. We developed four case studies, using previously unpublished data for specific actual grid disruptions. The cases include the 1977 New York City blackout, the 2003 Northeast blackout, multi-year national annual lightning-related electrical damage and multi-year national line-disturbance events. Insured losses represent between 3 and 64 per cent of total loss costs across the case studies. The household sector emerges as a larger locus of costs than indicated in previous studies, and short-lived events emerge as important sources of loss costs.

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Risk landscape

Electricity is a central pillar of energy systems and the economies of nations, and all segments of society depend on it. Reliance on continuously available electricity is rising, given the pervasive use of technologies for which electricity is the only suitable energy carrier such as motors, lighting and information technologies as well as substitution for fuels in other contexts. Manufacturing and its supply chains, communications infrastructure and financial markets are also increasingly dependent on reliable power. Electricity service disruptions have important direct links to insured risks such as property damages and business interruptions, as well as indirect links to events such as civil unrest and vandalism during blackouts.

The U.S. electric grid is complex, with over 5,800 power plants delivering electricity to 144 million customers over 450,000 miles of high-voltage transmission lines. This network is organised into eight regional networks before entering the lower voltage distribution network.[1] About 70 per cent of the transmission lines and associated transformers are over

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[1] Executive Office of the President (2013).

Table 1 Ten most severe blackouts by duration and population affected, sorted by number of people affected (Bruch *et al.*, 2011)[a]

Location	*Date*	*Duration to full restoration of power*	*Cause*	*People affected*
India	2-Jan-01	12 h	Substation failure	226,000,000
Indonesia (Java)	18-Aug-05	7 h	Technical failure	100,000,000
Brazil	11-Mar-99	5 h	Lightning	97,000,000
Brazil (most states) and Paraguay	10-Nov-09	7 h	Storms	87,000,000
Italy (national, excl. Sardinia)	28-Sep-03	18 h	Technical failure; poor communication/coordination	56,000,000
Brazil (8 northeastern states)	4-Feb-11	16 h	Technical failure	53,000,000
U.S.A. (Northeast) + Canada	14-Aug-03	4 days	Human error and equipment failure	50,000,000
Europe (parts of Germany, France, Italy, Spain and Portugal)	4-Nov-06	2 h	Forced transmission outage + generation overload	15,000,000
Spain	29-Nov-04	5 within 10 days	Human error/technical failure	2,000,000
New Zealand	20-Feb-98	4 weeks	Line failure	70,000

[a] Post-dating the source publication for this table, the 8 September 2011 U.S. Southwest blackout rendered 2.7 million customers (including some in Mexico) without power for 11 min. The cause was a combination of the loss of one transmission line, together with operational deficiencies and extreme heat and associated power demands (FERC and NAERC, 2012).

25 years old, and the average age of power plants is over 30 years.[2] Grid disruptions of various types, severity and scales are common. Major blackouts garner the most attention, as they abruptly impact a large number of customers and are easiest to quantify (Table 1). Between 1984 and 2006, blackouts in the U.S. affected 141 million customers, with an aggregate duration of 12,000 days.[2]

Grid disruptions range from subtle power fluctuations to full outages. The costs are broadly allocated between the impacted energy user, the energy provider, public entities assisting in relief or recovery and insurance companies. Estimates for the U.S. place the cost of such events at $79 billion per year,[3] with other estimates ranging from $28 billion to $209 billion per year.[1] Some studies are cursory, simply applying a stipulated "value" per unit of electricity to each un-served unit over the course of a given outage. Few prior studies have looked in depth at the insurance industry's perspective on the value of electricity reliability.[4]

The causes of events involving power outages and line disturbances are highly varied and include natural disasters, extreme weather conditions (heat/cold/dust storm), human error and mischievous acts, animals, equipment or software failure, under-served spikes in power demand and forced outages at power plants or within the transmission and distribution network. Grid disruptions can result from a confluence of multiple factors, as seen in the great European heat wave of 2003, where a period of prolonged extreme temperatures

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[2] Hines *et al.* (2009).

[3] LaCommare and Eto (2006).

[4] Lecomte *et al.* (1998); Eto *et al.* (2001); Lineweber and McNulty (2001); RMS (2004).

resulted in electric demand spikes, just as curtailed hydroelectric power output due to drought and overheated rivers forced the temporary shutdown of fossil and nuclear power plants for lack of adequate availability of cooling water.[5] While triggering events can impact the system at many points, ranging from power plants to the point-of-end use, all manifest themselves as the loss of services and some degree of associated economic impact. On the loss side, second-order impacts also occur such as the inability to pump fuel needed for backup generators or to pump rising water from flooded areas.

Many factors can be expected to drive insured losses from grid disruptions upwards in the future, including increasing dependency on electricity, changes in the reliability of the grid[6] and changing patterns of underlying hazards.[7] Weather extremes are the primary cause of power outages[8] and, on average, impact more customers per event than those attributed to other causes.[9] Insurers have attributed erosion of reliability in part to the curtailment of infrastructure maintenance and modernisation under power sector privatisation and liberalisation.[5]

This article characterises the nature of insurance industry exposure to losses resulting from electric grid disruptions, with a focus on U.S. loss statistics for four case studies. Given the lack of primary top-down data on economy-wide economic losses, including, but not limited to, those that are insured, we illustrate the bottom-up process of extrapolating what has been carefully measured by insurers and its potential applicability for estimating broader impacts. For a variety of reasons, insured losses represent only a portion of total economic losses. These factors include incomplete penetration of insurance, deductibles, limits and exclusions among those who are insured. Insured cost data thus help bound the lower end of total costs, but also illuminates where—both geographically and by type of customer—the costs of these events manifest. The risk-management dimension of insurance practices further illuminates how such costs can be controlled. Some insurers envision a future where more comprehensive insurance coverage for losses resulting from grid disruptions will be available,[5] but for this to be viable, the losses must be better understood and managed.

Insurance perspective

The insurance industry assumes risk across the entire grid—from power plant fuel supply to the point-of-end use. Insurers take an international view, as the largest companies are multinational and because vulnerable supply chains and communications infrastructure routinely cross international boundaries.[5]

Insurers engage with grid-disruption events at two levels. The first involves risk management, for example, via supporting pre-event loss prevention and post-event recovery and business continuity and, ideally, post-loss reconstruction to a higher level of resilience. The second involves risk-spreading through the collection of premiums and the payment of claims.

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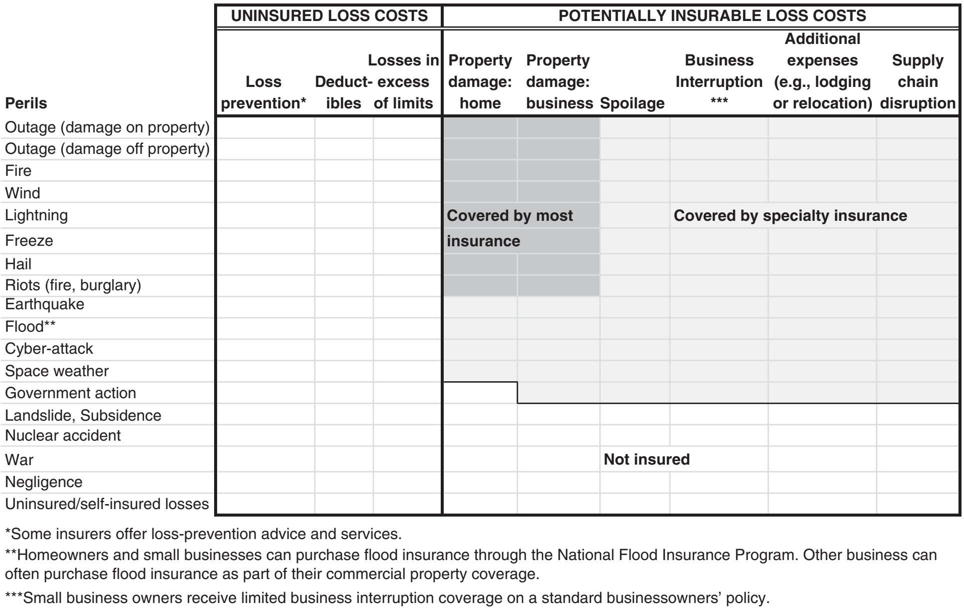
[5] Bruch *et al.* (2011).

[6] USDOE (2013); Larsen *et al.* (2014).

[7] The Geneva Association (2009); Executive Office of the President (2013); van Vliet *et al.* (2016).

[8] Campbell (2012).

[9] USGCRP (2009).



	UNINSURED LOSS COSTS			POTENTIALLY INSURABLE LOSS COSTS					
Perils	**Loss prevention***	**Deductibles**	**Losses in excess of limits**	**Property damage: home**	**Property damage: business**	**Spoilage**	**Business Interruption *****	**Additional expenses (e.g., lodging or relocation)**	**Supply chain disruption**
Outage (damage on property)				▓	▓	░	░	░	░
Outage (damage off property)				▓	▓	░	░	░	░
Fire				▓	▓	░	░	░	░
Wind				▓	▓	░	░	░	░
Lightning				**Covered by most**	▓	░	**Covered by specialty insurance**	░	░
Freeze				**insurance**	▓	░	░	░	░
Hail				▓	▓	░	░	░	░
Riots (fire, burglary)				▓	▓	░	░	░	░
Earthquake				░	░	░	░	░	░
Flood**				░	░	░	░	░	░
Cyber-attack				░	░	░	░	░	░
Space weather				░	░	░	░	░	░
Government action					░	░	░	░	░
Landslide, Subsidence									
Nuclear accident									
War						**Not insured**			
Negligence									
Uninsured/self-insured losses									

*Some insurers offer loss-prevention advice and services.

**Homeowners and small businesses can purchase flood insurance through the National Flood Insurance Program. Other business can often purchase flood insurance as part of their commercial property coverage.

***Small business owners receive limited business interruption coverage on a standard businessowners' policy.

Figure 1. Applicability of insurance to grid-disruption scenarios.

Figure 1 provides a qualitative indication of how insurance responds to various grid-disruption scenarios, by peril causing the loss and generic category of loss incurred. Table 2, in contrast, maps specific types of insurance to types of covered damages.

Insurers and their trade associations have long noted their concerns about electricity reliability, for example in a study of the Northeastern Ice Storm of 1998, which toppled 1,000 transmission towers and 30,000 wooden utility poles.[10] Following that event, 5 million people were left without power, resulting in 840,000 insurance claims valued at $1.2 billion. About 1 million homes were impacted in Canada (with 100,000 people going to shelters). The wide diversity of losses exemplified the common problem of isolating those pertaining directly to grid disruptions from those attributed to other sources of damage during such events. Insurers are devoting increased attention to the reliability of the electric system. Most recently, Hurricane Sandy refocused many U.S. insurers on the issue.[11]

The triggers ("perils") initiating grid disruptions are numerous, including natural hazards such as wind, ice, lightning, wildfire, drought or dust storm as well as a host of events ranging from machinery breakdown to human error to cyber-terrorism.[12] Insurers are also concerned with the effect of space weather on electrical systems.[13] The resulting losses can be direct (physical damage) or indirect (e.g. disruptions to business operations or the consequences of social unrest). As described in Table 2, many insurance lines can be

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[10] Lecomte *et al.* (1998).

[11] Zola and Bourne (2012); Claverol (2013).

[12] Healey (2014).

[13] Slavin (2010); USDOE (2013).

Table 2 Map of types of losses linked to electricity reliability and responding lines of insurance

Type of insurance	*Specific insurance lines*	*Nature of covered damages (assuming necessary contract coverages)*
Property	Homeowners, commercial, industrial (including boiler & machinery)	● Direct equipment damage: data loss,[a] perishables (food, flowers, pharmaceuticals) ● Indirect damage: frozen pipes, falsely deployed fire sprinklers, inoperable pumps, fire, vandalism, damages caused by backup generators
Business interruption (BI)	Commercial, industrial (typically requiring special "service interruption" policy coverage) (including boiler & machinery[b])	● Net revenue losses by energy user ● Supply chain disruptions ● Lost sales by utilities
BI: Extra expenses	Homeowners, commercial, industrial	● Costs of temporary accommodation, relocation, backup power
BI: Evacuation orders	Civil authority	● Complete disruption of business activity due to government order such as evacuation
BI: Inability for employees to reach workplace	Ingress/egress	● Disruption of access to workplace irrespective of damage; does not require government action ● Inability to refuel generators
BI: Disruption in trade and supply chain	Supply chain/trade disruption	● Remote (or even overseas) disruption in production or transportation of critical products or materials
Maritime	Marine	● Cargo loading/unloading disruptions; supply-chain disruptions
Airlines	Aviation	● Delay, rerouting, flight cancellation, property damage
Injury, mortality	Life/health	● Injuries or death arising from the disruption and its consequences (equipment failure, heat stress, roadway lighting, medical equipment, disrupted hospital operations, etc.)
Liability and Legal defence costs	General liability, environmental liability, directors and officers liability	● Utilities, waste treatment, etc. ● Triggering pollution releases or impeding cleanup ● Loss of ventilation in buildings ● One party may litigate against another to recover damages ● Insurance claims may be denied, resulting in litigation costs incurred by insurers

[a] Insureds themselves have claimed such losses, that is, *Great Northern, Pirie, and Glens Falls* case (Johnson, 2001).
[b] These policies typically require damage to covered equipment, not just disruption of operation.

involved. In addition to standard property damages, liability claims may also be made,[14] among which are environmental liability claims stemming from disruptions in wastewater treatment or pollution controls dependent on electricity for pumping, communications and control systems.[15] A wide variety of adverse health-care outcomes have also been associated with power outages,[16] invoking the relevance to life/health insurance lines.

Three broad categories of electric-reliability events that trigger losses are of interest to insurers. The first are rare large outages that occur on a wide scale and are often long in duration. The second are frequent outages at very local/small scales that result in large accumulations of claims. The third are localised line disturbances that disrupt service or affect power quality and may not involve a complete outage.

Power outages are distinctive events for insurers in so far as they can cover enormous geographic areas, potentially larger than any other loss event. They also affect most customer classes and a multiplicity of insurance coverages. Insurers perceive immediate consequences, such as equipment damage, as well as longer-term complications such as macroeconomic impacts. A major blackout was identified as one of the "top-10 risks" by a leading catastrophe modeller serving the insurance industry (Table 3). The potential claims from such an event were estimated at $2.7 billion in 2004 (approximately $3.3 billion in 2014 dollars). A more recent study was conducted using a blackout model developed expressly for insurers. The simulation assumed a wide-area blackout caused by sequential ice storms on the U.S. East Coast, resulting in 50 million people and 3 million businesses impacted (with 100,000 never reopening) with $30 to $55 billion in total direct losses, of which $9.5 to $15.5 billion were insured.[17]

Property damages are an important insurable consequence of grid disruptions and are relatively easy to define and verify. Business interruptions stand as another important insured risk and are much more complex.[18] In an annual survey by global insurer Allianz, 500 corporate risk managers from around the world rank business interruption risks and natural catastrophes (two often-related events) at the top of their list of concerns.[19] According to Rodentis,[20] U.S. businesses report that grid disruptions are the number-one cause of business interruptions. A 2005 survey found that 72 per cent of U.S. companies had experienced significant business interruptions because of power outage, and 34 per cent because of lightning storms.[21] In evidence of the potential magnitude of business interruption claims, 30 per cent of the $18 billion in insured losses associated with Hurricane Sandy, for example, were attributed to business interruptions.[22] Small businesses are most at risk and can be rendered insolvent by significant uninsured losses. A survey of 500 small businesses by the National Association of Insurance Commissioners[23] found that business interruption insurance coverage varies by business size: 33 per cent of firms with 1–19 employees were

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[14] Blume and Holmer (2013).

[15] NIST (2015).

[16] Klinger *et al.* (2014); McElroy (2015).

[17] Verisk Climate and HSB (2014).

[18] Zola and Bourne (2012).

[19] Kenealy (2015).

[20] Rodentis (1999).

[21] Zinkewicz (2005).

[22] Bartley and Rhode (2013).

[23] NAIC (2007).

Table 3 Loss costs for hypothetical U.S. events (RMS, 2004)

U.S. event	*Total cost ($2004 billion)*	*Insured cost ($2004 billion)*	*Fatalities*
Hurricane: Eastern Seaboard	74.6	45.1	85
Flood: Mississippi River	34.2	4.7	66
Oil spill: Puget Sound	18	3.6	5
Terrorism: Chicago Loop	24	14	5000
Blackout: Ice storm in Northeast	**17.1**	**2.7**	**?**
Wildfire: Drought and temperature extremes in California	8.7	4.9	25
Industrial accident: Petrochemical tanker fire in Houston	17–22	7–9	600
Cyber attack: Fortune 1000	Not estimated	Not estimated	NA
Pandemic: Mutated flu virus	Not estimated	Not estimated	200,000
Earthquake: Los Angeles	100	27	400

insured, vs 58 per cent of companies with 20–99 employees. For business interruption insurance contracts, deductibles are often expressed in the units of time rather than dollars or a percentage of loss. There is typically a waiting period (sometimes known as a "time-deductible") of 12–72 h before claims begin to accumulate, and the cutoff has been increasing.[24] Given that most of these events are relatively brief and that most economic damages are estimated to occur during the first few minutes of an event,[25] only a small fraction of the related losses would be insured.

In order to be deemed insurable, a risk must meet several conceptual core criteria. These include randomness of the triggering event, fortuitousness, ability to assess statistical likelihood of frequency and cost, a sufficient number of customers willing to participate in the risk pool by purchasing insurance and affordability of the associated products and services at risk-based premiums. The risk of fraud (moral hazard) must be minimised. In addition to these fundamental considerations is whether or not a given event falls within the terms of the given insurance contract. While some emerging risks to the electric grid, notably cyber-security and space weather,[26] do not clearly meet the standards for insurability, insurance products nonetheless are being developed *in lieu* of a traditional actuarial underpinning.

If insurability criteria are met or waived, then the practical insurability of a given event under a given contract is a function of the combined effects of (a) the nature of the damage, (b) whether the damage is caused by a named peril and (c) whether any exclusions apply.

Most standard insurance contracts (homeowner as well as commercial lines) require that the damage causing the disruption occur on the insured's premises, yet only 20–25 per cent of business interruption losses occur for this reason.[5] Recent tightening of the standard forms by the Insurance Services Office[27] even exclude failure of utility-owned property located on the insured's premises, and other exclusionary language can limit damages to power-delivery

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[24] *Bloomberg News* (2003).

[25] Sullivan *et al.* (2015).

[26] USDOE (2013).

[27] The Insurance Services Office (*www.verisk.com/iso.html*) is an insurance data-collection service specialising in loss data, market data and related topics such as building code effectiveness. Their focus is on property-casualty insurance as distinct from life-health.

equipment located inside the building.[28] Optional policy extensions such as "contingent business interruption", "spoilage" or "utility services disruption" can expand coverage to events occurring within a specified distance from the insured property. Insurance products are emerging that cover disruptions in distant supply chains, with waiting periods of 30 days or more.[29] Even here, if the disrupted utility is not the insured's direct provider, even utility services disruption coverage may be denied. Spoilage coverage, on the other hand, typically applies irrespective of the reason for power disruption. Exclusions may apply (e.g. insufficient fuel at the generator or a power outage triggered by government order). Human error or deliberate decisions (e.g. rolling blackouts) are important potential policy exclusions in the case of power outages.

Given the complexity of insurance contract language and the costs involved, claims often end up being litigated, resulting in additional costs.[30,31] Some legal decisions have covered losses where power line disruption is far from location: three examples of food loss in grocery stores are given in Lipshultz *v.* General Insurance Company of America, but two other decisions, also related to grocery stores, decided in favour of the insurer.[32] Many insurers initially argued that there was no physical damage, as called for in the policy language, and that claims were unjustified, but the courts decided in favour of the policyholders and claims were paid.[33] In this case, the unsuccessful argument made was that the underlying cause (human error) was excluded under the standard insurance contracts and could not be construed as "damage".

Assuming the damaged property is on the insured premises, the question then shifts to whether or not the underlying cause is an "insured peril" or otherwise excluded. Flood is a particularly important peril in that regard, because it is almost universally excluded by private insurance policies.[34]

Electricity producers and distributors are eligible for various forms of business interruption coverage as well. Insurers manage their own risk of frequent claims by stipulating high dollar deductibles for a given policy period. Utilities may also self-insure in total, or up to a high level of "retained risk", above which they spread risk by purchasing reinsurance. Specialised optional business-interruption coverages are available to cover lost revenues arising from failures to produce or deliver power not otherwise traceable to a physical damage. In this case, insured perils are defined as "data corruption" or "malfunction of data" due to human error, hacker attacks, etc.[5]

Insured costs of power outages and line disturbances

Understanding the magnitude of losses related to electricity reliability is important to insurers seeking to improve underwriting, risk management and loss prevention. Beyond

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[28] Massman (2012).
[29] Marsh (2012).
[30] Johnson and Churan (2004); Standler (2011a, b); Claverol (2013); Fickenscher (2013).
[31] Greenwald (2014).
[32] Johnson (2001).
[33] Widin (2009).
[34] The National Flood Insurance Program provides coverage for power outages (including food in freezers and damages due to failed pumps) if the damage causing the outage occurs on the insured property (NFIP, 2014).

that, insurance data can provide substantial value in understanding broader economy-wide losses, as other data-collection efforts are not always as rigorous as insurance claims processing. This approach has been applied successfully before in the study of natural disaster losses.[35] These authors adopt a similar approach as done here, beginning with insurance claims and making extrapolations where needed (e.g. for uninsured population segments). The technique is easiest to apply when total loss costs are sought, as aggregate insurance claims data are widely available. Where losses by underlying cause are sought, as in the case of power disruptions, a more specialised analysis must be conducted, and applicable insurance data are more difficult to obtain.

Highly fragmented data-collection practices impede our understanding of losses from natural and manmade events, including those related to electricity reliability.[36] Statistics are lacking on the numbers of customers possessing insurance policies that respond to electric grid disturbances, as well as on aggregate claims.[37] Insurance loss data are often collected and reported in highly aggregate form, making it difficult to isolate the costs of each underlying cause of loss or the customer subgroups affected. We found four exceptional cases in which data had been collected at a level with sufficient resolution to isolate losses related to electricity reliability. The first three are based on industry-wide claims tracking, and the fourth is a closed-claims analysis conducted by the largest individual insurer of the risks in question. The cases demonstrate a progressively complete ability to extrapolate insured losses from individual events to broader economic impacts at the national scale.

Analysis framework

Beginning with insurance loss data, we explore the ability to scale insured values up to total economic losses (insured plus uninsured), as described in Figure 2. We approximate economy-wide losses by applying the per-customer insured losses to all insured households and enterprises affected by the event. To provide consistent reporting across the cases and to observe trends over time where multi-year data are available, the final values thus obtained are normalised for inflation to year-2014 U.S. dollars.

Proceeding along the horizontal axis of Figure 2, the most elemental class of data typically encountered is the insured loss from a particular event. A more inclusive cost estimate can then be progressively built up if the insured's deductible is known. These values can be applied by proxy to uninsured losses, together with any remaining costs that are uninsurable.

Proceeding along the vertical axis, the most narrowly defined case would include costs for only some events and some insureds (e.g. those served by a particular insurer). A more inclusive estimate can then be progressively scaled up if the extent of analogous populations exposed to the events which are insurable but not insured is known, followed by the total number of insureds experiencing losses from other analogous events and, lastly, any

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[35] Smith and Katz (2013).

[36] Pendleton *et al.* (2013).

[37] Findings of research by librarians at the Insurance Library Association of Boston, Massachusetts, and Davis Library at St. John's University, Manhattan Campus, New York.

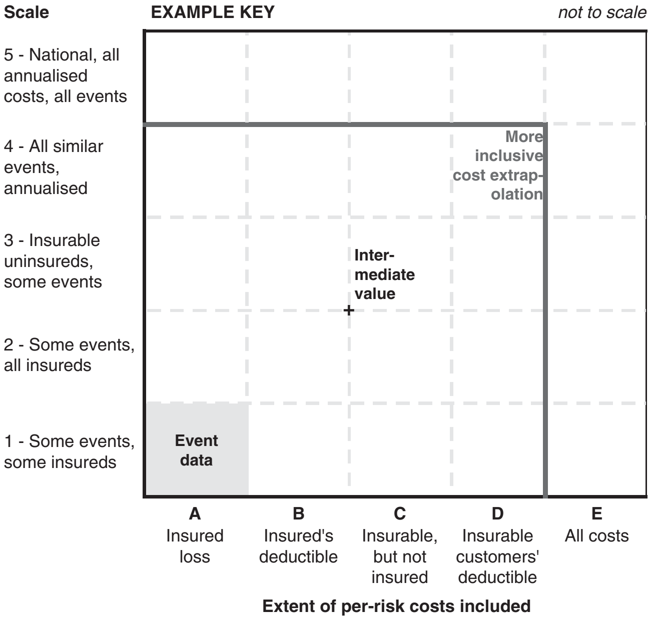

Figure 2. This framework for characterising the extensibility of insured losses from grid disturbances illustrates the components of total cost, with emphasis on the elements related to the presence or absence of insurance. The horizontal axis focuses on cost categories on a per-risk (per household or business) basis, and the vertical access represents scale (e.g. number of households or businesses). The product of these two factors represents the total cost for any particular pair of values.

remaining groups and/or costs applicable nationally (e.g. from uninsurable populations or perils).

For the hypothetical example depicted in Figure 2, insured data are available from one insurer for one major grid-disruption event, corresponding to the shaded area labelled "Event data". This core loss corresponds to the area of rectangle [A, 1]. Were additional data available for all insurers together with estimates of deductibles, rectangle [B, 2] would apply. If to this were added an extrapolation of costs to the insurable population that did not carry the applicable insurance, summed over all similar events each year, the extrapolated loss (bold outline) would correspond to rectangle [D, 4]. A fully inclusive estimate would provide costs for the rectangle corresponding to rectangle [E, 5], that is, all economic costs (insurable and uninsurable) for all customers affected by all events of this type in the country over the course of an average year.

We applied this framework to the four case-study events described in this article. They vary in terms of which sectors are included (homeowners and/or businesses).

Individual large power outages

Although power outages result in economic losses claims on essentially a daily basis, only two events (the 1977 New York City blackout and the 2003 Northeast blackout) have been recorded and quantified by the U.S. insurance industry's central loss tracking system (Property Claims Services, operated by the Insurance Services Office, ISO). These are, not coincidentally, the two largest blackouts in U.S. history by numbers of people impacted. This lack of insured-loss data attributed to power disruptions arises for three key reasons. Firstly, most outages accompany other events (storms, earthquakes, etc.) that result in losses unrelated to the outage itself. Secondly, data are aggregated and reported by ISO/PCS only by major customer category (in this case, homeowners and commercial) and state, resulting in any differentiated costs (e.g. food spoilage) being lost. Thirdly, ISO does not collect losses on what it regards as "small" events, that is, those not affecting "a significant number of policyholders and insurers" and resulting in at least $25 million in insured losses to property.[38]

The 1977 New York City blackout

Triggered by lightning strikes, the 1977 New York City blackout event is the earliest blackout for which we have identified insurance claims data (Table 4). This event illustrates several important considerations in viewing insurance data in the context of total economic costs, which in this case totalled $1,348 million (2014 dollars). Public and private insurance mechanisms each participated in shouldering the costs, amounting to $131 million, or 10 per cent of the $1.35 billion total economic impact (Figure 3). Second-order impacts (in this case fires and looting) resulted in substantial additional insured losses. Formal or informal limits on coverages attenuated the level of paid claims. In the period leading up to this event, New York residents found it difficult to obtain insurance for burglary through the private market. The Federal Government offered coverages, but losses were capped at $1,000 per claim.[39]

The 2003 Northeast blackout

The 2003 Northeast blackout left almost 20 per cent of the U.S. population in darkness for periods ranging from hours to days. Within 8 min, the outage took the equivalent of 62 billion watts of power offline (more than 500 generating units at 265 sites, including 10 nuclear plants), in the process impacting 50 million people across eight states and large parts of Ontario, Canada.[40] Power was largely restored in the U.S. within 30 h (an important consideration in light of waiting-period deductibles), but took significantly longer in parts of Canada.[41] Total economic cost estimates range from $4 to $10 billion,[40] with $6 billion ($7.7 billion in 2014 dollars) quoted by the U.S. Department of Energy as the central estimate. One source states that the costs could have been twice as high had it not occurred late in the working week.[42] Per Burch *et al.*,[43] examples of specific impacts include:

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[38] *www.verisk.com/verisk/property-claim-services/pcs-catastrophe-serial-numbers-verisk-insurance-solutions.html*, The cut-off point was $5 million prior to 1997 and $1 million prior to 1982.

[39] *New York Times* (2007).

[40] U.S.-Canada Power System Outage Task Force (2004).

[41] Information on the duration of the outage, particularly by and within states, is remarkably scarce.

[42] Anderson and Geckil (2003).

[43] Burch *et al.* (2011).

Table 4 Public and private insurance claims[a] from 1977 New York City blackout (PCS, 1977; SCI, 1978)

Type of insurance triggered	*Claims $ million (1977 prices)*	*Claims $ million (2014 prices)*
Federal crime insurance	$4	$14
Private property insurance	$20	$76
Fire insurance	$11	$41
Total	$34	$131

[a] The riots were denoted by the insurance industry's Property Claim Services (PCS) as Catastrophe Serial No. 99 and the blackout denoted as Serial No. 11. As of February 1978, only 40–50 per cent of these claims had been paid.

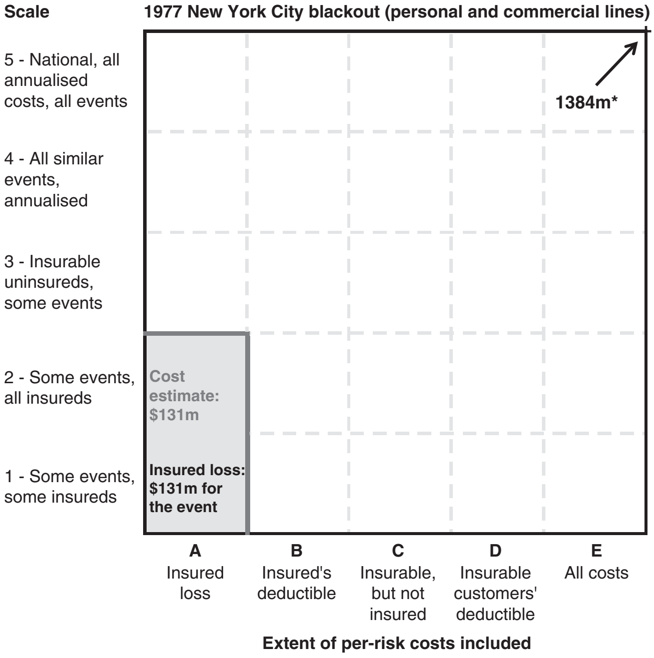

Figure 3. Extensibility of insured losses from 1977 New York City blackout. The total loss is not shown here because it was developed by others and not built up from the insurance loss estimates. 2014 price levels.

- *Daimler Chrysler*: production disruption at 14 of 31 plants, for example, 10,000 vehicles stranded in the painting assembly line were scrapped. Direct costs not reported.
- *Ford Motor Company*: solidified molten metal in furnace created a one-week disruption. Direct costs not reported.
- *Marathon Oil Corporation*: Emergency shutdown procedures triggered boiler explosion, followed by evacuation of hundreds of residents. Direct costs not reported.
- *Nova Chemicals Corp*. Business disruptions reduced earnings by $10 million at seven facilities.

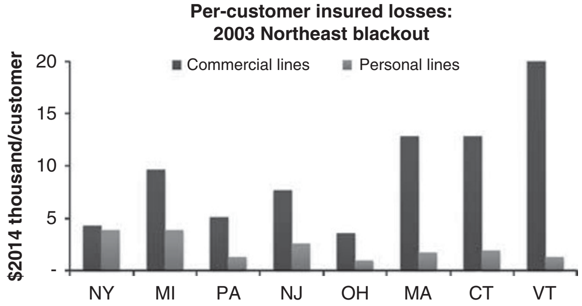

Figure 4. Insured losses from the 2003 Northeast blackout were dominated by household claims, centred primarily in New York but spanning eight states. Per-customer insured losses from the 2003 Northeast blackout varied significantly by state and were highest among commercial customers. Includes copyrighted material of Insurance Services Office, Inc., used with its permission. Values are inflation-adjusted to 2014 price levels by the authors.

- *Duane Reade Inc*. Drugstore chain closed all its 237 stores, losing $3.3 million in sales.
- *Airports*. Closed in 13 locations, with 1,000 flights cancelled. Direct costs not reported.
- *New York City*: $250 million in frozen and perishable food destroyed, among other losses.

PCS provided previously unpublished data for our study, breaking the costs out by broad category of insurance (personal and commercial customer types) and by state. PCS reported that the event resulted in $180 million ($2003) in insured losses, with 63,200 claims (of which 13,200 were from commercial customers and 50,000 from household customers). Note that 22 per cent of small businesses are based in the owner's home,[23] just under half of which depend on their homeowners insurance to cover business assets. Business-related losses incurred by this latter group would rarely if ever be insured. As discussed below, the PCS data do not include line-disturbance claims incurred by boiler-and-machinery insurers.

The aggregates as well as per-customer impacts varied significantly by both customer class and geography. The reasons for variations in losses per claim are not known or examined by PCS. These could well arise from differences in policy types and terms (deductibles and exclusions), in size and business activity of the insured, and in duration of the blackout (influencing size of the waiting-period deductible).

When adjusted for inflation to 2014 price levels, aggregate insured losses for the event are $230 million, of which $157 million fell in the household sector and $73 million in the commercial sector (68 and 32 per cent of losses, respectively). Normalised average insured losses were $3,149 per customer in the household sector and $5,527 per customer in the commercial sector (Figure 4).

A somewhat more inclusive cost estimate can be made when deductibles and insurance penetration are considered (Figure 5). For households carrying insurance, we assume a fixed deductible of $750 (midway between the standard $500 to $1,000 values). Consideration of the 74 per cent weighted-average owner and renter insurance penetration[44] implies about

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[44] According to III, 95 per cent of homeowners had insurance vs 29 per cent for renters (*www.iii.org/fact-statistic/renters-insurance*). As of 2003, 32 per cent of households were renters (U.S. Census). The net effect is 74 per cent of all households (owned and rented) being insured.

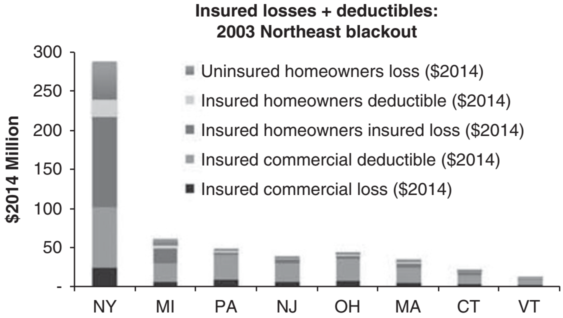

Figure 5. Values shown here include only insurance policyholders submitting insurance claims. Includes copyrighted material of Insurance Services Office, Inc., used with its permission. Values are inflation-adjusted to 2014 price levels by the authors.

17,000 additional uninsured households were impacted, with an aggregate insurable loss of $55 million plus associated equivalent deductible costs of $13 million ($2014). Total personal lines losses (insured and insurable but uninsured) totalled $263 million.

For commercial enterprises, these extrapolations are far more difficult to estimate. Property damage, food spoilage and business interruptions each have distinct deductibles and exclusions, which are generally not documented and publicly reported at the aggregate level. The majority of business-interruption losses likely occurred during the waiting period. We thus stipulate that only 25 per cent of overall business losses for the insured cohort tracked by ISO were claimable, which corresponds to a total cost to businesses with insurance cover that responded to the event of $292 million.

The total quantifiable cost was $555 million (excluding uninsured commercial enterprises, the number of which cannot be estimated) (Figure 6), representing approximately 7 per cent of the aforementioned total economic losses.

This low ratio is loosely consistent with the fact that the 50,000 insured homeowners filing claims—and the additional proportional uninsured cohort—represent only a small fraction of the 50 million people reported to have experienced this multi-state power outage. Many more than 13,200 businesses were also likely impacted (there are 1.8 million non-farm businesses in this region). However, directly extrapolating per-customer insured losses to the entire impacted population results on a value ($84 billion) an order of magnitude larger than the “top-down” published estimates. This suggests that the significant geographical and economic diversity of homes and businesses in this multi-state region renders the up-scaling method inappropriate in cases where information on specific impacted customer types and insurance penetration is highly limited.

We have insufficient information to scale up the insured losses to a full national cost estimate for the event because numbers of homes and businesses impacted by the event could not be found in the literature. A more detailed characterisation of insurance penetration and terms such as deductibles for each type of relevant insurance coverage would also be required. The outage duration for each state would be essential in estimating business-interruption costs incurred during waiting periods. In order to apply these per-event costs to other outage events, data by type of peril would need to be

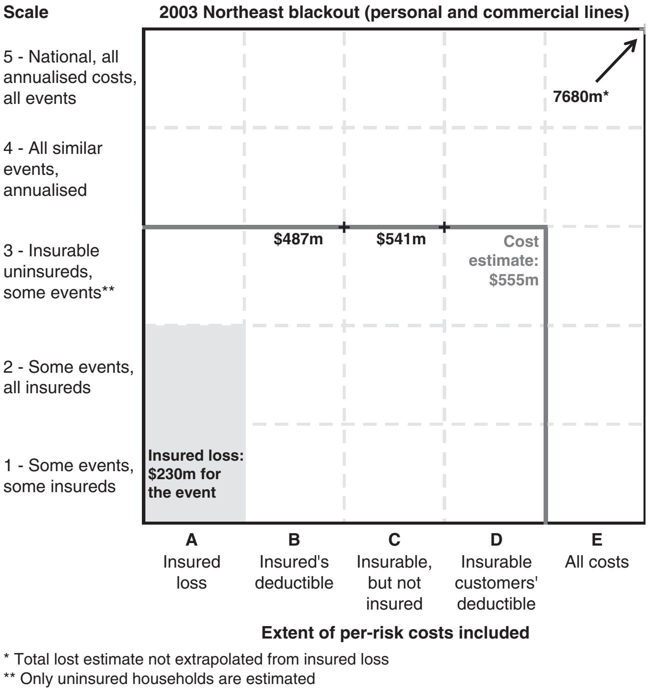

Figure 6. Extensibility of loss data from the 2003 Northeast blackout. Includes estimates of deductibles and insurable but uninsured homeowners and renters. Losses by uninsured commercial customers are not estimated. 2014 price levels.

utilised in order to estimate the portion of losses that were uninsured (e.g. from flooding) due to exclusions.

Accumulations of small-scale power outages

Lightning

Few data are available that attribute insured losses from power outages to specific perils. One exception is lightning. The Insurance Information Institute and State Farm[45] tabulated 2.2 million claims totalling $9.6 billion in insured U.S. homeowners' losses due to lightning strikes between 2004 and 2014. The number of claims paid over this period ranged from 100,000 to 278,000 per year (only about 2,000 per year involved fires; their share of total losses is not reported). The insured cost per claim roughly doubled to approximately $6,000 over this period, with a national aggregate average of $1 billion per year (64 per cent of total economic losses). The average annual outcome, based on multi-year data in Figure 7, including deductibles and adjustments for uninsured owned and rented homes brings the

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[45] III (2015a).

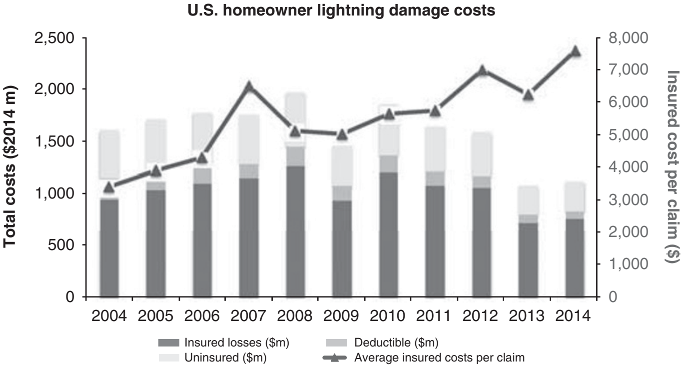

Figure 7. U.S. homeowner insurance claims plus deductibles and uninsured amounts from lightning strikes average approximately $1.6 billion per year. Uninsured values are estimated by applying insured costs to uninsured owner-occupied and rental dwelling stock (American Housing Survey, 2013; III, 2015b). Deductibles assumed at $750 per household. Fires represent only about 2 per cent of the total claim count. Values not adjusted for inflation.
Source: Insurance Information Institute and State Farm (III, 2015a).

total to $1.6 billion per year (Figure 8). Claims peak in summer months and are most common in the Gulf states (Table 5).

This estimation can be more specifically represented as follows:

- Average insured loss $1,022 million, that is, 197,635 paid claims per year × $5,173/claim
- Deductible $148 million, that is, $750/claim (centre of the typical range)
- Insurable but uninsured amount $427 million, that is, based on average insured fraction of 0.73 (the product of 95 per cent weighted average insurance penetration of owners with insurance, and 28 per cent renters and their shares in the housing stock, 67 and 33 per cent, respectively)
- Insurability assumed at 100 per cent, thus no additional amounts considered

One factor reported to be driving the rise in per-claim lightning damage costs is the increased penetration of valuable household electronics. The Insurance Information Institute points out that "wide screen TVs, home entertainment centers, multiple computer households, gaming systems and other expensive devices are having a significant impact on losses".[46] Even conventional appliances and equipment (refrigerators, air conditioners, boilers, etc.) contain increasing amounts of vulnerable electronic controls and are often not surge protected.

Line disturbances

Line disturbance insurance claims result when the quality or voltage of electricity entering the equipment is instrumental in causing loss of equipment function.[47] According to Hartford Steam Boiler Insurance and Inspection Company's (HSB) loss experience, line disturbance is

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[46] III (2007).
[47] Bendre *et al.* (2004).

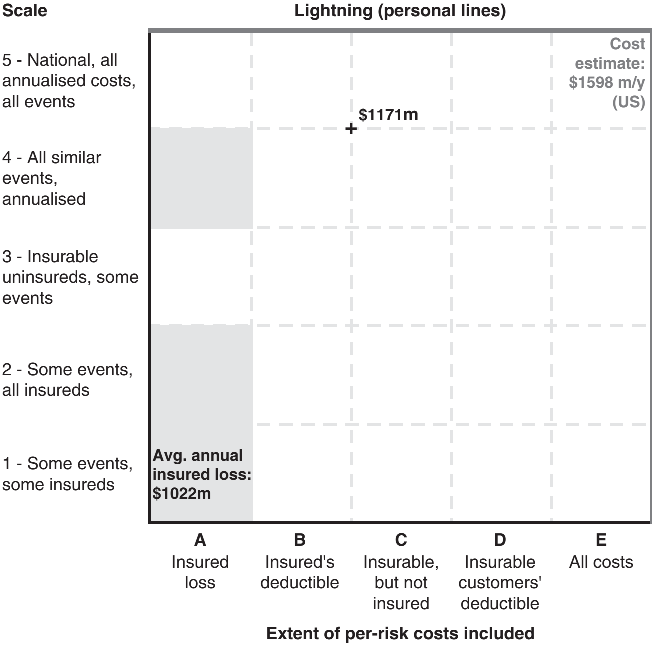

Figure 8. Extensibility of loss data from average annual U.S. household lightning claims. Extrapolation includes deductibles for insured and total losses for uninsured households. Assumes all losses insurable. 2014 price levels.

Table 5 Top 10 states for insured homeowner lightning losses by number of claims, 2014

Rank	*State*	*Number of paid claims*	*Average cost per claim*	*Insured losses ($ million)*
1	Florida	10,440	$7,075.0	$74
2	Georgia	9,805	6,341	62
3	Texas	5,622	10,671	60
4	Louisiana	5,007	5,009	25
5	North Carolina	4,886	5,891	29
6	Alabama	4,853	8,079	39
7	Illinois	4,049	6,348	26
8	Pennsylvania	3,960	5,491	22
9	Tennessee	3,638	8,583	31
10	Indiana	3,262	6,832	22
	U.S. total	99,871	7,400	739

Source: Insurance Information Institute, State Farm.

Note: For perspective, this claims frequency is about 0.1 per cent of policyholders, whereas roughly 7 per cent of policyholders experience claims overall. The average claim across all loss causes was $8,793 for the period 2009–2013. See *www.iii.org/fact-statistic/homeowners-and-renters-insurance*.

the most likely cause of insured loss for a "boiler and machinery" type of insured equipment claim in the United States for most insured customer types. Line disturbance claim frequency and severity data from insurable residential and commercial exposures represent statistically robust estimates for a component of the overall economic grid disruption costs.

As discussed above, insurable losses depend on contract language. Insurable damages may include equipment damage, food/product spoilage, data loss and business interruptions. Deductibles parallel those of typical property insurance policies, for example, $750 for homeowners and small businesses to tens or hundreds of thousands of dollars for large businesses. HSB estimates that aggregate deductibles are on the order of 3–5 times the magnitude of insured losses. An important indirect cost associated with line disturbances are the so-called "contingent business interruptions" that arise in the insureds' supply chain, either upstream or downstream of the entity directly experiencing the disruption. Those costs are not captured in line-disturbance insurance claims data.

Large power outages are a contributing factor but the majority of line disturbance equipment failures (by numbers of claims as well as aggregate loss) are caused by local power fluctuations arising either from the building's internal electrical distribution system or from the local external power distribution infrastructure. On-site systems can also cause power fluctuations if not properly maintained or from design limitations as the building's electrical needs evolve. Off-site power fluctuations are particularly difficult to identify since they can be caused by vehicle collisions with electric infrastructure, local weather and a host of other events.

The economic losses occurring in the United States from this cause of loss are pervasive yet not widely noted because the precipitating events are individually small and diffuse. Equipment that operates in a poor power quality environment may experience reduced service life rather than failing immediately (an uninsurable loss). Consequently, it is often the case that no single event can be identified as the root cause of failure. Power outages and some weather events can, in some cases, be associated with line disturbances by comparing loss dates and locations, and often these events can be seen in claim frequency spikes.[48]

One notable, easily identified event type is lightning strikes, which have the potential to cause line disturbances. However, lightning is a property, not an equipment-breakdown peril, and losses are thus aggregated with other property perils like flood and fire in property insurance reports. Lightning effects are an active area of research and some equipment insurers capture equipment claims that could be related to lightning.[49] However, these claims are a small fraction of total line disturbance claim counts and losses.

Equipment insurers categorise commercial and residential exposures from an engineering rather than activity perspective. For example, a property/casualty insurer will typically classify office buildings and apartments separately, but from an engineering perspective, both business types have common exposures. They generally both contain one or more transformers and various layers of electrical distribution equipment like switchgear, distribution panels and circuit breakers with centralised HVAC. Equipment insurers consider

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[48] Notably, the 2003 blackout represented the largest all-time number of daily claims for HSB, with the rank-ordering by state differing from that of the entire industry (PCS data for all types of insured losses). Hurricane Irene, the Southwest blackout of 8 September, and the Northwest storm on 29 October resulted in record line-disturbance claims. However, these events are rare, and the aggregate cost of small, frequent events is greater.

[49] Kolodziej (1998).

hundreds of location types. Here, we group those into "Exposure Categories", representing locations with broadly similar vulnerability characteristics.

In evaluating historical loss experience, our first objective was to rank exposure categories from the highest loss potential to the lowest across 28 exposure categories. Loss potential here is defined as the largest gross dollars paid (claims plus estimated deductibles) per location type insured. These results provide insights into the sensitivity of each exposure category to line disturbance losses. We compiled nationwide claims and exposures from HSB, the largest U.S. equipment insurer,[50] by detailed business line over the five-year period 2009–2013.

From this database, robust gross-loss cost per location insured estimates were computed for each exposure category, representing in excess of 10 million location-years of exposure and loss experience. Varying regional values represent a combination of weather, geography and a host of other factors. As the deductibles are also known and included, and insureds and uninsured experience involves analogous levels of damage, these values represent national estimates.

To visually display the findings, we normalise the results to the national average value of "Apartments/Office Buildings". This is a common electrical exposure—with very large claims in aggregate—and comparing other categories to this classification presents a meaningful reference point for relative value. The uncertainty range for each exposure category is defined by highest and lowest loss per region.

When viewed in terms of losses per location, the top sectors are clearly energy-intensive manufacturing industries and utilities, where repair, replacement and business interruption costs are very high. Office, warehouse and agricultural locations do not individually possess significant loss potentials from electrical line disturbance losses. The two lowest exposures on a per-site level are Apartments/Office Buildings and Residential locations, which tend to have simple load distribution systems and relatively constant or predictable electricity demand.

To estimate the aggregate insurable loss amounts for each category, we then multiply the per-location claims experience by estimates of the total number of locations nationally (Figures 9 and 10).

These results show the relative importance and pervasiveness of electrical line disturbance loss in the United States (Figure 11). The dominant aggregate loss categories are those where the loss per location is relatively small but are associated with a large number of locations. Foremost among these are apartment/office buildings and stores with refrigerated food—including restaurants and other food service facility types.

The household and business customer categories represent very large numbers of customers, with relatively low per-customer losses. On the other hand, Concrete Manufacturing, for example, is an extremely energy-intensive industry, where line disturbance mitigation may have a direct influence. Medical Offices & Nursing Homes are the fourth largest exposure category, reflecting the recent introduction of high-value diagnostic equipment such as medical imaging equipment in non-hospital environments. This type of equipment can be highly sensitive to line disturbance and power outages, and the risk can be

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[50] Insureds include over 5 million business and industry customers; 350,000 farm customers and 300,000 residential customers.

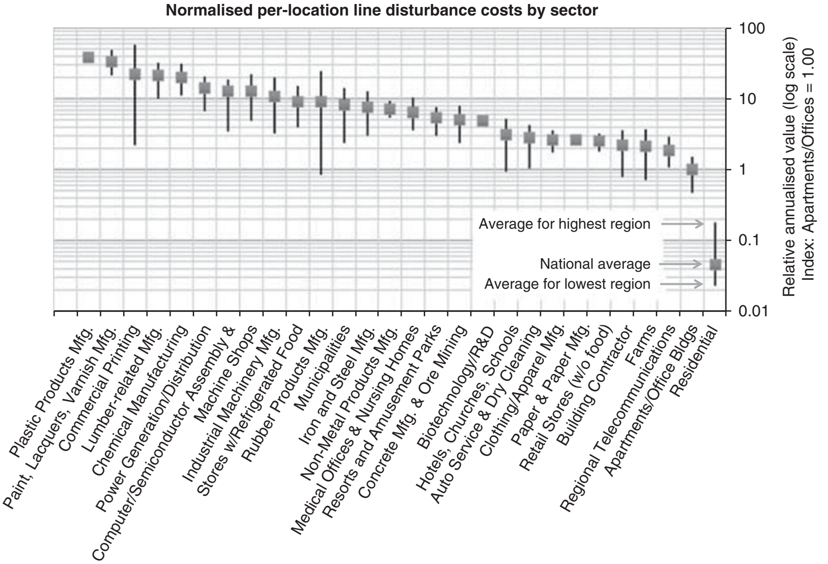

Figure 9. Per-location equipment breakdown loss costs associated with grid disruptions, based on HSB data for the 2009–2013 period, including deductibles paid. Relative values are indexed to the national average apartment/office building exposure category. Ranges reflect highest and lowest regional average outcomes. National counts of locations from NAICS, USDOE Energy Information Administration, U.S. Department of Commerce.

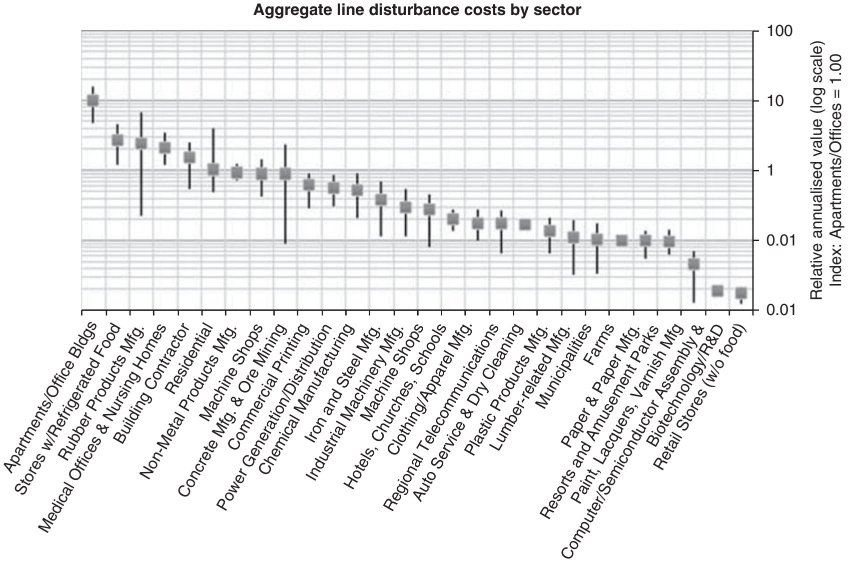

Figure 10. Aggregate equipment breakdown loss costs associated with grid disruptions, based on HSB data for the 2009–2013 period, including deductibles paid. Relative values are indexed to the national average apartment/office building exposure category. Ranges reflect highest and lowest regional average outcomes. National counts of locations from NAICS, USDOE Energy Information Administration, U.S. Department of Commerce.

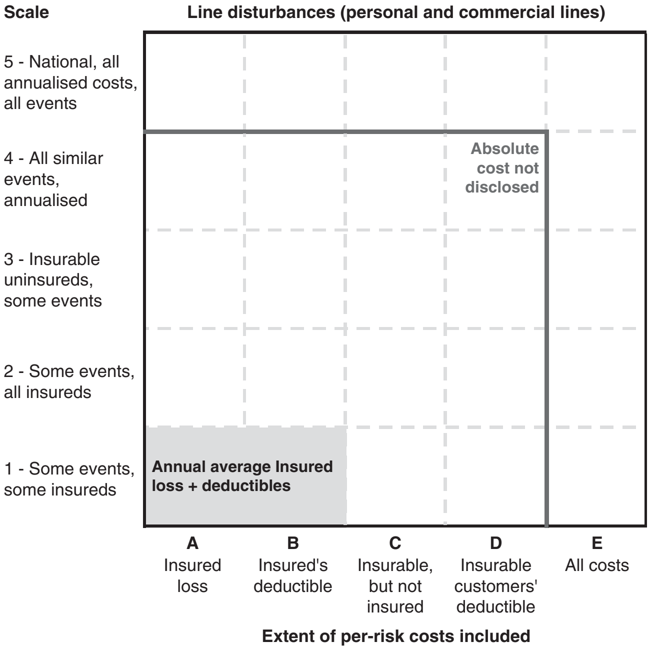

Figure 11. Extensibility of loss data from average annual national U.S. household and business line-disturbance claims, including deductibles recorded by HSB. Extrapolation includes non-HSB and uninsured customers. Results presented in terms of relative rather than absolute losses, by customer type.

easily reduced technically if owners (and insurers) begin to value the long-term benefit of risk reduction measures.

Discussion

The proportion of total grid disruption costs that are insured varies widely among the four case studies, depending on the nature of the event and the degree of overlap with insurance penetration and policy terms (Table 6).

At one extreme, approximately 64 per cent of the costs of household lightning-related disruptions are insured, and the balance (deductibles and costs of those not carrying insurance) is readily estimated such that the full economic costs can be derived from insurance data. A far lower fraction of total costs of power outages are insured or readily estimable using insurance data. For the 2003 event, the insured losses were 3 per cent of the total-cost estimate. Insured losses for the 1977 blackout represented 10 per cent of total cost estimates. Insufficient insurance data on blackouts make it not possible to readily estimate nationwide annual costs from these individual events. Line-disturbance losses represent only 15-25 per cent of the total insurable and uninsurable losses from electrical line disturbances. However, for all loss types, the total costs often reported are far less certain and well-defined than insured costs, albeit spread widely in the media. On the contrary, the scrutiny of

Table 6 Summary of case-study findings

	Total cost ($2014 million)	*Frequency*	*Insured cost ($2014 million)*	*Insured cost as % of total*	*Additional "bottom-up" estimated cost*	*Insured plus additional estimated costs as % of total (%)*	*Notes*
1977 New York blackout[a]	1,350	One time	131	10%			Insufficient info for bottom-up estimates
2003 Northeast blackout[a]	7,680	One time	230	3%	324	7	Bottom-up estimates exclude commercial uninsureds' losses
National average lightning	1,598	Annual	1,022	64%	576	100	Households only
National average line disturbances		Annual		15%–25%		100	

[a]Insured values exclude line disturbance impacts.

Sources for "Total cost": 1977 New York blackout—Systems Control Incorporated, Project 5236-100 (1978) and the Insurance Services Office; 2003 Northeast blackout—U.S. DOE—(Glotfelty, 2003); Residential lightning—Insurance Information Institute and State Farm claims data (III, 2015a, b; III, 2007) for 2004–2013 period, adjusted by LBNL for deductibles and uninsured customer population; line disturbances—Hartford Steam Boiler estimates based on 2009–2013 claims experience and deductibles.

insurance claims (within the terms and conditions of policies) results in some claims being rejected.

Sullivan *et al.*[51] conducted a meta-analysis of the literature on customer value of electricity reliability. Their study includes 34 different data sets from surveys fielded by 10 different utility companies between 1989 and 2012. Our results for commercial customers overlap at the low end of Sullivan *et al.*'s range. As our insurance data are not disaggregated by customer size, the level of agreement for commercial customers is not clear. Our findings for household customers are on the order of 50- to 200-times greater (Table 7).

In the two case studies for which we have sector-specific loss data (the 2003 blackout and line disturbances), aggregate insurance payments were greater in the homeowner sector than the business/industrial sector. This reflects at least in part the vastly larger number of policyholders, and perhaps also the less advanced level of loss-prevention through methods such as uninterruptible power supplies and backup generators, as well as surge protection devices. However, this finding suggests that traditional research methods (such as surveys about the value of service) may not fully capture the costs of grid disruptions to households.

Given that waiting-period deductibles are typically on the order of 24 to 72 h, it is likely that the majority of commercial lines losses in the 2003 blackout were uninsured. This would have been reinforced by the fact that the event took place late on a Thursday, indicating that

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[51] Sullivan *et al.* (2015).

Table 7 Comparison of our findings with value-of-service studies ($ loss/customer)

	Small commercial & industrial	*Medium & large commercial & industrial*	*Households*
Sullivan *et al.* (2015)[a]	$9,100	$165,000	$31 to $42[b]
2003 Northeast blackout—this study	$14,300 to 102,000		$1,700 to $4,600[c]
Lightning—this study	Not available		$8,347

[a] Values are for a 16-hour outage.
[b] Range shows variation by time of day.
[c] Varies by state.

only one full day of certain business activities were disrupted. This is reinforced by HSB's estimate that deductibles from line-disturbance events are 3–5 times the insured values. However, in the case of equipment damages (the primary loss in the line-disturbances example), duration of outage is not a factor as losses occur more or less immediately.

The top economic loss exposures encompass the majority of the U.S. population (homes and commercial businesses). This result challenges many business models as to how to cost-effectively reduce this apparent *societal* exposure. On a per location basis, cost-effective mitigation may not be possible, especially if financiers are looking for short pay back returns. Grid-disruption events are relatively infrequent, yet the exposures are very widespread. It is often difficult for a homeowner or business owner to financially justify spending funds today to directly mitigate future potential losses from future infrequent events.

However, from a societal or regional perspective, mitigation measures on this scale can yield substantial reductions in claims. This finding suggests that the most effective mitigation measures could be introduced across a region or exposure category and not necessarily on a site-by-site basis. This could be incentivised by insurers or other organisations that place value on the common good created from certain forms of risk mitigation.

The insurance industry is working to better understand the role of grid disruptions in their overall risk environment. The scale of losses from the 2003 blackout took leading insurance industry organisations by surprise, as actual claims of $180 million were at least seven-times greater than initial projections that they may not exceed $25 million.[52] Projections two months after the event were still less than 50 per cent of the ultimate loss.[24] Similarly, line disturbances are a previously underappreciated category of losses in both the insurance literature and the power-sector literature. These events affect many customer segments, occurring throughout the household, commercial, industrial, agricultural and power-production sectors.

Blackout modelling

Our case-study analysis of discrete historical events illuminates loss mechanisms, but cannot be always extrapolated to other scales or contexts. In the majority of cases actual loss data are

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[52] Levick (2003).

highly aggregated and do not isolate the costs solely related to grid disruptions from other impacts such as property damage. Modelling offers the potential to isolate costs of interest and to explore the sensitivity of different regions and customer types to grid disruption events.

The Blackout Risk Model$^{\mathrm{TM}}$ developed jointly by HSB and Atmospheric and Environmental Research (AER), a unit of Verisk Climate, is now being used to examine the influence of risks from wide-area blackouts. This is the first commercially available model of its kind.

The new modelling technology integrates a database of possible weather conditions, satellite analysis of trees near distribution lines, proprietary knowledge of the electrical grid infrastructure and detailed economic data. The model incorporates extensive data on four peril categories: hurricanes, winter storms, thunderstorms and equipment or operator error. The system can be applied to assess the exposures faced by individual insurers, individual communities or large regions.

More than 95,000 actual and potential hurricane events, 68,000 winter storms and 400,000 severe convective storms (tornados and thunderstorms) are included in the analysis. The model assesses impacts on electrical infrastructure including more than 11,000 power plants, 64,000 substations and 737,000 miles of transmission lines in the U.S. and Canada. Approximately 12,000 key substations have been classified through detailed satellite data analysis, engineering review and/or visual inspections. Power flows of the U.S. grid are simulated down to the local substation level. A U.S. population weighted, tree density sub-model accounts for the proximity of trees to power lines. Estimation of tree cover uses proprietary algorithms based on satellite data, vegetation type and density information. The analysis is performed at very high spatial resolution (Figure 12).

The model can be used for a specific, named storm to forecast hypothetical outage locations and durations based on AER's forecast track models or to examine probabilistic outage risks at a specific location. Localised events such as lightning strikes or line disturbances at individual locations are not addressed in the model.

Innovations in risk spreading and loss prevention

With rising awareness of electricity reliability risks will likely come increased demand for responsive insurance products and services. Loss-prevention measures may reduce current risks to a level that insurers can more readily assume, although it will be challenging in some customer classes, particularly households, where loss costs are small individually but large in aggregate. As is the case with many other large-scale risks (e.g. storm damage to the building stock), insurers' willingness to assume risks can increase where public policymakers take steps to prevent losses (e.g. by improving building and equipment codes and standards). Such considerations would no doubt apply in the case of electrical system maintenance and modernisation.

A range of customer-side risk-management technologies are employed today, including on-site primary or backup generators, uninterruptable power supplies (UPS), on-site energy storage, surge protectors and improved grounding (for lightning risk). Equally important are business-continuity programmes and financial risk-transfer mechanisms such as insurance.

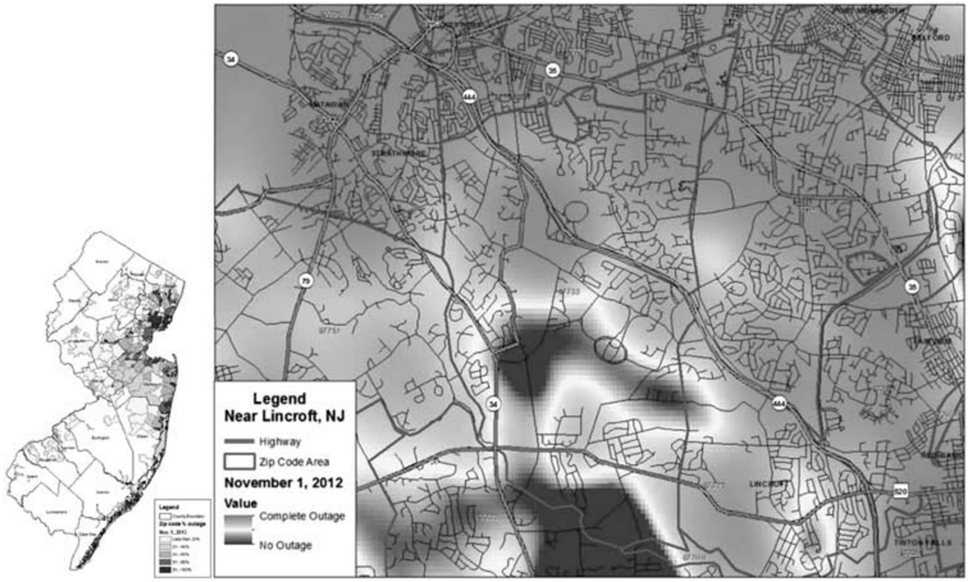

Figure 12. Per cent outage by zip code in affected counties New Jersey, New York and Connecticut (left) and per cent outage by exact location (ZIP 07733) (Bartley and Rhode, 2013).

Yet, little has been done to determine the levels of adoption and cost-effectiveness of these strategies.[53]

Insurers are finding new business opportunities to become more engaged, as advisors and service providers, in loss prevention. Some already provide premium credits for homes with permanently installed backup generators[54] or lightning protection devices. “Sue-and-labour” clauses within some insurance contracts, which have the insurer pay for efforts to avoid an insured loss (e.g. on-site generators), are an example of this thinking from early in the history of maritime insurance.[55] Such losses must be “imminent”, meaning that only those loss-prevention measures taken during an outage event may be claimed.

Insurance terms and conditions could more precisely reflect loss exposure and be used to reward loss-prevention initiatives. Potential underwriting criteria could range from equipment- and building-specific levels to the property’s location within the utility grid.

There is more that insurers can do. Emerging technologies are creating new opportunities for risk management, particularly with regard to the Smart Grid. Advanced metering infrastructure, for example, is reported to have improved response time during recent major hurricanes in the U.S.[56] Two-way communication between the grid and end-use loads offers a potential for strategic load shedding so as to preserve essential services and protect equipment during line disturbances. While present-day grid-intertied solar photovoltaic

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[53] LaCommare and Eto (2004).

[54] Spencer (2013).

[55] Johnson and Churan (2004).

[56] Campbell (2012); Executive Office of the President (2013).

systems go out of service when the broader grid is down, new approaches involving advanced batteries and controls could enable end users to "island" themselves and remain operational during outages. At a larger scale, micro-grids can similarly isolate large numbers of customers. On the demand side, energy-efficient technologies, such as high-performance refrigeration systems that can coast through outages, may help prevent losses and enable insurance holders to "shelter in place" and not incur insured extra expenses.

The insurance industry anticipates a spate of new products and services, and notes the potential benefits in the event of grid disruptions.[57] American Family Insurance Company, in partnership with Microsoft, is making equity investments in smart-home startups with promising insurance applications, including communications and loss prevention functionality in times of grid disruptions. The giant German insurer Allianz has also entered this market, in partnership with Deutsche Telecom. The Italian insurer BNP Paribas Cardif combines smart home technology with tailored insurance coverage, with sensors in place to detect a range of loss triggers, including power outages.[58]

While insurers are natural advocates of loss prevention, they are also sensitive to potential risks associated with customer-side responses to grid disruptions, such as fire or carbon monoxide poisoning resulting from the use of generators.[54] Similarly, smart-home technology has pros and cons. On the one hand, the connected home can keep insurers far better informed of practices that correlate with losses, including those stemming from power disruptions, as well as providing opportunities to automate loss prevention (thermostat management). On the other hand, these technologies can introduce new risks,[59] which, for example, on the supply side (e.g. wind, solar) or on the demand side (e.g. variable speed drives) may introduce new reliability-related risks.[60] In the electricity upstream, emerging risks such as oversupply from grid-connected renewables are also a consideration.[5]

Conclusions and further analysis needs

We find that the consequences of fluctuations in electric grid reliability are a substantial source of insurance claims, with a single blackout event potentially generating insured losses on a par with those experienced following a major hurricane. The causes and magnitude of these events are less well documented and understood than most insurance risks. Once regarded as minor events, multi-billion-dollar insured losses for a single power outage are today seen as a real possibility. Our analysis makes new insurance data available for analysts and decision-makers. We find that these data can be used to approximate part or all of the broader economic costs of certain events.

However, very substantial information gaps remain. More efforts are needed within the private and public and sectors (each of which has its domains of influence) to better document the role and insured and total costs of grid disruptions.

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[57] Galovich (2015).

[58] Smith (2014).

[59] Holbrook (2010); Business Insurance (2014).

[60] Lineweber and McNulty (2001).

Improved data and analysis

Insurance loss data are valuable in helping understand the broader societal costs of electric reliability disruptions. They offer perhaps the most rigorous and best quantification of impacts at a macro scale and, when taken as a proxy for costs analogously incurred by non-insureds, they can be extrapolated to estimate regional or national cost impacts. They can also provide fine-grain data onto how losses vary by geography or type of facility. This is particularly evident in the line-disturbance case study. Promising research avenues include:

- A better market-wide perspective is needed on the insured costs of power disruptions. We discovered that aggregate insurance data do not currently exist on numbers of policyholders with coverages that respond to outages, terms of these coverages (e.g. time-deductible periods) or loss experience. In tandem with these data gaps, utility-side statistics on outage duration and types and numbers of customers affected are also poor.
- For private-sector insurance, the PCS $25-million-per-event cutoff results in most power outages being unrecorded at an industry-wide level, and closed-claim analyses at the individual insurer level have not been published other than that provided here for HSB. Moreover, PCS statistics do not include claims data for line disturbances, presumably because of their decision rules (too few insurers in this sub-market and/or minimum claim size). This is a significant data gap, illustrated by the fact that three large outages in 2011 resulted in record line-disturbance claims. More comprehensive data collection would provide better estimates of aggregate claims faced by the insurance industry.
- As insurance premiums are actuarially based on exposures and expected values of specific losses, identifying the component of insurance premiums that is associated with grid disruption risk would provide an alternate avenue for understanding aggregate cost. In this sense, premiums can be looked at as a reflection of willingness to pay. However, as these premiums are typically “bundled” together with others (e.g. embedded in a general “homeowners” or “business interruption” premium), the underlying actuarial information would need to be identified.
- Outages and losses due to events triggered by natural disasters could be tracked more precisely. In particular, the coding and reporting mechanisms utilised in existing event-tracking (e.g. DOE and NERC) could be improved.
- Further analysis could focus on examining more events involving only electricity infrastructure such as the WSSC area events of summer 1996 (2 July, 3 July and 10 August), the San Francisco tripoff of 8 December 1998 and the Southwest blackout of 8 September 2011. These events offer the best remaining opportunities to identify outage costs independent of confounding factors such as storm damages.
- Further analyses could scale up existing estimates to expected values of national annual-average losses. Extrapolating insured losses incurred during large-scale power outages to national costs is confounded by highly variable penetration of relevant insurance as well as terms and conditions (e.g. exclusions and deductibles). While total costs may be estimable in this fashion, insured losses would require information on the penetration of responding policy types and numbers of customers impacted.

- Insurance costs incurred by publicly funded insurance mechanisms, particularly the National Flood Insurance Program, may yield additional relevant data; however, this programme's publicly available statistics do not separately identify losses associated with electric grid disruptions.[61]
- Better data, in turn, can help specify better models. As grid-disruption events triggered by extreme weather have been increasing faster than non-weather-related causes,[62] models must also consider the role of trends in extreme weather and climate change in shaping risks.[63] This is a natural initiative for public–private coordination.[36] Well-specified models can be powerful tools for investigating the cost-effectiveness of loss-prevention interventions.

Targeted risk management

Further analysis of the patterns of insurance claims data could inform risk-management efforts by shedding light on the anatomy of losses and providing information on underlying causes and vulnerable customer segments. Promising research avenues include:

- Deeper examination of losses by location type and exposure category could yield new insights into vulnerabilities and context-sensitive loss-prevention strategies. For example, examination of impacts in health-care settings has suggested a number of specific ways to prevent losses.[64] Enhanced understanding would also improve underwriting and enable more risk-based premiums.
- As innovations occur in the electricity sector, driven by goals for improving energy efficiency, making the grid smarter and deploying climate-friendly generation technologies, it is critical to conduct proactive technology assessments to ensure that reliability and resilience are maintained if not enhanced. Insurers are interested in both issues and are well positioned to capitalise on synergies.[65] These considerations could be more deeply integrated with energy technology R&D, on both the supply and demand sides.
- Many technologies exist for mitigating losses from grid disruptions, ranging from lightning protection to backup generators. Future analyses may enable insurers to encourage customer-side loss-prevention investments by reflecting their value in policy terms and conditions.
- While domestic interests tend to focus on domestic issues, grid disruptions and their impacts often extend over national borders. This is increasingly so given the role of global communications and supply chains, as well as transnational power pools. Analysis of vulnerability and international impacts of electricity reliability problems is merited, as it affects insurance claims. As noted above, some insurance products explicitly cover disruptions in distant supply chains.

In sum, there is clearly a greater role for insurers in spreading and managing the risks associated with electric grid disruptions. Basic consumer education about coverage gaps and

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[61] NFIP (2014).
[62] USGCRP (2009); Campbell (2012).
[63] van Vliet *et al.* (2016).
[64] Klinger *et al.* (2014).
[65] Mills (2009).

the role of optional policy endorsements could result in more homes and businesses utilising insurance. As loss prevention is a core precept in the insurance business, techniques already utilised by insurers may have broader value, and insurers are well positioned to develop new and improved techniques. Loss prevention also deserves increased attention, given multiple trends that can be expected to elevate future losses above what has been experienced historically. Public–private partnerships with insurers and policymakers could yield impactful results, particularly for customer types represented by large numbers of relatively low per-customer losses.

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