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Solar storms and their impacts on power grids
Recommendations for (re)insurers

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Abstract

As shown from past occurrences over the last few decades, solar storms have the potential to impact several human activities (satellites, aviation, power grids, etc.) through various physical phenomena. Coronal mass ejections in particular may generate quasi-DC currents in the bulk power system, causing disruptions which may go as far as the collapse of smaller or larger parts of the power grid, as well as permanent damage to transformers up to the point of failure. Although such situations have already been observed in relatively recent years (notably with the March 1989 power blackout in Quebec), no major solar storms, such as the spectacular 1859 Carrington storm, have been experienced in contemporary times. While there are reasons to believe that a one in 200-year solar storm would not be that different from the 1859 event, studies diverge as to what would be the impact on power grids. Some of them anticipate a major power blackout affecting millions of people people for several weeks or more, with consequences reaching up to trillions of dollars. Others foresee only temporary local outages. Despite these uncertainties and the 'emerging' nature of solar storm risk for (re)insurers, it is possible to make a series of recommendations. In particular, in light of the possibility for generating companies and Transmission System Operators (TSOs) to take mitigation measures, (re)insurers should promote such measures, either through reliability standards imposed by grid regulators or when underwriting insurance policies. Special caution is needed when underwriting Contingent Business Interruption (CBI) policies and service interruption extensions due to accumulation risk and sometimes imprecise policy wording.

Key words: solar storm, Carrington, insurance, power grid, blackout, emerging risk.

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SCOR Global Risk Center

Résumé

Comme elles ont eu l'occasion de le montrer au cours des dernières décennies, les tempêtes solaires ont la capacité d'affecter plusieurs activités humaines (satellites, transport aérien, réseaux électriques, etc.) via différents phénomènes physiques. En particulier, les éjections de masse coronale peuvent engendrer des courants quasi-continus dans les réseaux à très haute tension, provoquant des dysfonctionnements qui peuvent aller jusqu'à l'effondrement de tout ou partie du réseau, ainsi que jusqu'à des dégâts permanents aux transformateurs pouvant entraîner leur destruction. Bien que de telles situations aient été observées dans le passé récent (notamment lors de la panne d'électricité de mars 1989 au Québec), aucune tempête solaire comparable à la spectaculaire tempête dite de Carrington de 1859 n'est survenue à l'époque contemporaine. Alors qu'il paraît raisonnable de penser qu'une tempête solaire avec une période de retour de 200 ans ne serait pas fondamentalement différente de celle de 1859, les études divergent sur son impact sur les réseaux électriques. Certaines d'entre elles anticipent une panne d'électricité majeure affectant des millions de personnes pendant plusieurs semaines ou au-delà, avec des conséquences se chiffrant en milliers de milliards de dollars. D'autres études prévoient simplement des interruptions de courant temporaires et locales. En dépit de ces incertitudes et du caractère encore très émergent du risque de tempête solaire pour les (ré)assureurs, il est possible de formuler un certain nombre de recommandations. En particulier, compte tenu de la possibilité pour les producteurs d'électricité et pour les gestionnaires des réseaux de transport de prendre des mesures de prévention, les (ré)assureurs devraient promouvoir ces mesures, soit via des normes de fiabilité imposées par les régulateurs de réseaux ou lors de la souscription de polices d'assurance. Une attention particulière est par ailleurs requise lors de la souscription de polices couvrant les pertes d'exploitation en cas de carence fournisseur ou d'interruption de la fourniture de services, du fait du risque d'accumulation et de la rédaction parfois imprécise des polices.

Mots-clés: tempête solaire, Carrington, assurance, réseau électrique, panne d'électricité, risque émergent.

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I learned a lot from participants at the conference on solar storms organised by the Geneva Association in Berlin in July 2013, notably Jim Wild from Lancaster University, Alan Thomson from the British Geological Survey, Neil Smith from Lloyd's, Charles Trevor Gaunt from the University of Cape Town, Chris Rogers from National Grid UK, Risto Pirjola from the Finnish Meteorological Institute, Kyle Beatty from Atmospheric and Environmental Research and Emmilie Andersson from the Swedish Civil Contingencies Agency.

Even though I decided to focus this report on the impacts on power grids, I am grateful to Yohan Leroy and David Zamora from Eutelsat for the information they gave me on the way satellite operators cope with solar storms.

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Introduction

Grasping the issue of solar storms is not an easy task for the (re)insurance industry.

First, the somewhat exotic nature of this physical phenomenon, as compared to well-known perils such as hurricanes or earthquakes, makes it at best hard to visualize and understand. At worst, it prevents it from being taken seriously enough.

Second, it belongs to the category of emerging risks, which are new to the industry and for which it lacks the analytical tools it has for addressing better-established risks. This is paradoxical since solar storms have arguably existed long before any human being was there to watch. But what was a harmless phenomenon still a hundred years ago has become a real risk for the past decades due to technical evolutions ranging from the pervasive use of electricity to aviation and satellites.

Third, solar storms, at least as far as power grids are concerned, are low probability, high severity events. For that reason, they tend to be treated the way meteorites are. Why bother with the risk from solar storms more than with the risk from a large meteorite hitting the Earth? This is a misleading analogy however. Solar storms are not exceptional events, and plotting their severity against their frequency shows a rather smooth pattern suggesting that relatively severe storms may hit the Earth with return periods comparable to the ones considered for earthquakes for instance.

From that point, many questions arise: what would be the impact of a one in 200-year solar storm? Which insurance policies would be triggered? What can (re)insurers do in order to address this exotic emerging risk?

Because so many human activities – among which many are essential to our modern way of life - are crucially dependent upon the supply of electricity, blackouts resulting from solar storms are arguably the main risk that they pose to society. Therefore this report focuses on the impact of solar storms to power grids.

1 Overview of solar storms and how they impact human activities

According to the World Meteorological Organization, "Space weather encompasses the conditions and processes occurring in space, including on the sun, in the magnetosphere, ionosphere and thermosphere, which have the potential to affect the near-Earth environment".

Thus behind the generic term of "Space Weather" hide a wide variety of physical phenomena with different causes, characteristics and impacts.

Some of these phenomena, such as cosmic rays, originate from beyond the solar system. Although they can have an impact on human activities (LLoyd's, 2010), they are not within the scope of this report, which focuses on solar storms.

Solar storms are events which result from explosions on the surface of the Sun, themselves caused by instabilities of magnetic fields in the Sun's atmosphere.

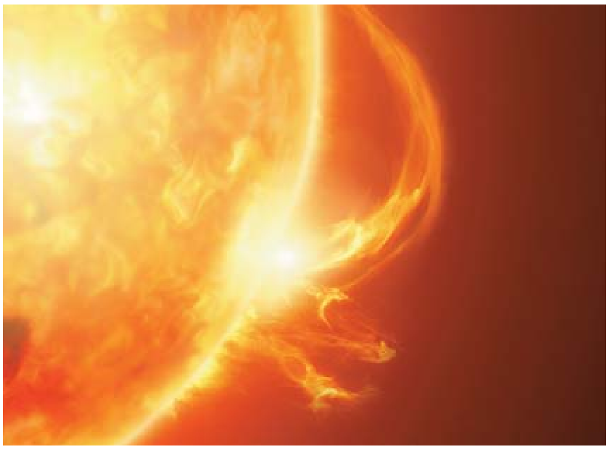


Figure 1 Solar eruption with coronal mass ejection

These explosions tend to be more frequent when the Sun's activity, as indicated by 'sunspots' that appear at its surface, is high. By observing the Sun, physicists have identified the existence of a 'solar cycle' which lasts approximately 11 years and contains a peak period for sunspots.

The notion of 'solar storm' actually encompasses three different components (Marusek, 2007): solar flares, solar energetic particles (notably protons) and coronal mass ejections (CMEs). A large solar storm would produce all three, while a more modest one would not necessarily.

The following table shows some of the characteristics of solar flares, solar energetic particles and CMEs.

	Solar flares	Solar energetic particles	Coronal mass ejections (CMEs)
Physical nature	X-rays, extreme UV, gamma rays, radio burst	Energetic protons and ions (typically 10 to 100 MeV, but up to 20 GeV)	Vast clouds of seething gas, charged plasma of low to medium energy particles with imbedded magnetic field
Time needed to reach the Earth	8 minutes (speed of light)	15 minutes to 24 hours	1 to 4 days
Duration of the interaction with Earth	Minutes to hours	Several days	One day or two

Table 1: The three components of solar storms (sources: (Marusek, 2007), (Wild, July 2013))

	Solar flares	Solar energetic particles	Coronal mass ejections (CMEs)
Ionospheric reflectivity and scintillation	X	X	X
High-energy particles and nuclear radiation		X	X
Geomagnetic field distortions		X	X
Induced electric currents in the ground			X

Table 2 Physical phenomena on the Earth due to the different components of solar storms (adapted from (Marusek, 2007))

In turn, these physical phenomena on Earth may have an impact on human activities.
(Marusek, 2007) provides an overview of these impacts.

Physical phenomenon	Direct impacts on human activities
Ionospheric reflectivity and scintillation	The modification of the characteristics of the ionosphere caused by solar storms affects electromagnetic signals going through it. This may result in disruptions to: • Radio communications (HF, VHF or satellite communications, including GPS signals). • Radar systems
High-energy particles and nuclear radiation	Solar energetic particles and nuclear radiation associated with them may hurt: • Solar panel arrays of satellites • Spacecraft, aircraft and ground based electronics • Spacecraft and aircraft crew and passengers
Geomagnetic field distortions	Geomagnetic field distortions may affect systems using compasses, notably: • Spacecraft • Ships
Induced electric currents in the ground	Electric currents induced in the ground by CMEs may cause disruptions to: • Power grids, potentially resulting in outages • Railway signalling systems • Oil and gas pipelines • Long Distance Communication Lines

Table 3 Impacts of solar storms on human activities (adapted from (Marusek, 2007))

These 'direct' impacts may then generate indirect consequences with potentially higher severity. This is the case with the disruption of radio and satellite communications, which has cascading consequences. Of course this is also the case with power outages, which, especially if long-lasting, would affect most human activities.

As a result, when assessing the potential impacts of solar storms on a given activity (i.e. aviation), one has to consider successively:

- the three different components of solar storms: solar flares, solar energetic particles and CMEs,
- the physical phenomena generated on Earth by each of them,
- the direct impacts (if any) of each of these phenomena on the activity in question,
- the indirect impacts on this activity via the disruptions to other activities.

Aviation is an interesting illustration of this. As a matter of fact, solar storms can affect it in a series of different ways (LLoyd's, 2010):

- Directly:
  - o by damaging inboard electronic chips,
  - o by increasing the nuclear radiation to which crews and passengers are exposed.
- Indirectly:
  - o by disrupting HF radio links between control centres and airplanes. These links are particularly critical as planes fly over polar regions and cannot use alternative satellite communications,
  - o by disrupting satellite communications used for navigation and precision landings.

These effects are not just hypothetical. For instance, a relatively modest solar storm in January 2012 led such companies as Delta Air Lines, Qantas, Air Canada and United Airlines to divert flights on polar routes (Johanson, January 25 2012).

(Marusek, 2007) and (LLoyd's, 2010) provide extensive overviews of the impacts of solar storms on human activities (transport, communications, etc.), as well as real-life examples from past events. Some studies even highlight risks to people's health at ground level: "Medical records collected in Moscow show that during such events an abnormally high incidence of cardiovascular events takes place even on Earth, with an increase in heart attacks of up to 13% and an increase in blood-strokes of up to 7.5%." (Pultarova, 2012)

Among all potential effects of solar storms, a prolonged blackout covering a large area are arguably the most severe. Therefore this report focuses on the impact of CMEs on power grids and, indirectly, on activities dependent upon the supply of electricity.

2 From solar storms to geomagnetically induced currents (GICs)

Understanding the science of solar storms and the chain of events by which they may affect power grids is essential for a correct risk assessment.

As mentioned in section 1, CMEs are vast clouds of seething gas, charged plasma of low to medium energy particles with imbedded magnetic field, which are ejected from the Sun following explosions of unusual violence on its surface. Unlike solar flares and solar energetic particles, they are the ones which have the potential to disrupt power grids.

These explosions usually occur at 'sunspots', which are spots on the surface of the Sun with a high activity. Therefore CMEs are correlated with the 11-year solar cycle for sunspots. But oddly enough, the peak period for CMEs does not fully coincide with the maximum of the solar cycle (i.e. the peak for sunspots). It is delayed by approximately two years (Ramesh, 2010).

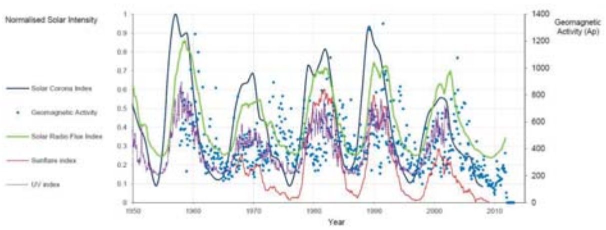


Figure 2 Observed metrics of solar and geomagnetic activity (Aon Benfield, January 2013)

This two year lag suggests that during the current solar cycle the risk of CMEs will reach its highest level in 2015. However, large CMEs can occur anytime during the cycle.
One could depict CMEs as energetic balls launched from the Sun. Depending on the location of the sunspot from where they are ejected and depending on the timing (the Sun rotates on itself with a period of 27 days), they might reach and affect the Earth or (fortunately, much more often) 'miss' it. When a CME reaches the vicinity of the Earth, its magnetic fields interact with the magnetic field of the Earth (the magnetosphere) and it distorts it.

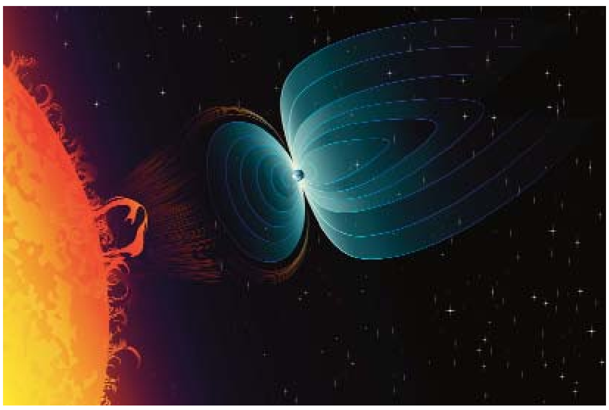


Figure 3 Distortion of the magnetosphere when hit by a solar storm.

Meanwhile, the charged particles within the CME ionize the ionosphere and produce electrons. As a result, strong electric currents (electrojets), reaching up to several million Amperes, are generated at altitudes of about 100 km and follow circular paths (called 'auroral ovals') around the geomagnetic poles. The diameter (typically between 3000 and 6000 km) and width (typically between 100 and 1000 to 2000 km) of the auroral ovals vary according to the intensity of the CME. In particular, the more intense the CME, the higher the diameter of the auroral oval, which can then span over lower geomagnetic latitudes (geomagnetic latitudes are latitudes with reference to the geomagnetic poles as opposed to the geographic poles).

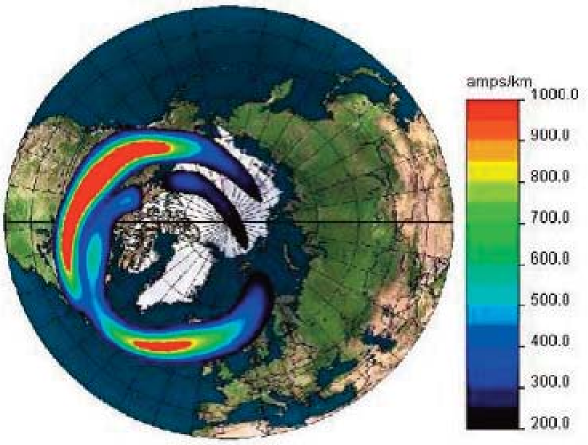


Figure 4 Auroral ovals (source: Electrical Power Research Institute, 2012)

These currents are responsible for the beautiful aurora borealis.

Figure 5 Picture of an aurora borealis

According to Faraday's law of induction, they also generate variations in the magnetic field in their vicinity, including at the surface of the Earth. Scientists refer to this phenomenon as 'geomagnetic storms' or 'geomagnetic disturbances'.

Magnetometers in observatories scattered around the Globe measure these variations. In March 1989, when a CME caused a power blackout in Quebec, the variations reached -589 nT/min. In October 2003, when another CME caused disruptions in Sweden and South Africa, they reached -347 nT/min. There are various hypotheses about the intensity of magnetic variations during the most severe CME observed to date, the 1859 so-called Carrington event. At the time, magnetometers were not sophisticated and for that matter not calibrated to record such high levels.

According to Faraday's law of induction again, these time-varying magnetic fields create electric currents in the ground and differences of electric potential that can reach several volts per km. For instance, while typical ground electric fields in the UK are of order 0.1 V per km, they may rise to 5 to 10 V per km during solar storms (Royal Academy of Engineering, February 2013). Thus the difference of electric potential at the ground between the two endpoints of a 100 km transmission line can typically reach 1 000 V.

3 Impact of solar storms on power grids

When a solar storm hits the Earth, electric lines whose extremities are grounded to the earth provide a shortcut between points with very different electric potentials[1]. This drives currents called Geomagnetically Induced Currents (GIC).

GICs in electric grids may reach high values: a GIC reaching 300 Amp was measured in a 400 kV transformer neutral in Sweden on 6 April 2000 (Pirjola, July 2013).

These GICs may damage grid transformers in the bulk power system:

- "step-up" transformers, which increase voltage and may belong either to the generating company or the transmission service operator (TSO),
- "step-down" transformers, which reduce voltage and belong to the TSO.

[1] The same is true for railways, communication cables (such as telegraph cables in 1859) and pipelines, causing disruptions of their own.

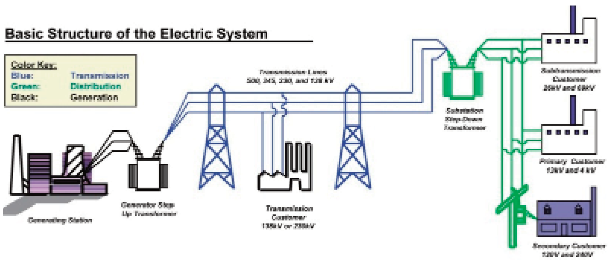


Figure 6 Basic structure of the electric system (source: Iowa State University)

GICs may damage grid transformers because these transformers are designed to deal with AC currents, not DC currents. And GICs are DC-like currents.

DC currents may cause overheating of transformers and the production of gases in the insulating oil, damaging them up to the point of failure, as illustrated in the picture below.

Figure 7 Picture of a transformer damaged by overheating

Tests have been carried out to assess the minimum DC current intensity level causing rapid heating and damage, but results vary a lot according to the design of the transformers. In his 2010 study, Kappenmann considered a range of 30 Amp/phase to 90 Amp/phase, even though transformer failures have been observed at lower thresholds.

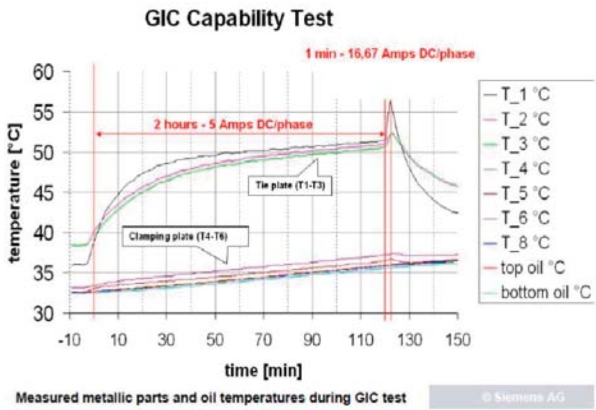


Figure 8 Increase in the temperature of a transformer submitted to DC current

Moreover, even before GICs damage any transformer, they may increase their reactive power consumption and cause a voltage collapse.

Furthermore, harmonic currents may cause the tripping of protective systems on the grid. This can also cascade into the collapse of parts of or even the whole of the grid.

4 Real-life examples from past events

September 1859 Carrington event

"As night was falling across the Americas on Sunday, 28 August 1859, the phantom shapes of the auroras could already be seen overhead. From Maine to the tip of Florida, vivid curtains of light took the skies. Startled Cubans saw the auroras directly overhead; ships' logs near the equator described crimson lights reaching halfway to the zenith. Many people thought their cities had caught fire. Scientific instruments around the world, patiently recording minute changes in Earth's magnetism, suddenly shot off scale, and spurious electric currents surged into the world's telegraph systems. In Baltimore telegraph operators laboured from 8 p.m. until 10 a.m. the next day to transmit a mere 400-word press report.

Just before noon the following Thursday, September 1, English astronomer Richard C. Carrington was sketching a curious group of sunspots—curious on account of the dark areas' enormous size. At 11:18 a.m. he witnessed an intense white light flash from two locations within the sunspot group. He called out in vain to anyone in the observatory to come see the brief five-minute spectacle, but solitary astronomers seldom have an audience to share their excitement. Seventeen hours later in the Americas a second wave of auroras turned night to day as far south as Panama. People could read the newspaper by their crimson and green light. Gold miners in the Rocky Mountains woke up and ate breakfast at 1 a.m., thinking the sun had risen on a cloudy day. Telegraph systems became unusable across Europe and North America." (Odenwald & Green, 2008)

Despite being spectacular, the Carrington event did not cause that much disturbance to human activities due to the low development of technology at the time. But the impacts of much more modest, but more recent storms suggest that it would have very severe consequences were it to happen today. Since it is the biggest geomagnetic storm observed in the 160-year record available, it is often considered for worst-case scenario simulations.

May 1921 solar storm

"At 7:04 a.m. on May 15, the entire signal and switching system of the New York Central Railroad below 125th street was put out of operation, followed by a fire in the control tower at 57th Street and Park Avenue. Railroad officials formally assigned blame for a fire destroyed the Central New England Railroad station, to the aurora. Telegraph Operator Hatch said that he was actually driven away from his telegraph instrument by a flame that enveloped his switchboard and ignited the entire building at a loss of $6,000. Overseas, in Sweden a telephone station was 'burned out', and the storm interfered with telephone, telegraph and cable traffic over most of Europe. Aurora were visible in the Eastern United States, with additional reports from Pasadena California where the aurora reached zenith." (Dorman et al., 2008)

March 1989 solar storm

"The 13-14 March 1989 geomagnetic storm is one of the most well-known for its effect on power systems. The storm reached -589 nT on the Dst scale, the strongest since standard storm strength indices were used in 1932. The size of the solar active region where the eruptions originated was one of the largest ever measured.

The geomagnetic storm struck around 3 a.m. Eastern Time on 13 March and collapsed the Hydro-Quebec power grid in less than two minutes. The resulting geomagnetically induced currents were severe enough that the harmonics tripped protective systems on several static VAR (volt-ampere reactive) compensators on the Hydro-Quebec grid, resulting in the loss of electric power to more than six million people for nine hours at an economic cost estimated to be around C$13.2 bn. Voltage oscillations caused more tripping of protective equipment, nearly bringing the Northeast Power Coordinating Council (NPCC) and the Mid-Atlantic Area Council (MAAC) down in a cascading collapse. Two transformers were damaged due to voltage overloads. The storm also caused permanent damage to a generator step-up transformer at a nuclear station in New Jersey owned by Public Service Gas & Electric, necessitating its removal from service." (LLoyd's & AER, 2013).

The March 1989 solar storm did not only affect Canada and the Northeastern part of the United States. It spanned over about 120 degrees of longitude and 5-10 degrees of latitude, damaging transformers as far as the UK (Aon Benfield, January 2013).

October 2003 "Halloween" storm

"In late October 2003, three large active regions were present on the solar surface. One of these was responsible for the majority of the flaring and eruptive activity during the 2003 storm events. Not only was the geomagnetic storm noteworthy, the solar proton event was the fourth largest in 25 years of records. The largest solar active region was responsible for the ~2000 km/s CMEs that triggered the geomagnetic storms of 29-31 October.

Minor power grid disturbances were experienced in North America, including a capacitor trip in the Northwest and transformer heating in the Northeast. Ground magnetic field fluctuations were stronger over Northern Europe, and Sweden experienced a blackout of less than an hour in length affecting around 50,000 customers. The blackout was attributed to the combination of harmonic distortions caused by geomagnetically induced currents and incorrectly set protective relay thresholds.

Perhaps the most surprising impact from this event was the twelve transformers in South Africa that suffered damage necessitating their removal from service. The low latitude of South Africa (~40 corrected geomagnetic latitude - roughly the same as the state of Florida) is usually assumed to be immune from surface electric fields strong enough to cause transformer internal heating." (LLoyd's & AER, 2013)

5 Factors influencing the impact of solar storms on power grids

Many factors govern the severity of the impact of a solar storm on power grids.

Factors related to the severity of the storm

- **The intensity of the CME** itself (e.g. the quantity of particles ejected from the Sun, their speed and the intensity of the magnetic field within the plasma cloud).
- **The direction of the CME**: depending on the direction towards which the charged particles are ejected, the CME will hit, skim past or miss the Earth.
- **The orientation of the magnetic field within the CME**: if the magnetic field formed by the charged particles within the CME has the opposite orientation to that of the geomagnetic field, the distortion of the magnetosphere will be much higher than if it has the same orientation. Scientists say that the "geoeffectiveness" of the CME is higher.
- **The impact of previous CMEs**: when a CME hits the magnetosphere, it changes its shape in a way that can make it more vulnerable to subsequent CMEs. Indeed the magnetosphere, after being hit by a CME, does not oppose the same barrier to following ones, and it might take a few days before it recovers its original shape. A second or third CME might therefore create greater geomagnetic disturbances than the first, even though they might be less powerful.

Factors related to the vulnerability of a given area to solar storms in terms of the creation of high electric potential gradients in the ground

- **The latitude**: auroral ovals tend to be centred around the geomagnetic poles[2], and thus more frequent and more intense at high geomagnetic latitudes.

[2] In April 2007 a French-Canadian team found the position of the North geomagnetic pole to be 83.95°N, 121.02°W, i.e. 800 km north-west to the island of Ellesmere in the North of Canada. The North geomagnetic pole currently drifts towards Siberia at a speed of about 55km per year. If it holds this speed, it could reach Siberia by 2040 (Chulliat).

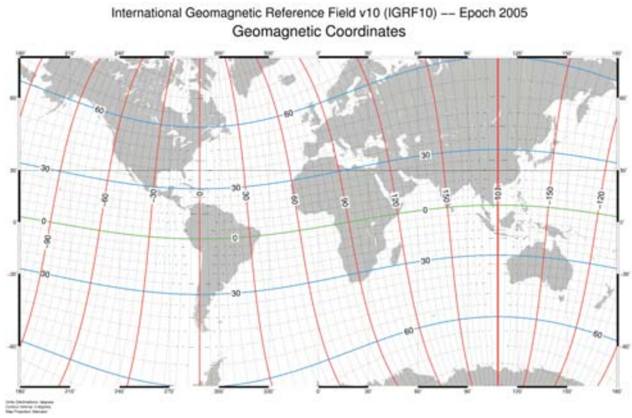


Figure 9 Map of geomagnetic coordinates (National Oceanic and Atmospheric Administration, 2010)

Since the North geomagnetic pole is located to the north of Canada, geomagnetic latitudes are higher in North America than they are in Europe for the same geographic latitude, implying more risk in North America, all else being equal. Maps of geomagnetic coordinates illustrate this. However, the failure of a dozen transformers in South Africa during the 2003 "Halloween" storm bears testimony to the fact that regions situated at a relatively low geomagnetic altitude can be vulnerable to solar storms too. One also has to recall that a massive CME such as the one responsible for the Carrington event would create auroral ovals with a very large diameter. During such an event, regions at relatively low geomagnetic latitudes would find themselves at the vertical of these ovals and would experience high geomagnetic disturbances.

- **The conductivity of the ground**: the more conductive the ground, the easier it is for currents to flow and thus reduce the differences of electrical potential between two points. Conversely, the less conductive the ground, the greater the differences of electrical potential between two earthed transformers linked by a transmission line, and the more intense the GIC in that line. As a result of variations in ground conductivity, relative risks may differ significantly.

Figure 10 Relative risk from strong electric field fluctuations in the US and Canada based on ground conductivity models. Red and blue represent the highest and lowest risk regions respectively (LLoyd's & AER, 2013)

- **The length of transmission lines**: the longer a line, the higher the difference of electric potential at the ground between its two endpoints.
- **The conductivity of transmission lines**: the more conductive a transmission line, the more intense the GICs in that line.
- **The orientation of transmission lines**: GICs tend to be slightly more intense along east-west lines. But this factor is usually considered not very significant (Pirjola, July 2013).
- **The relative position of the transformers within the grid**: GICs are more intense at corners and the end of a grid (Pirjola, July 2013).
- **The design of the transformers**:
  - o One-phase transformers are more vulnerable than three-phase transformers, since GICs flowing through three-phase transformers are split between all phases, resulting in a reduction of their intensity (Sabot, 2004).
  - o Old generation transformers are usually more vulnerable than new ones. In particular, in the United States experts tend to distinguish between transformers built before and after 1972 (LLoyd's & AER, 2013).
- **The number of transformers at a given node of the grid**: nodes with only one transformer are more vulnerable than nodes with multiple ones, since the failure of that single transformer would cause the failure of the entire node.

  Nodes with multiple transformers can still operate after the failure of one transformer, albeit possibly in a degraded mode. In this respect, step-up transformers (the ones connecting generating units to the grid) are likely to be more vulnerable because they would typically be single.
- **The design of the grid**: the more meshed the grid, the more resilient it is to the failure of transformers and even nodes, since the current can be brought to any point via multiple routes.
- **The degradation of transformers due to previous solar storms**: as shown by Moodley and Gaunt based on in-site tests on a transformer in South Africa, even mild solar storm events can degrade a transformer, up to a point where their cumulative effects may cause its failure (Moodley & Gaunt, 9-13 July 2012).

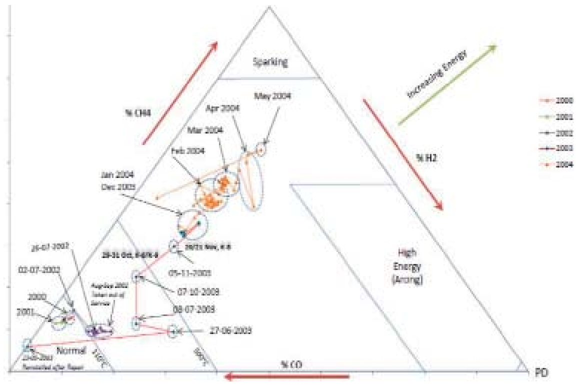


Figure 11 Progressive degradation of the insulation of a transformer following a series of geomagnetic storms

- **The prevention and mitigation measures taken**: see section 8.

Regions and grids most vulnerable to solar storms

Due to the multiplicity of these factors, it is not an easy task to assess which regions and which portions of power grids are the most vulnerable to solar storms.

Geomagnetic latitude is certainly an important factor. Its relevance is confirmed by real-life observations of the magnitude of GICs in the grids, as shown by results from the EURISGIC project.

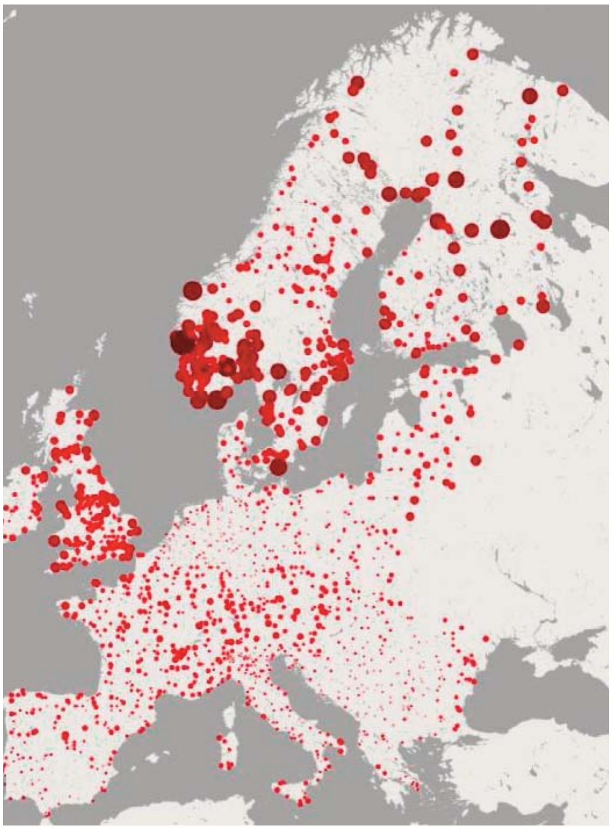


Figure 12 Largest GICs measured in Europe, 1996-2008 (source: EURISGIC project)

On this map, the circles illustrate the magnitude of the most severe GICs measured in the power grids during the period 1996-2008. The maximum GIC reached about 400 Amp and was measured in Norway. In Great Britain, the maximum was about 100 Amp. The correlation between geomagnetic latitude and GIC intensity appears quite clearly.

But geomagnetic latitude is not sufficient when assessing risks from solar storms.

As illustrated in Figure 10, the addition of only one other factor (ground conductivity) already leads to a very different picture. Putting in other factors leads to similarly surprising results.

Because of the "coast effect", simulations of GICs in the United States by AER show relatively high currents along the Gulf of Mexico, despite the low latitude of this part of the country.

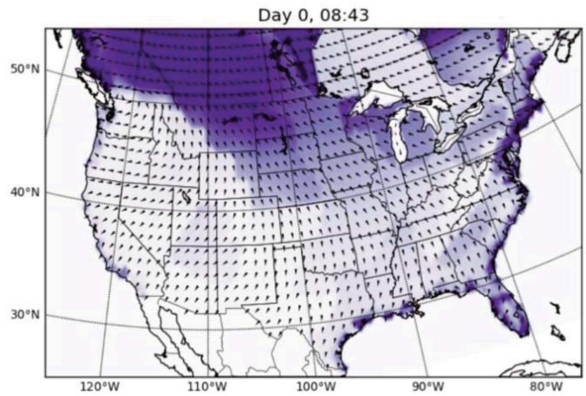


Figure 13 Electric field amplitudes and directions across the US at a single time step during a simulated Carrington storm. Regions shaded in dark purple are experiencing the strongest ground electric fields (LLoyd's & AER, 2013).

Similarly, the comparatively low resistivity of Chinese very high voltage transmission lines, combined with their length and east-west orientation, may result in intense GICs at a latitude as low as Hong Kong's. On 9-10 November 2004, a GIC of around 65 Amp was measured in the transformer neutral lead at the Ling'ao Nuclear Power Plant, although the geomagnetic storm was very weak (Pirjola, July 2013).

Lastly, the design of the grid as well as prevention and mitigation measures play a major role. Many experts believe that these factors make the United States, where old pre-1972 one-phase transformers are still used, more vulnerable than higher latitude Canada, where series capacitors have been installed in some parts of the grid.

Combining different factors, RTE, the French TSO, estimated in 2004 that the risk of damage to the power grid from solar storms was lower in France than in North America by two orders of magnitude (Sabot, 2004), for the following reasons:

- the geomagnetic latitude of France is currently lower
- ground conductivity is generally higher in France (reducing the difference in electrical potential between two points in the ground)
- distances between nodes of the grids are comparatively smaller
- the grid is highly meshed, facilitating the splitting of GICs into smaller currents

- transformers' neutrals are grounded via spires with some resistivity
- transformers are typically three-phase column transformers
- the setting of reactive power is different.

Another take-away from recent research is that the granularity of the analysis needs to be quite high when assessing the risk, which may vary significantly even at local level. Modelling the risk of power outage by county in the United States, AER identified that relative risk was ranging over a factor of 1000 (LLoyd's & AER, 2013).

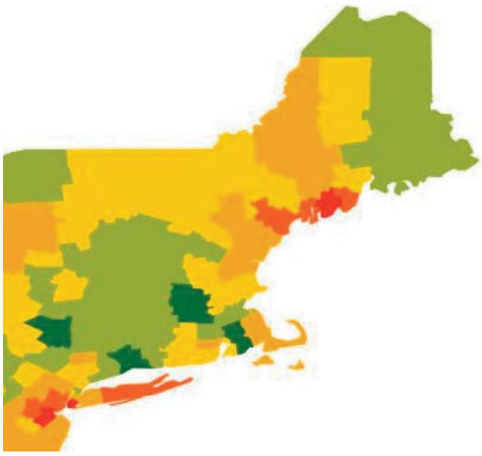


Figure 14 Relative risk of power outage by country in New England (LLoyd's & AER, 2013)

6 Impact of a Carrington-like solar storm

Solar storms have a proven ability to damage transformers, and even to provoke the failure of entire parts of a power grid, as demonstrated by the March 1989 event in Quebec.

Given the relatively modest intensity of the geomagnetic disturbances created by the March 1989 solar storm (– 589 nT/min, see section 4) compared to the intensity of the 1859 Carrington event (the UK National Grid and the BGS assume a 5000 nT/min rate of variation of the magnetic field for their Carrington-like scenario), many experts believe that a superstorm occurring today would provoke the collapse of large portions of power grids over a large area.

Moreover, contrary to most other types of outages, power blackouts caused by solar storms, if triggered by the destruction of transformers (as opposed to being triggered by the tripping of protective equipment), may last for an extended period of time. This is because transformers are essential to the functioning of power grids, and because damaged transformers could neither easily be repaired in situ or replaced by new ones. Indeed it takes several months to build a transformer (Office of Energy Delivery & Electric Reliability, June 2012), manufacturing capacities are limited to around 70 units per year (Aon Benfield, January 2013) and spare inventories are low.

6.1 The prolonged blackout scenarios

The vulnerability of modern societies to prolonged blackouts is very high. The CRO Forum, a group consisting of Chief Risk Officers from large multi-national insurance companies, published a report on this issue in November 2011:

"Electricity is the backbone of each industrialised society and economy. Modern countries are not used to having even short power blackouts. The increased dependency on continuous power supply related to electronics, industrial production, and daily life makes today's society much more vulnerable concerning power supply interruptions. A brownout (reduced voltage) of some minutes or a similar blackout (complete failure of electricity supply) may cause some inconvenience at home such as having the lights turn off. But a blackout of a few hours or even several days would have a significant impact on our daily life and the entire economy. Critical infrastructure such as communication and transport would be hampered, the heating and water supply would stop and production processes and trading would cease. Emergency services like fire, police or ambulance could not be called due to the breakdown of the telecommunication systems. Hospitals would only be able to work as long as the emergency power supply is supplied with fuel. Financial trading, cash machines and supermarkets would in turn have to close down, which would ultimately cause a catastrophic scenario. If the blackout were to spread across the border lines, which is more likely today due to the interconnection of power grids between different countries, the impacts would escalate as a function of the duration of the interruption […]."

Immediately after a blackout, it is not possible to purchase any goods without cash as no electronic payment is possible. The 2003 blackout illustrated that after 3 to 6 hours without power most fuel stations and the refineries had to close down, leaving the public without fuel for cars or backup generators as the pumps did not operate. Aluminium melting furnaces will already sustain irreversible physical damage after 4-5 hours without electricity. Governments have typically, however, implemented emergency fuel storages to keep most critical facilities alive for several weeks up to a month. After one month with no electrical power, water, transportation, emergency services, critical manufacturing, and chemical sectors can face widespread outages within the affected region. The loss of water systems due to a power outage leads to many cascading effects. Hospitals, schools, nursing homes, restaurants, and office buildings all rely on water to operate. Water is used for drinking, sanitation, and heating and cooling systems in those facilities. Many manufacturing operations either use water as an ingredient in their processes or rely on wastewater systems to remove and process their manufacturing waste. Fire fighters depend on water to carry out their emergency response, and access to safe water is necessary for providing mass care services and preventing the spread of disease. Without electricity most heating systems do not operate. During winter typical homes can cool to below freezing level within a few days. It must be expected that people will try to heat their homes using open fires, leading to many homes burning while there is no water for emergency response teams." (CRO Forum, November 2011).

In a January 2013 report, AON Benfield provided a mapping of potential consequences from the collapse of electricity grids due to a solar storm, showing serious disturbances in a matter of days (not to speak of weeks or months):

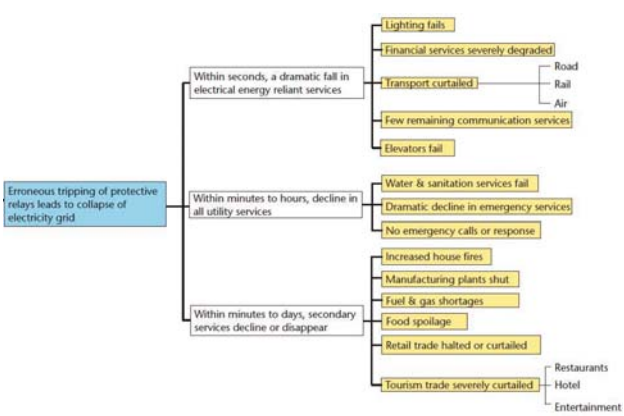


Figure 15 Some potential consequences of a repeat 1921 space weather event (extracted from AON Benfield, January 2013)

A number of studies and reports conclude that the occurrence of a Carrington-like solar storm in today's world would indeed result in a prolonged blackout affecting a significant area. Some of these studies also estimate the associated costs.

Estimating the economic costs that would result from severe blackouts caused by solar storms is a daunting task. It requires first an assessment of the characteristics of the blackout, second the identification of potential costs, and third the quantification of these costs.

Estimates of the costs of "business-as-usual" outages exist. For instance, it has been estimated that power outages in the US (on average, 9 hours of disruptions each year for every customer) generate at least $ 150 bn of economic losses each year (CRO Forum, November 2011). But the cascading effects of a prolonged outage lasting several weeks would be utterly different in nature, limiting the relevance of extrapolations.

In a 2004 report, the US National Academy of Sciences mentioned a scenario in which a repeat of the May 1921 solar storm, though significantly less severe than the Carrington event, would leave 130 million people without power in the US for an extended period of time, with economic costs skyrocketing to USD 2 trillion for the first four years and recovery taking up to ten years (Aon Benfield, January 2013).

In a 2010 report, Metatech, an engineering consulting firm, estimated that a 4800 nT/min geomagnetic storm could create a loss of over 70 percent of the electrical service of the United States.

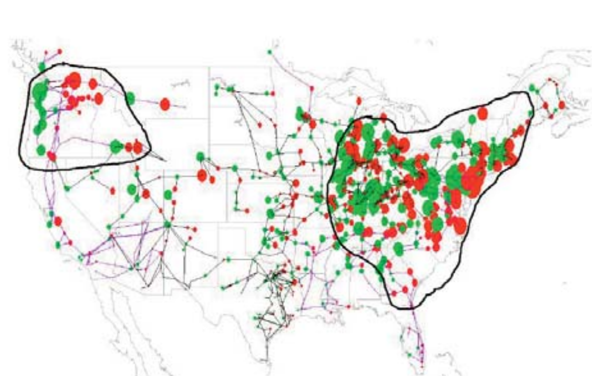


Figure 16 Regions susceptible to system collapse due to GIC disturbance in a 4 800 nT/min geomagnetic storm scenario (Kappenman, January 2010)

Assessing the age statistics on extra high voltage (EHV) transformers for approximately 20% of the U.S. Grid, Metatech found out that the weighted average age for installed EHV transformers in the ECAR region, Northeast of the United States, was greater than 30 years, out of an economic life of about 40 years. It concluded that in case of a 4 800 nT/min geomagnetic storm 20% to 76% of EHV transformers would experience GIC levels high enough to have the potential to cause their failure. This relatively wide range reflects differences according to voltage, as well as the uncertainty as to the minimum GIC intensity level that would put the transformers at risk (30 Amp per phase in the pessimistic scenario, 90 Amp per phase in the optimistic scenario). In addition, in the Northeastern region of the US around 30% of generation resources may be lost due to the failure of step-up transformers (Kappenman, January 2010). Such a system collapse in the US may take many years and trillions of dollars to restore (Royal Academy of Engineering, February 2013).

Another in-depth study conducted in 2013 by AER concludes that a Carrington-level storm would deprive between 20 and 40 million people of electricity in the US, with durations of 16 days to one to two years, with economic costs estimated at $0.6-2.6 trillion (LLoyd's & AER, 2013).

These various estimates of the economic costs of a Carrington-like (or May 1921-like) storm are high, even when compared to the most severe natural disasters experienced by the world over the past decades. For instance the costliest one on record, Hurricane Katrina, cost approximately USD 76bn[3] (Swiss Re sigma, 2013). This justifies the following recommendation.

Recommendation 1: Include solar storms in the list of emerging risks to be monitored by risk management. Designate an owner in the risk management team.

6.2 The "temporary local outages" scenarios

Other studies indicate more limited disruptions.

Modelling done for the UK National Grid suggests that a Carrington-like solar storm, calibrated to correspond to a rate of change of the geomagnetic field of 5000 nT/min, would only result in "temporary localized power interruptions" (National Grid, December 2012).

Around six super grid transformers in England and Wales and a further seven grid transformers in Scotland could be damaged and could fail. But sufficient transformer spares would be available, allowing for the replacement of the damaged transformers within 8 to 16 weeks. Most critically, most of these failures would not cause an outage, since most nodes have more than one transformer (see section 5). According to National Grid, only two nodes in Great Britain could experience disconnection, resulting in local blackouts lasting only a few hours (Royal Academy of Engineering, February 2013).

As far as the United States is concerned, the North American Electric Reliability Corporation (NERC) played down the risk of a prolonged blackout in a February 2012 report: "NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. Based on the results of this chapter, the most likely worst-case system impact from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support and simultaneous to a dramatic increase in reactive power demand […] Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Québec GMD-induced blackout" (NERC, February 2012).

6.3 Cost estimates from (re)insurers

Few estimates seem to exist in the (re)insurance industry. Swiss Re performed such simulations for two types of solar storms: a Carrington-like solar storm, and a less severe one inspired from the March 1989 event (Schneider R. , 5/6 September 2012).

The table below shows some of the assumptions made.

[3] This figure only includes insured losses.

	Carrington-like event	Less severe storm
%age of transformers damaged in the region	10%	3%
Duration of the total blackout	3 weeks	2 days for the region plus 8 weeks for a smaller area
%age of GDP affected in the region	10%	3% during 2 days (regional blackout) and 1% for 4 to 8 weeks (smaller area blackout)
Accumulation among regions	No accumulation among regions due to area and grid independency, except Europe	Europe mainly country impact, but accumulation due to grid connectivity possible
Time for GDP to recover after the end of the total blackout phase	Services: 4 weeks Production: 8 weeks	
GDP split	70% Services / 30% Production	

Table 4: Assumptions for estimating economic losses from solar storms (Schneider D. R., Prolonged Power Blackout, 5/6 September 2012)

The "less severe storm" scenario is also interesting because it is not that different from the scenario considered by the UK National Grid for a Carrington-like event.

According to this study from Swiss Re, economic losses for a Carrington-like event would range between $7.6 bn and $164 bn (worst-case for a Carrington-like event affecting the US and Canada).

Economic Loss in million dollars	Carrington-like event Best case	Carrington-like event Worst case	Less severe storm
US & Canada	128,808	163,866	
Scandinavia & UK	28,903	37,210	192
Germany, France, Italy, Switzerland, Austria	73,934	95,185	492
Accumulation Europe	102,837	132,395	
Japan	41,746	53,745	
Australia	7,617	9,806	

Table 5: Economic losses from solar storms (Schneider D. R., Prolonged Power Blackout, 5/6 September 2012)

6.4 An alternative scenario: the prolonged "brownout"

Standing halfway between prolonged blackout scenarios and scenarios in which grid operations can be restored quickly due to the lack of serious physical damage to transformers, the "prolonged brownout" scenario also has some likelihood[4].

In case of intense GICs caused by a Carrington-like CME, it is likely that a number of transformers would fail in a given area, but not all of them. The cascading effects of the failures of even a limited number of transformers, combined with the tripping of protective systems, may cause disruptions to the point of total collapse of a large portion of the grid, potentially spanning over several interconnected countries. In a worst-case scenario, going back to normality might indeed take weeks, or even months, due to the lack of spare transformers available. But it does not mechanically entail that the full blackout situation would last that long.

TSOs would probably manage to progressively restore the functioning of parts of the grid, first by carefully reoperating sections where transformers are not damaged, then by moving a few unimpaired transformers to the nodes where they would most badly be needed. Moving transformers might take several weeks, given their size and weight – typically 400 tonnes.

Thus, the initial full blackout would develop into a partial blackout (so-called "brownout"). It may be partial with respect to its geographical extension: not all areas would suffer the same. It may also be partial with respect to time: being unable to restore the full load to the grid due to failed transformers, public authorities and TSOs may decide to organize a "rotating" or "rolling" blackout whereby a given area would have an intermittent access to electricity. And it may be partial in the sense that the power available might be reduced.

Such a partial blackout, especially if it were to last for months, would still have severe consequences on the economy. But it would not create such chaos as a full blackout.

[4] Source: conversation with Charles Trevor Gaunt, Professor at the University of Cape Town, 16 July 2013. Errors are the sole responsibility of the author.

6.5 Building extreme scenarios

As for other low probability, high severity risks, (re)insurers may want or may be requested to build "extreme" scenarios involving solar storms. For instance, all syndicates operating at Lloyd's are asked to regularly assess their exposure to so-called "realistic disaster scenarios" (RDS) defined by Lloyd's. One of these RDS addresses the risks posed by solar storms to satellites.

As far as the risks to power grids are concerned, building a realistic scenario is difficult given the considerable divergence between, on the one hand, studies highlighting a serious risk of prolonged blackout with dire consequences reaching billions of dollars of costs, and on the other hand, studies concluding that the risk is limited to temporary local outages, even for a Carrington-like storm.

Considering two or three different scenarios illustrative of this wide spectrum, as Swiss Re did (see section 6.3), could be a reasonable – and instructive - thing to do for (re)insurers. A good place to start, before quantifying potential losses, would be to map their exposure and identify which insurance policies may be triggered in such an event.

Recommendation 2 : Map the exposure of (re)insured risks to solar storms. Build extreme scenarios corresponding to possible consequences of a major solar storm (ranging from temporary local outages to a prolonged blackout). If feasible, quantify these extreme scenarios.

7 Return period of a Carrington-like solar storm

Since risk can be defined as the product of severity by frequency, then the next question that arises after the cost of a Carrington-like solar storm is its frequency (or, equivalently, its return period). One of the difficulties is that geomagnetic data records only extend back 170 years. And the sole fact that the Carrington storm occurred 154 years ago is not sufficient for drawing conclusions. Interestingly enough, it is thought that a storm which reached the Earth in August 1972 would have been similar to the Carrington storm if the magnetic field within the CME had been pointing southwards, instead of northwards (Royal Academy of Engineering, February 2013), making it a near miss.

One can think of many different ways of estimating the return period of a Carrington-like storm.

Physical model of solar eruptions

Building a physical model of solar eruptions seems to be a natural way of assessing the probability of a Carrington-like CME to occur and be directed towards the Earth.

But scientists have not managed to do this to date due to the complexity of the task.

Ice cores studies

When high-energy protons emitted by solar storms[5] enter into the Earth's atmosphere, they generate reactions which produce nitrogen oxides that settle on the planet's surface and can be detected in ice cores. This method suggests that the Carrington storm was the most intense for the past 450 years, and possibly beyond (Marusek, 2007). But it does not give a clear answer to how likely a Carrington-like storm really is.

Extrapolation from smaller events

Applying a regression function to the severity/frequency curve of observed disturbances is a way of extrapolating severe geomagnetic disturbances from smaller events. Using this method, it was recently estimated that the probability of another Carrington event occurring within the next decade was around 12% (Riley, On the probability of occurrence of extreme space, 2012), corresponding to a return period of 79 years (Royal Academy of Engineering, February 2013).

[5] A solar storm large enough to include a CME would typically involve a solar flare as well as solar energetic particles.

In its February 2012 Special Reliability Assessment Interim Report, NERC cites a similar study by Pulkkinen et al. concluding to a one in 100-year peak electric field value of 20 V/km for Quebec based on extrapolation of lower values (NERC, February 2012).

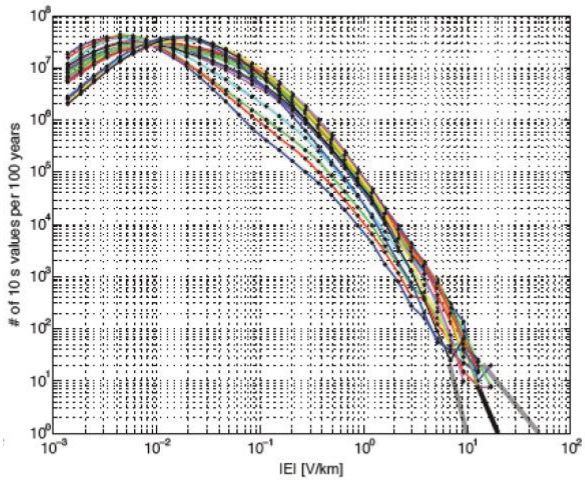


Figure 17 Statistical occurrence of the geoelectric field computed using the ground conductivity structure of Quebec. The thick black lines indicate approximate visual extrapolations of the statistics to 100-year peak magnitudes. The thick grey lines indicate the reasonable lower and upper boundaries for the extrapolated values (Pulkkinen, Bernabeu, & Eichner, 2012).

Use of historical records of visual observations of aurora borealis

AER used this last method, based on the collection of reports of significant aurora in the last 2 500 years or so, to assess the return period of a Carrington-like event (LLoyd's & AER, 2013). This method uses the fact that extreme geomagnetic storms generate a spectacular red aurora at unusually low magnetic latitudes.

Thus, according to AER, the fact that seven 'aurora-like torch' sightings were observed over Greece, Italy, and southern Gaul between 371 and 17 BC suggests a return period of 50 years or less for Quebec-level and greater storms. Using East Asian reports from the period 1137-1648 AD and Arabian reports from the period 817 AD to 1570 AD, it is estimated that "the mid-point for the return period of a Carrington-level is 150 years, with a reasonable range of 100 - 250 years".

The one in 200-year return period solar storm – Consequences for internal models

Risk-based prudential regulations typically ask (re)insurers to hold enough capital to be able to face losses with a return period below a certain threshold. In particular, (re)insurers using internal models need to assess their exposure to corresponding risks.

In Europe, Solvency 2 refers to a 200-year return period. Hence the emerging question among (re)insurance experts as to whether the return period of a Carrington-like storm is less or more than 200 years. Science does not seem to be able to provide a clear-cut answer to this question. It can only be said that various studies conclude to return periods in this range or even below. But it is important to keep in mind the chart on Figure 17: assuming one can extrapolate very large storms from milder ones (which amounts to assuming that the physics of very large solar storms is not different from the physics of "normal" solar storms), the severity/frequency curve of solar storms is a continuous line. This means that the notion of a one in 200-year solar storm exists. Such a storm may be more or less severe than the 1859 Carrington storm. But its severity is arguably of a similar order of magnitude.

Therefore the question for (re)insurers is not "Is the return period of a Carrington-type solar storm above or below 200 years?", but "What would a one in 200-year solar storm look like, and what would its effects be?". As far as power grids are concerned, trying to answer the latter question arguably comes down to choosing between the "prolonged blackout" scenario favoured by some studies (see section 6.1) and the much milder "temporary local outages" scenarios favoured by other studies (see section 6.2).

Recommendation 3 : Prepare for the fact that in the future supervisors may ask reinsurance companies to consider a one in 200-year solar storm as part of Solvency 2-compliant internal models. Engage in a dialogue with modelling firms on this issue.
Anticipate the need to choose between the "prolonged blackout" scenario and the "temporary local outages" scenario.

8 Mitigation measures

Mitigation measures exist in order to minimize the impact of solar storms on power grids.

Section 8.1 contains a list of 'long-term' measures that can be taken at any time to reduce the vulnerability of power grids, irrespective of any specific solar storm event.

Section 8.2 describes the 'emergency' actions that can be taken in response to a specific event.

8.1 Long-term measures to reduce the vulnerability of power grids – importance of modelling tools

8.1.1 List of long-term measures

- **Replace transformers with more resilient ones.** As mentioned in section 5, all transformers are not as vulnerable to GICs. New transformers tend to be better designed than old ones, three-phase transformers with a three-limb core tend to be more resilient than one-phase transformers, etc. But the cost of a transformer, typically USD 10m (CRO Forum, November 2011) makes it a rather costly solution for TSOs and generating companies, except if it is part of a wider plan to replace transformers for other reasons. Since 1997, network transformers installed by National Grid in the UK have been three phase with a three-limb core (Royal Academy of Engineering, February 2013).

- **Increase spare holdings**. This is less costly than the previous option, since the number of spare transformers to buy would be lower than the total number of transformers in the grid. But it is no panacea. All transformers are not alike and there may be compatibility issues. Moreover, transporting and installing transformers typically weighing 400 tonnes is in any case challenging, and may require weeks or even months (Office of Energy Delivery & Electric Reliability, June 2012). Nonetheless, National Grid, which mentions a maximum replacement time of 16 weeks (National Grid, December 2012), recently decided to increase its spares holding following the reassessment in 2011 of the extreme space weather risk (National Grid, July 2013).

- **Fit devices in order to block the propagation of DC currents in the grid**. Resistors can be put in the neutrals of transformers, as is the case in Finland (Sabot, 2004), with seemingly good results judging by the absence of serious solar storm-induced disturbances to the grid of that country in spite of its high geomagnetic latitude. Transmission-line series capacitors can also be installed in the grid. Following the March 1989 blackout, Hydro-Quebec took such measures at a total cost of over $ 1.2 billion (Zurich Insurance Group, August 2010). Such devices may have their own drawbacks though. In particular, when positioned at certain locations of the grid to protect certain transformers, they may have the unintended effect of redirecting GICs towards other transformers and making them more vulnerable. Nevertheless, they are often considered as attractive options, notably because they are far less expensive than the previous ones.

- **Adjust protection systems against harmonics in order to avoid unnecessary tripping**. This is important because these unnecessary trippings pose as big a risk of grid collapse in case of a solar storm as do transformer failures.

Such a list of long-term measures that generating companies and TSOs can take can be found in the Industry Advisory issued by the North American Electric Reliability Corporation (NERC) in May 2011 (see section 9.2 for more details).

Recommendation 4 : When underwriting insurance policies covering generating companies or TSOs in countries above a certain geomagnetic latitude, check that they have taken measures to reduce their vulnerability to solar storms. The Industry Advisory issued by NERC in May 2011 seems a good place to start a dialogue on possible measures.

8.1.2 Modelling tools

Given the cost or potential negative side-effects of these options, they should not be deployed in an indiscriminate way. Hence the importance of being able to model the impact of solar storms on the generation of GICs in power grids, for instance in order to identify vulnerability hotspots and focus on them. Such models have already been built, or are in the process of being built, by academics or service providers.

The British Geological Survey has developed such a model for the UK. Given an assumed anomalous variation pattern of the magnetic field, this tool, using ground conductivity maps, simulates electric fields in the ground. Applying these electric fields to a simplified model of the UK grid (provided by National Grid and including 701 transformers, with data related to transformer, earthing and line resistances), the BGS was able to produce simulations of GIC intensity in that grid for a Carrington-like event.

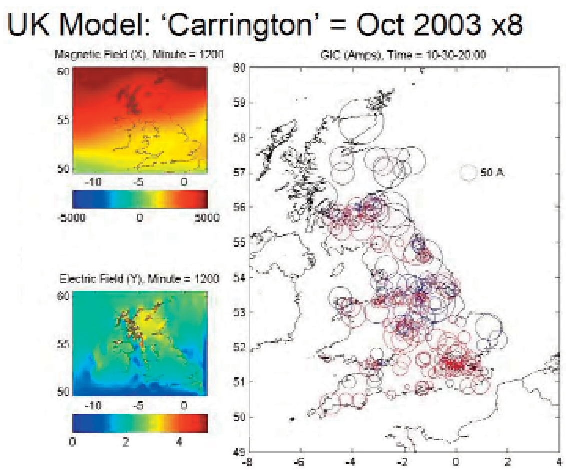


Figure 18 Simulation of GIC intensity in the UK grid for a Carrington-like event (Thomson, July 2013)

AER have built another model for North America. Using assumptions on the resilience of transformers in that region, they have produced quite detailed outage scenarios (LLoyd's & AER, 2013). These scenarios are precisely the ones they have used to estimate the population affected by a Carrington-like storm in the US and the associated costs (see section 6.1).

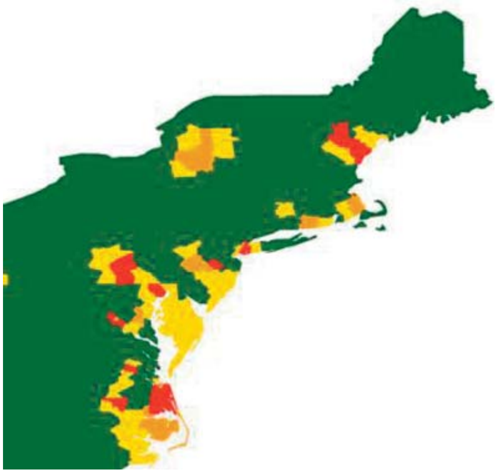


Figure 19 Fraction of EHV transformers damaged by county during an extreme geomagnetic storm scenario. Red and orange are likely to be without power. Yellow is uncertain. Green would be very likely to have power (LLoyd's & AER, 2013).

In order to calibrate these models, grid operators of course need to put sensors in place which are able to measure real GICs.

> ***Recommendation 5 : When underwriting insurance policies covering generating companies or TSOs in countries above a certain geomagnetic latitude, check whether they have developed modelling tools in order to assess the impact of solar storms on the generation of GICs in the grid.***

8.2 Emergency mitigation measures – importance of forecasting capabilities

8.2.1 Solar storm forecasts

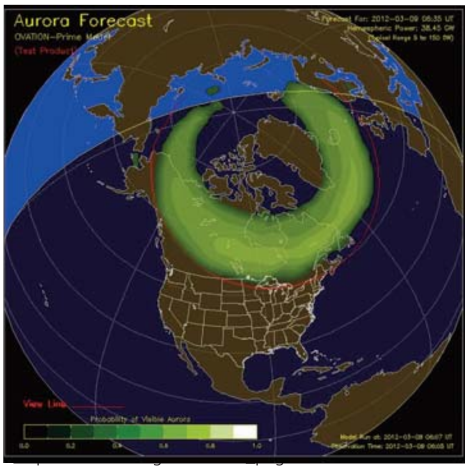
When a coronal mass is ejected from the surface of the Sun, the cloud of charged particles typically reaches the Earth after one to four days (see section 1). The image of this ejection is available much sooner though, since it only takes eight minutes for the light to cover the distance between the Sun and the Earth.

Images of the Sun's surface are available thanks to a series of observation satellites, notably SOHO, STEREO A, STEREO B and ACE. The STEREO satellites, located on opposite sides of the Sun, are particularly helpful since, as portended by their name, they provide a "stereo" vision of a CME which makes it easier to track its direction and speed, and ultimately predict whether it will hurt the Earth or not.

ACE (Advanced Composition Explorer) is critical too. Located at the so-called Lagrangian point L1, where the Sun's gravitational pull and that of the Earth cancel each other out, it has the ability to give more information on the CME when it is itself hit by the storm. In particular, it can tell which way its magnetic field is pointing, a crucial piece of information for assessing the severity of the geomagnetic disturbances that the CME will generate.

ACE is 1.5 million kilometres from the Earth. Therefore, depending on its speed, the storm might reach the Earth as quickly as 15 to 30 minutes after reaching ACE (Royal Academy of Engineering, February 2013), making it difficult to react and take appropriate actions in the meantime. The Sunjammer Project[6], which involves a solar sail propelled satellite, could make it possible to get this information a bit sooner, but it has not been fully committed yet.

Thanks to these satellites, agencies such as the Space Weather Prediction Center (SWPC) of the National Oceanographic and Atmospheric Administration (NOAA) are able to produce and broadcast solar storm forecasts.



il_overview.html

Figure 20 Aurora forecast for 9 March 2012 (source: NOAA)

Recommendation 6 : Draw the attention of governments to the importance of maintaining current observation and forecasting capabilities (which implies replacing satellites such as ACE when their service time expires) and improving them (such as with the Sunjammer project).

To take a real-life example, the UK National Grid was warned on 15 February that a CME would hit the Earth on 17 or 18 February, with an uncertainty as to the precise timing of + or – 6 hours. On 18 February 2011 ACE measured that the magnetic field of the CME was headed North, suggesting a low risk. A few minutes later, magnetometers recorded modest disturbances (Rogers, July 2013).

Recommendation 7 : When underwriting insurance policies covering generating companies or TSOs in countries above a certain geomagnetic latitude, check that they receive and check space weather forecasts.

8.2.2 Mitigation measures when a CME comes

Solar storm forecasts only bring value if mitigation actions are taken when a big storm is spotted to be on its way to hit the Earth.

Some TSOs' have indeed developed operational procedures to cope with such events.

This is the case of the UK National Grid. On top of receiving forecasts, it has put in place real-time monitoring systems of GICs flowing through the grid. Similar monitoring systems have been installed in a number of other grids, including in North America with the Sunburst project led by the Electric Power Research Institute.

Figure 21 Real-time monitoring of GICs by National Grid (Rogers, July 2013)

Based on these forecasts and real-time monitoring, the operational mitigation strategy of National Grid involves the following actions, which are aimed at making the grid as resilient as possible when the storm arrives (Rogers, July 2013):

- all circuits returned to service and switched in
- all supergrid transformers connected in order to spread the load
- substations run solid in order to maximise the connectivity of the grid
- extra generation instructed to synchronise
- extra reactive support made available to compensate for the increased reactive power consumption of transformers.

Shutting down the whole or parts of the grid is sometimes cited by experts as a serious option to consider in case of a Carrington-like storm, the rationale being that it is better to be deprived of electricity for a few hours than to be left without it for weeks or months. But it does not seem that the TSOs' operational procedures consider such drastic options as of today.

Some TSOs' hold internal exercises to test their operational procedures. National Grid has carried out such exercises three times, with an event calibrated to lie between the March 1989 storm and the Carrington storm in severity. "This has been used to practise procedures, increase awareness of space weather effects among control room staff, test communication channels and improve business procedures" (National Grid, July 2013).

It is worth noting that the Industry Advisory issued by NERC in May 2011 and already mentioned in section 8.1 contains a list of possible actions to include in operational procedures.

Recommendation 8 : When underwriting insurance policies covering generating companies or TSOs in countries above a certain geomagnetic latitude, check that they have operational procedures in place in case a major solar storm should approach the Earth. The Industry Advisory issued by NERC in May 2011 seems a good place to start a dialogue on the content of these operational procedures.

8.3 Current research efforts

It is clear that the improvement of modelling and forecasting tools is essential in order to tackle the risk from solar storms in the most efficient and cost-effective way.

At EU level, an ambitious research project called EURISGIC and funded under the European Community's Seventh Framework Programme is currently under way.

The goals of this project are the following[7]:

- produce the first European-wide real-time prototype forecast service of GIC in power systems, based on in-situ solar wind observations and comprehensive simulations of the Earth's magnetosphere,
- produce the first map of the statistical risk of large GIC throughout Europe,
- investigate worst-case GIC scenarios in terms of destruction of transformers and risk to power grids, based on historical data. The results of this study will help in the future design of more robust and secure protection against GIC in power transmission grids in Europe.

In the US, the Solar Shield project aims at developing GIC prediction models based on solar wind observations and magnetospheric magnetohydrodynamic simulations (NERC, February 2012).

Recommendation 9 : Draw the attention of governments to the importance of funding research aiming at better modelling of solar activity, the occurrence of CMEs, their interactions with the magnetosphere and the creation of GICs.

Recommendation 10 : Monitor new results coming out of ongoing research (notably the EURISGIC project).

[7] Source: http://www.eurisgic.eu

9 Public authorities' awareness

9.1 Governments

While the scientific community, space agencies and some TSOs are well aware of solar storms and the threat they pose to power grids, this issue has not traditionally stood high on the agenda of governments and regulators.

At EU level, the Council Directive 2008/114/EC on critical infrastructures identifies power networks as European critical infrastructures whose disruption or destruction would have a significant impact on at least two member states. But up to now this has not led to any concrete actions in terms of increasing the resilience of European power grids to solar storms.

The British government recently made a noticeable move towards recognizing solar storms as a serious risk. In the mid-2000s, it put in place a risk management process whereby the most significant emergencies that the UK and its citizens could face over the next five years are monitored. The public version of the findings is published under the name 'National Risk Register' (NRR).

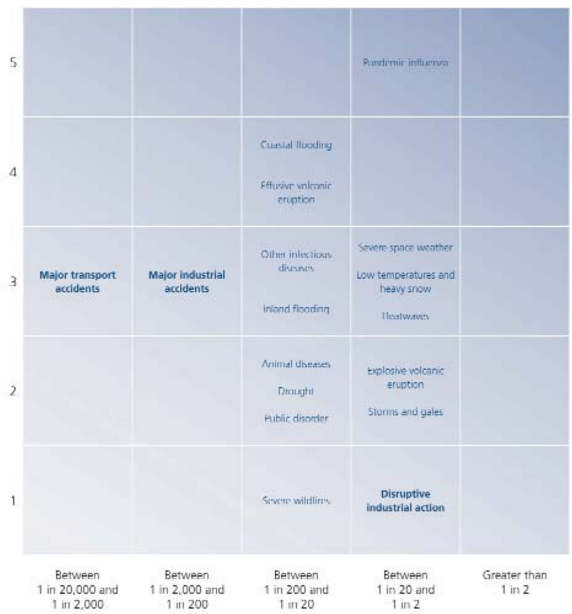


Figure 22 Risks of natural hazards and major accidents as per the UK National Risk Register (UK Cabinet Office, 2012)

Interestingly enough, the first version of the NRR, published in 2008, did not mention space weather as a risk. But the January 2012 update does, and puts it in a quite high position with respect to likelihood and impact.

9.2 Regulators

In the United States, where several studies have outlined the risk of a severe prolonged power blackout causing extensive economic damage (see section 6.1), the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) are taking solar storms seriously. Working groups have been put in place and comprehensive reliability assessments have been produced, notably in February 2012 (NERC, February 2012).

In terms of actions taken, a grid Reliability Standard issued in 2005 provides that "Each Reliability Coordinator shall ensure its Transmission Operators and Balancing Authorities are aware of Geo-Magnetic Disturbance (GMD) forecast information and assist as needed in the development of any required response plans".

In May 2011, NERC issued an Industry Advisory in order to "provide the industry with a set of operational and planning actions to prepare for the effects of severe Geo-Magnetic Disturbances on the bulk power system" (NERC, May 2011). This document lists a series of actions that grid operators may want to take either as a response to an immediate threat from a solar storm or as long-term actions to prepare for the risk of future occurrences.

On 16 May 2013, the Federal Energy Regulatory Commission (FERC), an independent agency which regulates the interstate transmission of electricity and protects the reliability of the high voltage interstate transmission system through mandatory reliability standards, went one step further by issuing a rule. This rule "directs NERC to submit to the Commission for approval proposed Reliability Standards […]. The Commission directs NERC to implement the directive in two stages:

- In the first stage, NERC must submit, within six months of the effective date of this Final Rule, one or more Reliability Standards that require owners and operators of the Bulk-Power System to develop and implement operational procedures to mitigate the effects of GMDs […].
- In the second stage, NERC must submit, within 18 months of the effective date of this Final Rule, one or more Reliability Standards that require owners and operators of the Bulk-Power System to conduct initial and on-going assessments of the potential impact of benchmark GMD events on Bulk-Power System equipment and the Bulk-Power System as a whole […]. If the assessments identify potential impacts from benchmark GMD events, the Reliability Standards should require owners and operators to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the Bulk-Power System […]. The development of this plan cannot be limited to considering operational procedures or enhanced training alone, but will […] contain strategies for protecting against the potential impact of GMDs […]. These strategies could, for example, include automatically blocking geomagnetically induced currents from entering the Bulk-Power System, instituting specification requirements for new equipment, inventory management, isolating certain equipment that is not cost effective to retrofit, or a combination thereof." (FERC, May 16, 2013)

This rule is important because it is mandatory and requires both operational mitigation procedures in case a solar storm should occur and permanent protection measures. Moreover, the requirement for owners and operators of the Bulk-Power System to conduct assessments of the potential impact of GMDs should give a boost to the development of models.

The real effects of the rule will not be felt immediately though. First, NERC will have to draft and submit the Reliability Standards. Only then will owners and operators have to comply. The way in which the Standards will be effectively enforced will be a test of the seriousness with which regulators want to tackle this issue.

Recommendation 11 : When underwriting insurance policies covering generating companies or TSOs:
- in the US, as soon as NERC Reliability Standards are applicable, make sure that coverage is subject to the respect of these standards by operators.
- in other countries located above a certain geomagnetic latitude, promote the application of these standards by operators even though they do not legally apply.

Recommendation 12 : Promote awareness of solar storms by non-US governments and power grid regulators of countries above a certain geomagnetic latitude. Promote the inclusion of risks from solar storms in grid reliability standards. The Industry Advisory issued by NERC in May 2011 and future NERC Reliability Standards seem a good place to start a dialogue.

10 Impact of a major solar storm on insurance policies

Were a solar storm to generate large economic costs, (re)insurers would most likely incur significant losses. In spite of the damage caused by recent events such as the 1989 and 2003 'Halloween' storms though, very few insurance policies currently mention solar storms[8].

This was highlighted by Aon Benfield in a recent January 2013 report: "mainstream (re)insurance professionals are unlikely to be able to accurately price this risk, offer coverage or issue exclusions […] Insurance policies and reinsurance treaties are likely to contain the legal triggers for liability in the event of the catastrophic failure of electricity distribution […]. However, these contracts are unlikely to have been drafted with any degree of consideration for a loss occurrence of the type initiated by extreme solar weather" (AON Benfield, January 2013).

Consequently:

- Solar storms would arguably be covered by 'all risks' policies, given the absence of any exclusion clause.
- Solar storms would arguably not be covered by 'named perils' policies, given the absence of any inclusion clause, unless they indirectly provoke one of the perils named in the contract (fire, explosions, etc.).

This section attempts to review potential impacts from solar storms on various insurance policies covering generating companies and TSOs, as well as electricity consumers, both large corporate and retail. It does not address the case of nuclear power plants, which are usually covered under specific insurance policies and schemes.

10.1 Property insurance

Property insurance policies may be triggered by a major solar storm. In that case they may cover:

- physical damage incurred by the insured
- business interruption caused by such damage
- business interruption caused by physical damage incurred by a supplier/service provider/client

In all cases, someone needs to incur physical damage for the policies to be activated. In this respect, it is interesting to keep in mind that, as mentioned in section 3, a major blackout could happen without being caused by property damage to the grid: the loss of reactive power or the tripping of protective equipment may result in a partial or full collapse before transformers suffer from overheating.

10.1.1 Physical damage incurred by the insured

Generating companies/TSOs
A major solar storm could damage transformers up to the point of failure, if the grid does not collapse before. The destruction of a transformer would be indemnified by the property cover of the owner: generating company or TSO.

As mentioned in section 8.1, the typical cost of a transformer is USD 10 million. The overall cost would depend upon the number of transformers affected: around 13 for the UK in National Grid's simulations of a Carrington scenario (Royal Academy of Engineering, February 2013), and many more in more pessimistic studies.

As explained in section 3, damage to transformers would most probably extend beyond the ones which would have failed: many transformers would be partially damaged. After a major event, it is likely that public

[8] The author has only found one recent insurance policy for a Telecom operator in the Middle East, containing the following exclusion: "Excluding loss/damage due to solar disturbances viz, solar tsunami".

authorities would stiffen their requirements towards generating companies and TSOs and would ask for the repair or replacement of partially damaged transformers. The owners of these transformers would most certainly turn to their insurers and present them with corresponding claims. The number of such transformers may be significantly higher than the number of failed transformers, bringing costs upwards.

Large corporate
A power outage, especially if prolonged, may cause physical damage to large corporate clients. This is the case for manufacturers using certain types of processes. For instance, aluminium melting furnaces will already sustain irreversible physical damage after 4-5 hours without electricity (CRO Forum, November 2011).

The blackout experienced by large portions of the Midwest and Northeast United States and Ontario, Canada in August 2003, although not provoked by a solar storm, is an interesting precedent. Although it 'only' lasted up to four days, it caused physical damage in several plants (CRO Forum, November 2011):

- in six Daimler Chrysler plants, which were assembly plants with paint shops, 10,000 vehicles had to be scrapped because they were moving through the paint shop at the time of the outage,
- at Ford's casting plant in Brook Park, Ohio, the outage caused molten metal to cool and solidify inside one of the plant's furnaces,
- at Marathon Oil Corporation's Marathon Ashland refinery about 10 miles south of Detroit, the blackout was responsible for triggering emergency shutdown procedures which caused a small explosion and the release of chemicals.

Property insurance policies would typically cover such damage.

For some plants, potential damage are so high that the setting up of specific operational procedures to follow when a big solar storm is about to hit the Earth could make sense. Such procedures already exist when a hurricane is forecasted: manufacturers likely to suddenly lose power because of the hurricane put their plants in safety mode and even stop production in an orderly way, in order not to run the risk of irremediable damage.

The same could be envisaged for solar storms: manufacturers with potential losses above a given threshold could put such procedures in place and organize themselves so as to receive alerts (via their power supplier rather than directly from space weather centres) whenever a major solar storm is forecasted and may cause an outage.

Recommendation 13 : When underwriting property insurance covers for manufacturers with high potential physical damage in case of a prolonged power blackout, encourage them to liaise with their power supplier so that they receive an alert whenever a solar storm above a given intensity is forecasted and may cause an outage. Encourage them to set up operational procedures in order to cope with such exceptional situations.

Having such procedures in place would certainly help mitigate the consequences of a solar storm. If the procedure were not followed properly, there could be a discussion between the insurer and the insured as to whether or not the claim is due.

Retail
Due to a power blackout, retail electricity consumers may suffer from various kinds of physical damage: loss of food in freezers, frozen water pipes, etc. Traditional property covers may cover some of this damage.

10.1.2 Business interruption

If the insured suffered both physical damage and a loss of revenue due to this physical damage, this loss of revenue would fall under the 'business interruption' (BI) extension of its property cover, such an extension being widespread, not to say systematic, for large corporate insureds in developed countries.

Business interruption extensions typically include the following provisions:

- Waiting period (i.e. period of time which must pass before coverage begins): one to four weeks
- Deductible (i.e. amount of losses retained by the insured, generally combined with the waiting period): a few hundred thousand to millions of dollars.
- Indemnity period: 12 to 24 months

- Limit: generally shared with property damage (up to hundreds of millions or even billions of dollars).

Generating companies

For a generating unit to be cut off from the grid for a period longer than the waiting period stipulated by its insurance policy, it would generally take the step-up transformer that links it to the grid to fail. Indeed, if this transformer were intact, current from the generating unit would most certainly be able to flow through due to the meshed nature of the grid.

Step-up transformers linking generating units to the grid are sometimes owned by the generating company and sometimes by the TSO. But in most cases, the insurance policy of the generating company stipulates that its BI cover can be triggered even if the physical damage is incurred outside of its premises, provided that it is incurred by the transmission system less than 300 metres away (some policies mention a higher distance). Therefore the failure of the step-up transformer linking the generating unit to the grid would generally trigger its BI cover even though this transformer is not owned by the generating company.

The amount of the claim would correspond to the net loss of revenue of the generating company. This amount would partially depend on the spot price of electricity during the period when the power plant would not be able to operate. This spot price might behave unexpectedly given the circumstances, adding uncertainty to the amount of the claim.

TSOs

Similarly, TSOs not being able to transport power to end customers (large corporate or retail) because of physical damage to their own property could claim loss of revenue.

Contrary to generating companies, they are typically paid a fixed sum for each MWh they transport.

Large corporate

Physical damage directly suffered by large corporate electricity consumers (such as aluminium producers) may halt production for a certain period of time. If this period is longer than the waiting period stipulated by the insurance policy, BI covers could be triggered.

10.1.3 Service interruption / Contingent business interruption

In a severe solar storm-induced blackout scenario, many companies relying upon electricity for their operations would suffer from disruptions and loss of revenues, even if they don't incur physical damage themselves. Actually these companies, for which business interruption extensions would not be applicable, would most likely be far more numerous than those incurring physical damage.

In most cases these losses of revenues would be eligible for coverage under 'service interruption' extensions of property covers, which are also widespread, not to say systematic, for large corporate insureds in developed countries. As a matter of fact the purpose of these extensions is precisely to cover insureds against loss of revenues caused by the interruption of services such as power, gas or water supply.

Service interruption extensions generally include the same provisions as BI extensions in terms of waiting period, minimum combined deductible and indemnity period. However, the limit is typically 10% to 15% as high as the limit applicable to property and BI losses: if a large corporate client has a USD 500 million limit for property damage, it will typically have a USD 50 to 75 million limit for service interruption. In addition, insurers sometimes include a second waiting period clause stipulating that the service interruption cover can only be triggered if the service interruption itself lasts longer than, say, 48 hours, whatever the duration of the disruption of the operations of the insured. However, such clauses tend to be less frequent nowadays, in part due to the relatively soft market.

The waiting period parameter is important because a power outage will only trigger business interruption claims if the disruption to the operations of the insured extends beyond this period of time. This is a protective clause for the insurer, since 'common' power outages are usually quite short, making it unusual that their effects last that long. But for solar storm-induced blackouts, which may last for weeks or even months, the waiting period hurdle may be easily overcome.

In such a situation, insurers may face an 'accumulation' problem, with a large number of policies (virtually all policies including a service interruption extension in the area affected by the blackout) being triggered at the same time.

Recommendation 14 : monitor and manage the accumulation risk linked to service interruption extensions that would all be triggered simultaneously in case of a prolonged blackout scenario.

For some companies, the loss of revenues may be eligible to indemnification under a contingent business interruption (CBI) extension, rather than a service interruption extension. This may be the case for TSOs (respectively generating companies) losing revenues because of the failure of a transformer belonging to a generating company (respectively TSO).

However it is worth noting that:

- as far as generating companies are concerned, disconnection from the grid beyond the waiting period would most often be caused by physical damage to the step-up transformer linking it to the grid, making the loss of revenue eligible to classic BI cover rather than CBI (see section 10.1.2),
- as far as TSOs are concerned, the link between the failure of a given power plant and a loss of revenue may be difficult to establish, since a TSO is generally supplied by a variety of power plants which can be plugged in and out depending on conditions (notably the spot price).

In theory, claims could be compounded by a cascade of disruptions down the supply chain. To reduce this risk, insurers traditionally used to require the physical damage to be incurred by a direct supplier or customer. Given the ambiguity of that notion, which gave rise to diverging interpretations after the Tohoku earthquake and Thai floods in 2011, insurers now tend to make a distinction between named and unnamed suppliers/customers, with two different limits for each category. The limit applicable to unnamed suppliers/customers would typically be around half the limit applicable to named ones, the latter being typically 10% to 15% of the property damage limit (as for service interruption extensions).

Recommendation 15 : When assessing the risk of cascade triggering of CBI covers along supply chains, take prolonged blackout scenarios into account.

10.1.4 Insurance policy wording

Since the awareness about solar storms remains limited among risk managers, brokers, insurers and reinsurers, policy wording does not take this risk into account. This is a real source of uncertainty as to the triggering or not of insurance policies, all the more so since court decisions may bring their lot of surprises.

Notion of physical damage

(Suriano & Haas, 2012) mention a series of cases judged by US courts which illustrate the kind of interpretation issues that may arise when a major solar storm occurs, especially around the notion of 'physical damage'. They are summarized and discussed in this section.

As mentioned in section 10.1, the triggering of property covers, including BI / service interruption / CBI extensions, requires physical damage to be incurred (as far as service interruption and CBI extensions are concerned, this damage would not be incurred by the insured itself).

But an imprecise wording may cause the insurer to pay claims even if there is no such 'physical damage'. In the Ferraro v. North Country Insurance case, which followed the August 2003 power blackout in the US (approx. 50 million people were affected), the insurer failed to refer to 'physical damage' and only referred to 'damage'. The court pointed out "the failure of the insurer to define 'damage' as 'physical' damage in the wording of the policy", and followed the insured who argued that 'damage' included the 'impairment of usefulness' of the power companies' generating and delivery of power to customers.

Even if the policy wording specifically refers to 'physical damage', the insurer may have bad surprises. As a matter of fact some courts have had a broad interpretation of what 'physical damage' can be. In the Wakefern Food Corp. v. Liberty Mutual Fire Insurance Co. case, which also followed the August 2003 power blackout in the US, the appellate court ruled that, although the grid had collapsed as a result of protection measures, and had suffered no 'physical damage', the loss of function itself of the grid constituted such damage. Therefore the insured, a group of supermarkets, was right to present claims. The court insisted that any other interpretation would make the 'Services Away Extension' virtually worthless because the power grids were created in such a way as to avoid physical damage as described by the insurer. This case is of particular interest in light of solar storms, since as explained in section 3, many solar storms scenarios include the collapse of the grid before it incurs any physical damage.

Another case, *American Guaranty & Liability Insurance Co. v. Ingram Micro, Inc*., illustrates a similarly broad interpretation of the notion of 'physical damage', this time when incurred by insureds. In that case, Ingram's computer network had been rendered inoperable by a power outage. The court held that 'physical damage' cannot be restricted to "physical destruction or harm" to the computer network system, but includes "loss of access, loss of use, and loss of functionality."

A possible option for underwriters is to refer to 'direct physical damage', but ambiguities may persist even then. Replacing these terms with more comprehensive definitions may be the safest option, but it may appear impractical.

Notion of electricity supplier

It is apparent from section 10.1.3 that the simultaneous triggering of the service interruption extensions of commercial/industrial clients dependent upon electricity in a region affected by a prolonged blackout is one of the highest risks for insurers.

Hence the importance of the wording of these extensions. Typical wording refers to "the interruption of incoming services consisting of electricity […], by reason of direct physical loss or damage of the kind insured by this Policy to the facilities of the supplier of such service located within the Policy Territory that immediately prevents in whole or in part the delivery of such usable service". This raises the question of whether generating companies and TSOs would all be considered by a court as 'suppliers' of electricity. This is of particular importance for TSOs, which are likely to be the ones incurring physical damage on the grid.

For large industrial electricity consumers directly connected to the high-voltage transportation network, courts would probably consider that the TSO is indeed their supplier, all the more so since there would typically be a contractual relationship between them.

For smaller corporate electricity consumers with no contractual relationship with the TSO, there might be room for interpretation.

Recommendation 16 : Review insurance policy wording in light of the risk of prolonged power blackout caused by solar storms. In particular:
_ clarify the 'physical damage' requirement clause, especially with reference to a scenario where the grid would collapse without incurring any physical damage in the strict sense. Referring to 'direct physical damage' is a simple, though imperfect solution.
_ clarify the notion of 'supplier' in service interruption extensions: who is / who are the 'electricity supplier(s)' of the insured?

10.2 Liability insurance

A major solar storm could result in the impossibility for certain parties to perform their contractual obligations towards other parties, or even in damage caused by certain parties to other parties.

For instance, a TSO may not be able to fulfil its contractual obligation to transport electricity. By doing so, it may also inflict damage to a third party, such as an aluminium producer sustaining irreversible damage.

This raises the question of whether such parties would be held liable and their liability covers would be triggered.

At first glance, one could argue that a major solar storm would fall under the exception of 'force majeure'. As a matter of fact, such a phenomenon may be seen as an unforeseeable and extraordinary event beyond the reasonable control of anyone.

However, it does not seem possible to sweep aside any liability risk altogether.

Since the consequences on businesses and individuals of a serious and prolonged blackout may be very severe, there may be a search for liability. This would notably be the case if people were to die for lack of appropriate care or treatments due to the blackout.

Plaintiffs may try to show that the risks posed by solar storms to power grids were well known and that mitigation measures (see section 8.1) were available, with a cost/benefit ratio that would, in retrospect, look compelling.

They may challenge the idea that solar storms are unpredictable by pointing at existing space weather forecasts (see section 8.2.1), which make it possible to identify CMEs one to four days in advance, even though the danger cannot fully be assessed more than 15 to 30 minutes before a solar storm hits the Earth. They may point at deficiencies in operational procedures meant to react to such events. In the absence of any such procedure, they may use the fact that some TSOs such as the UK National Grid have put in place comprehensive procedures as a proof that they could/should have done the same.

Today, it seems that no binding standard or regulation applicable to power grid operators specifically addresses the risks from solar storms. In particular, the Advisory issued by NERC in May 2011 (see section 9.2) is not binding: "This NERC Advisory is not the same as a reliability standard, and your organization will not be subject to penalties for a failure to implement this Advisory" (NERC, February 2012). But the FERC rule mentioned in section 9.2 will change this situation. When the reliability standards are defined, failure by US operators to comply will most certainly lead to liability in case of the occurrence of a superstorm with heavy consequences. It is not clear whether such liability would extend to operators from outside the US. Although they would not be legally bound by these standards, they may be considered negligent for not having implemented them.

If generating companies or TSOs were held liable for a blackout, their liability covers could be triggered. However losses for (re)insurers would be limited by two factors. First, contrary to electricity consumers, the number of generating companies and TSOs in a given area is relatively small. Even if they were all held liable, losses shouldered by their (re)insurers would be capped by the limit per cover times the (small) number of insurance policies concerned. Second, liability insurance policies for generating companies and TSOs usually only cover liability arising from bodily injury, personal injury and property damage. Consequently, these policies would not cover business interruption losses suffered by industrial electricity consumers merely due to their inability to operate without electricity. They would only be triggered if the industrial electricity consumers suffered physical damage (as can be the case for aluminium producers for instance).

10.3 Wider impacts in the event of a prolonged blackout scenario

If a solar storm were to cause a prolonged blackout, indirect impacts would cause severe losses on top of the losses addressed by sections 10.1 and 10.2.

For instance, disruptions suffered by firefighting units (lack of fuel, lack of water) may reduce their capabilities, which may result in more destructive fires. After days or weeks of power outage, distressed populations may resort to looting.

For insurers, losses on the P&C liability side may be compounded by losses on the asset side. For instance, a prolonged blackout affecting the Northeastern part of the United States, such as described by some of the studies mentioned in section 6, would certainly affect stock markets. The insurance industry, which holds USD 24 trillion worth of investments, would be affected.

These wider impacts show that solar storms should not be the concern only of (re)insurers' underwriting power, BI or CBI/service interruption policies. If one gives faith to the prolonged blackout scenario supported by the studies mentioned in section 6.1, all (re)insurance companies would be heavily affected by a major solar storm. Consequently, the industry as a whole should engage with governments, power grid regulators, power generating companies and TSOs in order to raise awareness and promote concrete answers.

11 Awareness of the (re)insurance industry – summary of recommendations

11.1 A growing, but still limited awareness

Over the past few years, several reports on solar storms have been published by the (re)insurance industry players, showing their interest for this issue. These reports include, among others, the 2011 CRO Forum report on Power blackout risks (CRO Forum, November 2011), the 2012 Allianz Global Corporate and Specialty report on Space Risks (Allianz Global Corporate and Specialty, 2012), the 2010 and 2013 Lloyd's reports on space weather and on the solar storm risk to the North American electric grid (LLoyd's, 2010) (LLoyd's & AER, 2013), as well as the 2013 Aon Benfield report on geomagnetic storms (AON Benfield, January 2013).

However, as underlined by Aon Benfield in the latter report: "(re)insurance industry awareness of geomagnetic storms has grown in recent times, but accurate assessment of risk still remains in its infancy for all but a few niche sectors".

As already mentioned in section 10, "mainstream (re)insurance professionals are unlikely to be able to accurately price this risk, offer coverage or issue exclusions […] Insurance policies and reinsurance treaties are likely to contain the legal triggers for liability in the event of the catastrophic failure of electricity distribution […]. However, these contracts are unlikely to have been drafted with any degree of consideration for a loss occurrence of the type initiated by extreme solar weather" (AON Benfield, January 2013).

Aon Benfield gives a series of reasons for this situation:

- "The absence of a defining industry-wide loss occurrence from extreme solar weather that has triggered large scale economic and social disruption and recoveries on insurance policies.
- Most risk professionals lack an understanding of the technical complexities of the hazard and vulnerability of components of insured assets to geomagnetic storms.
- The continued dependence of the majority of direct and contingent business interruption contracts on the loss of use of property due to physical damage.
- The potentially exotic nature of recoveries, with material damage and replacement costs ultimately to be a very small component of total losses."

11.2 Possible actions for (re)insurance companies

This section consolidates the recommendations made in previous sections. Since this report focuses on the impact of solar storms to power grids, these recommendations do not specifically address other potential impacts. However some of them can be transposed to other risks (for instance, it seems prudent for (re)insurance companies underwriting satellite risks to enquire about the resilience of the satellites they insure to solar energetic particles that can be generated by solar storms even in the absence of a CME).

Risk management

- Include solar storms in the list of emerging risks to be monitored by risk management. Designate an owner in the risk management team.
- Map the exposure of (re)insured risks to solar storms. Build extreme scenarios corresponding to possible consequences of a major solar storm (ranging from temporary local outages to prolonged blackout). If feasible, quantify these extreme scenarios.
- Prepare for the fact that in the future supervisors may ask reinsurance companies to consider a one in 200-year solar storm as part of Solvency 2-compliant internal models. Engage in a dialogue with modelling firms on this issue. Anticipate the need to choose between the 'prolonged blackout' scenario and the 'temporary local outages' scenario.
- Monitor new results coming out of ongoing research (notably the EURISGIC project).

Underwriting

- When underwriting insurance policies covering generating companies or TSOs in countries above a certain geomagnetic latitude:
    - o Check that they have taken measures to reduce their vulnerability to solar storms. The Industry Advisory issued by NERC in May 2011 seems a good place to start a dialogue on possible measures.

- o Check whether they have developed modelling tools in order to assess the impact of solar storms on the generation of GICs
- o Check that they receive and check space weather forecasts.
- o Check that they have operational procedures in place in case a major solar storm should approach the Earth. The Industry Advisory issued by NERC in May 2011 seems a good place to start a dialogue on the content of these operational procedures.
- o In the US, as soon as NERC Reliability Standards are applicable, make sure that coverage is subject to the respect of these standards by operators. In other countries, promote the application of these standards by operators even though they do not legally apply.

- When underwriting property insurance covers for manufacturers with high potential physical damage in case of a prolonged power blackout, encourage them to liaise with their power supplier so that they receive an alert whenever a solar storm above a given intensity is forecasted and may cause an outage. Encourage them to set up operational procedures in order to cope with such exceptional situations.
- Monitor and manage the accumulation risk linked to service interruption extensions that would all be triggered simultaneously in case of a prolonged blackout scenario.
- When assessing the risk of cascade triggering of CBI covers along supply chains, take prolonged blackout scenarios into account.
- Review insurance policy wording in light of the risk of a prolonged power blackout caused by solar storms. In particular:
  - o clarify the 'physical damage' requirement clause, especially with reference to a scenario where the grid would collapse without incurring any physical damage in the strict sense. Referring to 'direct physical damage' is a simple, though imperfect solution,
  - o clarify the notion of 'supplier' in service interruption extensions: who is / who are the 'electricity supplier(s)' of the insured?

Governmental affairs

- Draw the attention of governments to the importance of maintaining current observation and forecasting capabilities (which implies replacing satellites such as ACE when their service time expires) and improving them (such as with the Sunjammer project).
- Draw the attention of governments to the importance of funding research aiming at better modelling solar activity, the occurrence of CMEs, their interactions with the magnetosphere and the creation of GICs.
- Promote awareness of solar storms by non-US governments and power grid regulators of countries above a certain geomagnetic latitude. Promote the inclusion of risks from solar storms in grid reliability standards. The Industry Advisory issued by NERC in May 2011 and future NERC Reliability Standards seem a good place to start a dialogue.

12 Glossary

AC	Alternative current
ACE	Advanced composition explorer
BGS	British geological survey
BI	Business interruption
CBI	Contingent business interruption
CME	Coronal mass ejection
CRO	Chief risk officer
DC	Direct current
Dst	Disturbance storm time
EHV	Extra high voltage
EURISGIC	European risk from geomagnetically induced currents
FERC	Federal energy regulatory commission
GIC	Geomagnetically induced current
GMD	Geomagnetic disturbances
GPS	Global positioning system
HF	High frequency
NASA	National aeronautics and space administration
NERC	North American electric reliability corporation
NOAA	National oceanic and atmospheric administration
NRR	National risk register
P&C	Property and casualty
RDS	Realistic disaster scenarios
RTE	Réseau de transport d'électricité
SOHO	Solar and heliospheric observatory
SPWC	Space weather prediction center
STEREO	Solar terrestrial relations observatory
TSO	Transmission system operator
VHF	Very high frequency
UV	Ultraviolet

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