Space Weather

The Sun emits bursts of electromagnetic radiation and energetic particles causing utility outages and damage to infrastructure in the United States, resulting in direct economic losses greater than $1 billion.[1]

Data Summary

In the following table, note that the low and high likelihoods do **not** correspond to the low and high impacts. Low and high impacts are correlated between the fatalities, injuries and illnesses, direct economic loss, and (for low estimates) social displacement. The high estimate of social displacement represents a subset of the high estimate scenario on other impact scales. For environmental impacts, the best estimate corresponds to the low and the second best to the high estimates respectively on other impact scales.

Category	Description	Metric	Low	Best[2]	High
Health and Safety	Fatalities	Number of Fatalities	90[3]	N/A[2]	2,000[4]
	Injuries and Illnesses	Number of Injuries or Illnesses	400[5]	N/A[2]	10,000[6]
Economic	Direct Economic Loss	U.S. Dollars	$5.7 Billion[7]	N/A[2]	$2 Trillion[8]
Social	Social Displacement	People Displaced from Home ≥ 2 Days	0	N/A[2]	40 million[9]
Psychological	Psychological Distress	Qualitative Bins	See text		
Environmental	Environmental Impact	Qualitative Bins[10]	*De minimus* (Best); Moderate (Second Best)[11]		
LIKELIHOOD[12]	Frequency of Events	Number of Events per Year[13]	1/600 years	1/150 years	1/70 years

[1] The term "space weather" describes phenomena taking place in the near-Earth environment, primarily due to influences of the solar magnetic field. The largest space weather events are geomagnetic "storms" that are caused by huge magnetic eruptions from the Sun called "coronal mass ejections" or CMEs. Such eruptions are usually accompanied by bursts of X-ray photons ("solar flares") and energetic particles that can have prompt effects on the Earth's atmosphere.

[2] Best estimates for fatalities, injuries and illnesses, direct economic loss, and social displacement were not calculated for this event.

[3] The low estimate for fatalities is informed by the excess fatalities in New York City attributed to the loss of electric power in the 2003 Northeast Blackout (Anderson et al (2012)) and not directly caused by the space weather itself. This event is used as a proxy for the low economic impact scenario because it is cited by the electric industry (NERC (2012)) as a model for a scenario of electric grid collapse caused by a solar storm not resulting in permanent transformer damage (i.e. the grid shuts down and is able to be restarted within days). The scope of the study was limited to the 8 million residents of New York City out of the 50 million who lost power nationwide.

[4] SNRA project team assumption based upon extrapolation of the 2003 East Coast Blackout (50 million people assumed out of power for average of 1 day) to the Lloyd's high estimate scenario of 40 million people out of power from 16 days to up to two years (Lloyd's (2013)). Because of the multiple uncertainties involved, the SNRA project team made the assumption of one month average outage having disruptive effects (i.e. the 16 days plus two weeks in addition) for a scaling estimate of 1.2 billion person-days, or 24 times that of the East Coast Blackout. This factor was applied to the 90 fatalities of the low estimate, for a lower-bound estimation of a true high estimate of 2,000 fatalities (rounded to one significant figure). Although the initial health impacts of a large-scale, sudden blackout may subside in initial days as affected populations adapt to life without power, the exhaustion of fuel and lifeline resources and impacted supply chains for critical goods may result in significantly compounded total population health impacts days or weeks into the blackout. The SNRA high estimate thus almost certainly represents a substantial under-representation of the true numbers of fatalities which may be expected from a catastrophic, multi-state extended power outage disaster. However, the SNRA project team judged that it would be more misleading and unrepresentative of the uncertainties in potential impacts of a space weather event to report no high estimate at all, rather than reporting a high estimate that itself is deeply uncertain.

[5] The low estimate for injuries and illnesses is informed by the excess hospitalizations for complications of respiratory illnesses in New York City for August 14-15 attributed to the loss of electric power in the 2003 Northeast Blackout (Lin et al (2011)) minus the three fatalities due to respiratory illness of Anderson et al (2012), on the assumption that these deaths were most likely pronounced in hospital. This epidemiological study examined hospitalizations for respiratory, cardiovascular, and renal diseases: only respiratory diseases showed statistically significant hospitalizations over prior year averages (from a subset with comparable temperature ranges) of the same days in August. Other studies have examined excess hospitalizations

Event Description

The Sun emits bursts of electromagnetic radiation and energetic particles at an intensity that saturates the G-5 level on the National Oceanic and Atmospheric Administration (NOAA)'s Geomagnetic Storm Space Weather Scale.[14] The storm is greater than solar storms observed in North America in the past three decades, reaching to the northern tier of the United States (approximately 50° geomagnetic latitude). Such a storm is potentially strong enough to cause widespread and prolonged electric utility outages, and it may be strong enough to cause significant damage to communications and navigation satellite infrastructure. Although the likelihood of such an event may be difficult to study because of its rarity and limited historical data, strong space weather events have happened in the past—most recently with a near-miss in July 2012[15]—and could theoretically cause widespread, lasting damage to our electric power supply system.

for severe diarrheal illnesses caused by eating spoiled meat products due to loss of refrigeration [Marx et al (2006)] and other measures of increased burdens on emergency responders and the hospital system in New York City due to the blackout [Prezant et al (2005)] but did not provide quantitative estimates which could be extracted for this summary sheet. The 2003 Blackout is used as a proxy for the low economic impact scenario because it is cited by the electric industry (NERC (2012)) as a model for a scenario of electric grid collapse caused by a solar storm not resulting in permanent transformer damage (i.e. the grid shuts down and is able to be restarted within days). The scope of the study was limited to the 8 million residents of New York City out of the 50 million who lost power nationwide.

[6] Scaled in a similar fashion to the high estimate of fatalities: see note to fatality high estimate above.

[7] The low estimate of $5.7 billion represents the low end of the economic impact estimate and is based on the inflation-adjusted estimate of the 2003 Northeast Blackout using FEMA's Benefit-Cost Analysis guidance on the economic impact of electricity outages [FEMA 2011], using an assumption of 50 million persons without power for an average of one day. The 2003 blackout has been previously cited by the electric industry (NERC (2012)) as a model for a scenario of electric grid collapse caused by a solar storm not resulting in permanent transformer damage (i.e. the grid shuts down and is able to be restarted within days), and is the lowest estimate of solar storm impacts located in the literature.

[8] Lloyd's (2013) pg. 6. The inflation-adjusted value of $2.51 trillion (2011 USD) is rounded down to $2 trillion to represent uncertainty in the range of potential true impacts (rounding to one significant figure) and to represent the losses accumulated in the first year (rounding down) of the Lloyd's high end scenario of 40 million people out of power from 16 days to 2 years (i.e. 2 years to restore power to the last person). Power restoration curves following a disaster are typically sinusoidal or logarithmic (Executive Office of the President (2013) p 21): restoration is faster nearer the beginning, and longer for the remaining tail at the end. However, even a linear restoration function (constant restoration rate) results in 75% of the total person-days out of power accumulating in the first year, resulting in a low bounding estimate of $1.88 trillion of the total $2.51 trillion estimated costs (the Lloyd's model proportions costs to total person-days without power, Lloyd's (2013) p. 17) accumulating in year 1.

[9] Based upon the high end of Lloyd's (2013) scenario of 20 to 40 million people without power for 16 days to 1-2 years. It is possible for many or nearly all of 40 million people without power under circumstances where essential societal lifelines are functioning to stay in their homes for an outage of up to two weeks, even in temperate conditions. However, this may not hold true for a long-term, very extensive power outage affecting total regions and survival lifelines: the high estimate of displacement reflects this possibility.

[10] In 2011, the United States Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event in the 2011 SNRA. The comments and rankings presented in this Risk Summary Sheet have not undergone review by the EPA and only represent the opinions of the group. Estimates pertain to the potential for adverse effects on living organisms associated with pollution of the environment; they are grouped into high, moderate, low, and de minimus (none) categories. Experts provided both first (Best) and second choice (Second Best) categories, allowing the experts to express uncertainty in their judgments as well as reflect the range of potential effects that might result depending on the specifics of the event. The first choice represents the 'Best' estimate.

[11] Experts identified the best estimate for environmental impacts as "de minimus" or none. Experts indicated environmental/ecological effects would likely depend on duration of outages. For one day to a few days, the damage would be relatively minimal/de minimus (this is in the scope of typical power outages due to snowstorms, rain, and other natural disasters). If the outage persisted for weeks, then there is the potential for backup systems to fail. If backup systems (such as diesel fuel delivery) failed, then the lack of power to treatment plants and chemical plants could have a massive impact. A space weather event would most likely affect a large geographic area in addition to having the potential for a longer duration.

[12] Note that low and high likelihoods do NOT correspond to low and high impacts. Low, best, and high likelihoods represent the low, best, and high estimates for the likelihood of occurrence of the set of scenarios or incidents captured within the scope (as defined by the event thresholds and other elements of the event description) of the SNRA hazard event as a whole. Low and high estimates of impact (fatalities, direct economic loss, and so on) are provided to represent a range of impacts that could result, given the occurrence of an incident within the scope of the event. When considered as variables defined by these reported and depicted ranges, likelihood and each impact represent independent variables within the SNRA methodology.

[13] Low, best, and high one year frequency estimates come are those of Love (2012), cited by NERC (2014) (p. 9) as the probability model for a Carrington-level storm. The best estimate of frequency corresponds to a return period of 153 years, rounded to 150 years in the data table. The low and high estimates of 1/600 years and 1/70 years represent the 1 standard deviation (68.3%) confidence interval as cited by NERC. The Lloyd's study uses the same probability model.

[14] Geomagnetic storms, solar flares, and solar energetic particles are classified by NOAA's Space Weather Prediction Center on scales ranging from 1 to 5, in analogy to the hurricane and tornado magnitude scales.

[15] Phillips (2014). A powerful CME—potentially as strong as, if not stronger than, the Carrington event—passed through the Earth's orbit on July 23, 2012. The Earth was not there when it happened, so there were no impacts. NASA had a record of it because the storm cloud hit the STEREO-A spacecraft.

Event Background

"Space weather" refers to variations in the space environment between the sun and Earth. In more common contexts, space weather refers to the phenomenon where emissions from the sun—such as solar flares[16] and coronal mass ejections (CME)[17]—affect the Earth and its surrounding space with geomagnetic storms. There have been several key events that are widely discussed in the space weather literature. Two of them in particular are referenced throughout this assessment:

- **Carrington Event:**

  The Carrington Event is frequently referenced in space weather literature. From August 28 to September 2, 1859 the U.S. experienced the "most extreme space weather events in recorded history. Looking at four key measures of geomagnetic storm strength (sudden ionospheric disturbance, solar wind, geomagnetic storm and aurora), it is the only event that appears within the top five events in each category."[18] The probability model cited by the North American Electric Reliability Corporation (NERC) estimates a return period of approximately 150 years for Carrington-level storms, but with a wide range of uncertainty (range 1/70–1/600 years).[19] Because of the existence in the literature of recent peer-reviewed U.S. impact models for this return period and storm magnitude,[20] the SNRA space weather scenario focuses on a Carrington-level storm.

- **Quebec Storm:**

  The March 13–14, 1989 geomagnetic storm is one of the most well-known storms because of its impact on the electricity grid. It collapsed the Hydro-Quebec power grid and resulted in the loss of power for more than six million people for nine hours. It also tripped equipment and nearly collapsed other parts of the Eastern interconnection of the U.S. electric grid.[21] The sources used for the primary estimates in the SNRA estimate an approximately 1/50 year frequency (range 1/30–1/100 years) for a Quebec-level storm.[22]

Space weather events have occurred throughout human history, but they were not recorded until human technology advanced to the point of developing systems that could be affected by geomagnetic and electrical disturbances. The Carrington Event in 1859 resulted in an observable solar flare that disrupted telegraph communications. Research has been done to study how geomagnetic-induced currents affect electric power disturbances. Based on statistical analysis, researchers concluded that roughly four percent of all insurance claims related to electric power

[16] A solar flare is an intense burst of radiation from the sun. It comes from the release of magnetic energy and is associated with sunspots.
[17] The corona is the outer solar atmosphere and is structured by strong magnetic fields. Where these fields are closed, often above sunspot groups, the confined solar atmosphere can suddenly and violently release bubbles of gas and magnetic fields, and these are called coronal mass ejections.
[18] Lloyd's (2013) 6.
[19] NERC (2014) 9, Love (2012).
[20] Lloyd's (2013), Wei et al (2013). An input-output analysis (Schulte in den Bäumen (2014)) estimates U.S. costs of $2.65 billion from a Quebec-level storm (and $1.2 trillion for a Carrington event assuming recovery within five months), but the correspondence of this cost to direct economic impacts as considered in the SNRA are unclear. A 1990 Oak Ridge National Laboratory calculation (Barnes et al (1990)) estimates a range of $3.042–$6.100 billion ($5.2–$10.5 billion in 2011 USD) direct economic losses to the U.S. for a Quebec-level storm occurring at peak power which damages four transformers and blacks out the northeastern U.S. for 16–48 hours. However, this study is not as recent as Lloyd's (2013). Swiss Re reports estimates of $200–500 million of economic loss to Europe for a Quebec-level storm affecting that continent (and $129–$164 billion in impacts to the U.S. and Canada for a Carrington level event resulting in a 3-week blackout) from a transparent economic model reported in sufficient detail to replicate (Swiss Re (2012), Swiss Re (2014)). However, the Swiss Re figures were not used for primary estimates in the SNRA because they could be found only in presentations (slide decks) and conditional probabilities for the different scenarios among them were unclear.
[21] Lloyd's (2013) 7.
[22] Lloyd's (2013) 4, NERC (2014), Love (2012).

disturbances in North America could be attributed directly to space weather, equating to 500 insurance claims per year.[23]

While research has suggested that space weather affects the electric grid, there is still a great deal of debate and uncertainty across the scientific, regulatory, policy, and infrastructure operator communities regarding the likelihood that a solar storm could cause significant damage to critical infrastructure, and the extent and duration of that impact. There are two schools of thought on the potential impacts of space weather events:

- One perspective forecasts a cataclysmic scenario of half the Nation's electric grid out of commission for up to a decade.[24] This is because geomagnetic storms can induce currents in the electric power grid that can last for hours, exciting voltages in an electric power transformer core and magnetically saturating the device. The electromagnetic charge overwhelms the transformer core, melting the copper windings, leading to failure. The transformers cannot be repaired, but rather would need to be replaced, which could take several months to years. The impacts to the national and global economies would be as severe as any economic challenge faced by the U.S. in the past, or greater.[25]
- The other approach asserts that a true reasonable worst-case scenario could look more like the large-scale but temporary August 2003 blackout in the Eastern U.S. and Canada[26] (which was caused by a computer error, not a solar storm). Such a blackout impacting a large portion of the United States would be a genuine disaster, but manageable in a way that the high-end scenario would not be.[27] One reason for this is that coronal mass ejections (CME) are not no-notice events, and this allows operators time to adapt and mitigate the potential effects. Even during the Carrington event in 1859, which is the basis for much of the concern, scientists noticed the solar flare associated with the CME about 18 hours prior to its arrival. Generally, the CMEs leave the sun at varying speeds and interact with the constant electrically-charged solar wind that travels to the Earth at about 250 meters per second. The estimated time from when a CME-event occurs and its arrival at Earth ranges from about 15 hours to several days.[28]

For the purposes of this assessment, each methodological perspective is taken as one of the endpoints to represent the full span of uncertainty around likelihood between them.

Direct environmental and health effects from space weather are minimal, as damage occurs mainly through the medium of disruption of technology. However, our society's dependence on technology, in particular refrigeration[29] and electric-powered medical devices,[30] mean that there could be significant impacts on health (fatalities, injuries, and illnesses) depending on the severity of a solar storm and its impact on power generation and communications.

[23] Schrijver et al (2014). For this statistical analysis, the researchers studied 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in NorthAmerican commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment.
[24] Note, although this assessment uses the 1/150 year return period, there are other experts who suggest the return period may be even more frequent. For additional information, see National Academies (2008) pp 77–79 (John Kappenman's presentation); Metatech (2010) pp 3–22–3–29.
[25] Moran (2014).
[26] NERC (2012) pp 16–24, 46, 69, 85; Pulkkinen (2012).
[27] Mark Lauby, NERC, written submission in Attachment A, FERC (2012). NERC notes that its 2012 conclusion that the most likely outcome of a severe space weather disaster would be a reactive voltage collapse is based on its genuine belief rather than an attempt to dismiss the issue: NERC and the industry regard the possibility of a reactive voltage collapse as unacceptable and are taking action to prevent and mitigate such an event (same reference).
[28] NERC (2011) 4.
[29] Marx (2006).
[30] Anderson et al (2012), Lin (2011), Prezant (2005).

Technologies that can be directly affected by extreme space weather include the electric power, spacecraft, aviation, and Global Positioning System (GPS)-based positioning industries. Within the last 30 years, space weather events (of magnitudes below the threshold of the National-Level Event as defined here) have disrupted all of these technologies. Severe storms could result in additional consequences for numerous systems that rely on the electrical grid.

Another factor to consider is the possibility that a localized impact to transformers in one region could also result in a national event if their failure were to disrupt one of the major U.S. grid interconnections. In this situation, "the total number of damaged transformers is less relevant for prolonged power outage than their concentration. The failure of a small number of transformers serving a highly populated area is enough to create a situation of prolonged outage."[31] Considering the impacts on society and population, the Lloyd's study concluded that the highest risk of solar storm induced power outages was the Washington D.C. – New York City corridor, on the Eastern Seaboard. Additional highly vulnerable areas included the Midwest (due to latitude) and along the Gulf Coast (due to ground conductivity and coast effects).[32]

The potential for loss of life *directly* attributed to a solar storm event is believed to be low compared to some other hazard events. Any deaths occurring in large numbers would be caused by the loss of electricity and the resulting cascading effects on other critical infrastructures. Examples include the following:

- The loss of electricity could cause mass transit and passenger rail control systems to fail, potentially causing accidents with fatalities.
- Water shortages may be caused by the failure of electrical pumps to convey water. Power loss at purification plants could lead to acute exposure to toxicants or disease. By extension, firefighters would not have access to water to put out fires, and hospitals would not have access to water to take care of at-risk patients.
- Even in the low-end scenario, the number of fatalities, injuries and illnesses may be expected to reach the dozens or hundreds due to power losses causing the failure of important systems: home medical devices, refrigeration units, and (in a hot summer or cold winter) air conditioning and electric heating systems.

The injury and fatality estimates of this event come from epidemiological studies of excess fatalities and hospitalizations in New York City during the 2003 East Coast blackout.[33] Although the eight million population of New York City represents a sixth of the 50 million people affected in the U.S. and Canada, many of these hospitalizations and fatalities were attributed to sociological aspects (higher proportion of home medical devices, failure of water pressure and difficulty of response to high-rise buildings without power) that are particular to densely populated urban areas: thus although these numbers understate the true totals, they are likely closer to them than a straight proportion would suggest (and in any case, are likely to be at least within an order of magnitude). In short, injury, illness or death in mass numbers would likely only be caused by the resulting impact on lifeline functions by a geomagnetic event on critical infrastructure—not directly by the space weather event itself.[34]

[31] Lloyd's (2013) pg. 13.
[32] Lloyd's (2013) pp 10–11.
[33] Anderson et al (2012), Lin (2011).
[34] OECD (2011) p.25.

Assumptions

Like other natural hazards, changes in the occurrence or severity of solar storms are magnified by the way our society's vulnerability to them has changed in recent decades. Due to an increasing critical dependency on the satellite, navigation, and extra-high-voltage (EHV) electric transmission systems, the impact of a Carrington-sized event today would not simply be a display of nature, but could represent a catastrophe. Although there is some uncertainty in the frequency of occurrence of severe space weather, the dominant uncertainties lie in the potential impacts. These knowledge gaps come from 1) the fact that these critical systems have not yet been tested by a real event, 2) the destructive testing necessary to narrow the uncertainties around their true vulnerability has been too costly to undertake, and 3) the speed with which the national economy—possibly handicapped by the loss of critical electric and communications infrastructure—would be able to restore substantial losses to them is unknown.

The SNRA project team used the following assumptions to estimate economic impacts resulting from a space weather event across the following types of infrastructure:

Effects on GPS services:

Direct estimates of the potential cost of a loss or degradation of GPS services from a severe space weather event were not found. However, the total economic benefit of GPS services to users (i.e., not counting sales of GPS devices) has been estimated at $28–51 billion per year.[35] Space weather can create microwave emissions that can act as "natural jamming"[36] of GPS singles for about an hour. During the length of a geomagnetic storm, GPS may be unavailable because of interference in the L band. Organizations that rely on GPS for location and timing signals may experience significant disruption.[37]

Effects on Aviation:

A severe event might force the rerouting of hundreds of flights not just over the pole but also across Canada and the northern U.S.[38] These adverse conditions could last for a week.[39] A National Weather Service (NWS) study estimated the cost of such diversions as approximately $100,000 per flight.[40] In addition, GPS-based air navigation could be disrupted. The Federal Aviation Administration's GPS-based Wide Area Augmentation System (WAAS) was disabled for 30 hours during the severe space weather events of October–November 2003.

Effect on Cellular Communications:

Loss of GPS timing signals of greater than two hours may negatively impact cellular and public safety radio base stations' ability to work together. For example, "these base stations would be unable to hand off calls to another base station for mobile users moving between coverage areas, and users near the edge of coverage areas may experience interference from adjacent base stations or loss of service."[41]

[35] Pham (2011).
[36] Cerruti et al (2008).
[37] MacAlester et al (2014).
[38] National Academies (2008) pp 50-52.
[39] Odenwald et al (2008).
[40] NOAA (2004) 17.
[41] MacAlester et al (2014).

Effects on Satellites:

Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers.[42] In addition to direct effects of radiation, the expansion of the Earth's atmosphere from a superstorm will cause atmospheric drag on low Earth orbit satellites.[43] In January 1994, Telesat's Anik E1 and E2 telecommunications satellites were affected by a space weather event; E2 required six months to repair at a cost of $50–70 million. The U.S. Department of Defense has estimated that solar disruptions to government satellites currently cost about $100 million per year.[44] A study by Odenwald and Green[45] estimated total costs due to satellite damage and loss of satellite services at $20–70 billion for a severe event.

Effects on Public Safety Telecommunications:

The vast majority of public safety radio communications, including line-of-sight VHF air-to-ground communications used for search and rescue and HF groundwave transmissions out to 10–60 miles, should not be affected.[46] It is possible, however, that cellular base stations—including public safety radio base station antennas—that face the sun could experience increased noise from solar radio bursts at dawn and dusk.[47]

Effect on Electricity Supply:

The effects on the electricity sector could be the most severe from an extreme space weather event, with estimates ranging from billions to trillions of dollars. However, since there is an order of magnitude of difference between the low and high estimate, it is important to be aware that there is significant uncertainty about how much damage an extreme space weather event would do to the physical grid infrastructure, which would determine the duration of an outage. Experts are conflicted on what the impacts of space weather may be.

A low impact scenario which caused a large-scale power collapse of large portions of the national grid but little to no permanent destruction of electric transformers could look like mass blackouts of past experience, such as the August 2003 Northeast Blackout. However, destruction of key transformers or large numbers of transformers could have significantly more complicated impacts. If there was a prolonged outage for months or even years, this could significantly impact the national economy. The electrical grid is essential to supporting the national economy and our way of life, and unlike the other critical infrastructure sectors and subsectors which could be (and routinely are[48]) impacted in some way by solar storms, the uncertain risk to the electric grid has been a recurrent focus of discussions about solar storm risk.

One core reason is that the grid is the only subsector that needs to already be substantially functional in order for any permanent damage to be repaired. If there is a collapse of the grid due to widespread damage to electric transformers, it could severely compromise the Nation's ability to manufacture the replacement transformers needed to get the grid back online. This chicken-

[42] National Academies (2008) p. 1.
[43] Royal Academy (2013) 35.
[44] *Supra* note 42.
[45] *Supra* note 42.
[46] MacAlester et al (2014).
[47] Royal Academy (2013).
[48] Odenwald et al (2008) communicate estimates that, as normal background noise, sub-catastrophic solar storms cost the Nation about $450-500 million per year through disruptions to the electric grid's normal operation (a proportion of the $500 million cited for the 19 month period from June 1 2000 to December 31 2001) and damage to USG -owned satellites ($100 million per year, Defense Department estimate).

and-egg dependence not only exponentially increases the time needed to replace physically damaged core equipment, but it can also leave the grid in a crippled state that is out of proportion to the actual extent of the damage. Furthermore, knock-on or cascading effects of the electrical outage on other sectors of the economy would also then continue for the same, disproportionally extended period of time.

Although not analyzed within this assessment, in the event of a widespread persistent loss of power supply, there could be significant psychological impacts through job loss and displacement from uninhabitable areas, and the businesses (such as gas stations and grocery stores) that are able to function may not be able to accept any form of payment other than cash.

Frequency

Low, best, and high one year frequency estimates are those of Love (2012), cited by NERC as the probability model for a Carrington-level storm. The best estimate of frequency corresponds to a return period of 153 years, rounded to 150 years in the data table. The low and high estimates of 1/600 years and 1/70 years represent the 1 standard deviation (68.3%) confidence interval as cited by NERC. The Lloyd's study uses the same probability model.[49]

Health & Safety Impacts

The low estimates for fatalities and illnesses come from epidemiological studies of excess fatalities and hospitalizations in New York City during the August 2003 Northeast Blackout. The fatalities are on the order of 100, much larger than the eleven directly attributed to the blackout in its immediate aftermath.[50] Since the approximately eight million residents of New York City represent a fraction of the 50 million US customers who actually lost power, they represent a lower bound to the true total; however, since the fatalities and illnesses in NYC had much to do with local factors such as high-rise buildings (failure of water pressure, Emergency Medical Technician (EMT) difficulty reaching people on high stories) and being an urban center (older people dependent on home respirators living near a high concentration of world-class hospitals), the true national totals are probably less than seven times the NYC figures, which a proportional scale-up by population would suggest. However, the August 2003 blackout lasted two days, so the potential for fatalities could also increase exponentially in areas with far longer outages. No data could be found to fully calculate these particular impacts of long-term, prolonged blackouts.

The high estimates represent an extrapolation of these known effects to longer blackouts, which required a scaling assumption by the SNRA 2015 project team. The health impacts of the low scenario were scaled up in proportion to the total person-days without power of the 2003 Northeast Blackout (50 million people assumed out of power for average of one day), to the Lloyd's high estimate scenario of 40 million people out of power from 16 days to up to two years. Because of the multiple uncertainties involved, the SNRA 2015 project team made the <u>assumption</u> of one month average outage having disruptive effects (i.e. the 16 days plus two weeks in addition) for a scaling estimate of 1.2 billion person-days, or 24 times that of the East Coast Blackout. This factor was applied to the 90 fatalities of the low estimate, for a lower-bound estimation of a true high estimate of 2,000 fatalities (rounded to one significant figure).

[49] Most SNRA events having a defined frequency distribution cite the 5th and 95th percentiles as the low and high estimates (Appendices B and I), following customary practice in probabilistic risk assessment (PRA). (For the Love model, the 5th and 95th annual frequencies are 1/3,000 years and 1/51 years respectively.) For the space weather event, the SNRA project team judged that maintaining consistency with the electric power industry source was a higher priority for risk communication purposes.
[50] Minkel (2008).

Although the initial health impacts of a large-scale, sudden blackout may subside in initial days as affected populations adapt to life without power, the exhaustion of fuel and lifeline resources and impacted supply chains for critical goods may result in significantly compounded total population health impacts days or weeks into the blackout. The SNRA 2015 high estimate thus almost certainly represents a substantial under-representation of the true numbers of fatalities which may be expected from a catastrophic, multi-state extended power outage disaster. However, the SNRA 2015 project team judged that it would be substantially more misleading and unrepresentative of the uncertainties in potential impacts of a space weather event to report no high estimate at all, rather than reporting a high estimate that itself is deeply uncertain.

One health impact not projected is the impact of increased radiation on the health and safety of airline pilots, crew members and passengers due to a major space weather event. Most flights in the U.S. to expose crew members and passengers to cosmic radiation well above what is experienced on the surface. Dose rates can increase by 10 times or more: exposures depend upon the altitude and latitude of the flight path (polar routes are irradiated most), as well as solar activity. A particularly strong solar storm can boost radiation levels 100 times.[51] However, prior warning of solar storms allow polar flights to be rerouted—the Federal Aviation Administration can issue solar radiation alerts so that pilots know to fly at lower elevations or avoid Polar Regions—and so this particular societal risk is primarily factored in as the increased economic costs from rerouting flights rather than the health impacts to passengers that are averted by this mitigation measure. While a risk, the marginal impacts of increased solar radiation are difficult to quantify—especially when they are in the context of long-term, regular exposure that the aforementioned groups already regularly experience. Therefore, no health impacts can be directly attributed to impacts from space weather in this iteration of the SNRA.

Economic Impacts

The economic impacts to the nation are dominated by the estimates of possible damage to the electric sector. Although existing estimates of the range of possible damage to the transportation, communications, and government facilities sectors are described below and could be quite substantial, their contribution does not register within the single order of magnitude of the total economic damage estimates.

Transportation Sector: Aviation

Aviation	Low	Best	High
Direct Economic Loss	$500,000	$1.3 Million	$3.5 Million

In 2008, the National Research Council (NRC) of the National Academies hosted a two-day workshop on the societal impacts of space weather.[52] The NRC workshop report notes that thirteen air carriers flew a total of 7,300 flights over polar regions in 2007, of which United Airlines alone flew 1,800.[53] Although the NOAA report on the solar storms of October–November 2003[54] notes that two U.S. carriers fly polar routes,[55] the other carrier and its total number of flights is not given, so with the understanding that the true figure will be

[51] Phillips (2013).
[52] National Academies (2008).
[53] National Academies (2008) pp 50–51 [panel].
[54] 2003 saw a significant number of solar storms which did not cause widespread electric outages, in addition to the August 2003 electric outage cited as a model for a solar-storm caused outage but which was not itself caused by a solar storm: it is easy to get these mixed up.
[55] NOAA (2004) p 18.

underestimated, the 2007 United Airlines total is used as a proxy for the annual total of all U.S.-flagged air traffic over the poles, giving a daily average of 4.9 (rounded to 5.0) U.S.-flagged polar flights. The NRC report also notes that a severe solar storm can cause hazardous conditions requiring rerouting of polar flights for several days,[56] and Odenwald et al note that these disruptions may last for up to a week.[57] For a broad range, the SNRA project team selected one day as the minimum polar air disruption time and one week as the maximum. The estimates in the above table were found by using the average cost of $100,000 for the rerouting of a polar flight given by the NOAA study:[58] these estimates are factored in as direct economic loss.

Communications and Government Facilities Sectors: Satellites and GPS

Satellites	Low	Best	High
Direct Economic Loss	$50 Million		$68 Billion

The low end estimate of $50 million damage (repair costs) to the Telsat Anik E2 satellite damaged by the 1994 solar storm cited by the NRC report[59] is taken as the low estimate for direct economic loss. Odenwald et al (2005)'s estimates of $24 billion in direct property damage (replacement costs) and $44 billion in business interruption costs (lost transponder revenue) for a solar storm three times that of the 1859 Carrington event in magnitude were summed for the high estimate of direct economic loss.

Indirect economic loss consequent to this direct damage was not estimated. Direct and indirect losses due to physical damage to or service interruption of the GPS satellite system in particular are excluded from the above:[60] no estimates for these are included here.

Energy Sector[61]

Electric Grid	Low	Best	High
Direct Economic Loss	$5.7 Billion		$2 Trillion

The potential impacts on the grid and the economic impacts of an outage are heavily debated in the space weather community. One of the main uncertainties is whether there will be disruptions to the transformers. The *Solar Storm Risk to the North American Electrical Grid* report published by Lloyd's in 2013 noted that "large amounts of geomagnetically induced currents (GIC) flowing through the power grid can damage power transformers and/or lead to voltage collapse, resulting in widespread power outages."[62] Indeed, Lloyd's further concluded that even if a few transformers were damaged (10–20) it could cause significant regional power disruptions.[63]

For the low estimate in this assessment, the G-5 storm disrupts the electric grid and overloads the system, causing widespread outages across the Eastern and Pacific Northwest interconnections and leaving 50 million people without power for a day. Therefore, the low estimate is informed

[56] National Academies (2008) pp 50–51.
[57] Odenwald et al (2008).
[58] NOAA (2004) p 17.
[59] National Academies (2008) p 25.
[60] Odenwald et al (2005) pp 15–16.
[61] A note on the methodologies—in order to inform this assessment, this analysis is based on two separate benefit-cost analysis (BCA) models. The low estimate is informed by the FEMA BCA guidance released in 2011 and the high estimate is informed by the BCA used within the Lloyd's report. This decision was made because of the understanding that there are different BCA considerations for short term (day) electricity outages than there would be for long-term (year) outages. For additional information on the methodologies, see FEMA (2011) and Lloyd's (2013).
[62] Lloyd's (2013) pg. 6 (see also Molinski et al (2000)).
[63] Lloyd's (2013) pg. 6.

by the Northeast Blackout in 2003, previously cited by the electric power industry[64] as a model for the reasonable-worst-case scenario of an electric grid collapse caused by a 1/100 year solar storm: it is the lowest estimate of solar storm impacts located in the literature. The low estimate of $5.7 billion represents the low end of the economic impact estimate and is based on the inflation-adjusted estimate[65] of the 2003 Northeast Blackout using FEMA's Benefit-Cost Analysis (BCA) guidance on the economic impact of electricity disruption from outages.[66,67]

The high estimate for economic impact[68] is the high end of the estimate provided by Lloyd's in their 2013 report. Using a benefit cost analysis approach that evaluates the residential, commercial, and industrial costs from an electrical service disruption,[69] The Lloyd's study estimated that 20–40 million people could be affected for anywhere from 16 days to 1–2 years, and it concludes the economic costs could range from $0.6–$2.6 trillion.[70] While there is considerable debate within the space weather community about the feasibility of such an event, if one considers the catastrophic scenario[71] described in the Lloyd's report and by experts like John Kappenman in which tens of millions of people do not have power for months or even years, economic losses in the trillions of dollars for such an event[72] are reasonable and possibly understated.[73]

Psychological Distress

Psychological impacts for the SNRA focus on significant distress and prolonged distress, which can encompass a variety of outcomes serious enough to impair daily role functioning and quality of life. An index for significant distress was created that reflected empirical findings that the scope and severity of an event is more important than the type of event.[74] The equation for this index uses the fatalities, injuries, and displacement associated with an event as primary inputs. A multiplicative factor elicited[75] from subject matter experts weights the index for differing psychological impact based on the type of event, but as a secondary input.

[64] NERC (2012).
[65] FEMA (2011). According to FEMA's BCA methodology, the impacts of electricity disruption on economic activity are estimated to cost $114.39 per capita per day in direct economic costs (adjusted for inflation in 2015 terms). (This reflects the component for Impact on Economic Activity, $106.27 in 2010 USD; the Impact on Residential Consumers component of $24.58 is not included.)
[66] See also the SNRA 2015 Risk Summary Sheet on Physical Attack on the Power Grid.
[67] It is worth noting that after the Northeast Blackout, the Department of Energy released an after action report that cites the Electricity Consumers Resource Council (ECRC) estimate of $4–$10 billion of total economic loss from the blackout of the 2003 Northeast Blackout. In addition, other methodologies can be used to determine the economic cost, but these figures take into account some indirect as well as direct costs. Using a proportional relationship between electricity consumption and national GDP, one calculation of the impacts of the 2003 blackout showed that "50 million people were without electric power for a day, and so it [is] estimated to have cost $5.6 billion, which is within the range of [other, more complex] estimates that have been published." Zimmerman (2005) 17–18.
[68] Due to a widespread and long-term electric outage because of the long replacement-time of critical equipment (up to 365 critical Extra-High Voltage [EHV] electric transformers).
[69] Lloyd's (2013) pg. 17. The research assumes a linear relationship with time and electric power consumption: $2.00/kWh, $19.38/kWh, and $8.40/kWh for residential, commercial, and industrial customers, respectively. A factor of 1.31 accounts for inflation from 2001 to 2013.
[70] Lloyd's (2013) pg. 6.
[71] 130 million people without power in a way similar to the 2003 blackout, but widespread destruction of transformers and the long replacement times (the 18 months under ordinary circumstances is lengthened by a crippled national industrial base as a result of the extensive damage to the grid) prolongs the outage from three days to several years.
[72] Extrapolating the cost estimate (approximately $5.7 billion) of the 2003 East Coast Blackout which affected approximately 50 million people for an average of 1 day to 365 days results in $2.1 trillion. The high estimate from Lloyd's assumes more rapid power restoration, but higher economic impacts per unit of power lost.
[73] Continued loss of nearly all the infrastructure dependent upon electric power would most likely have a negative impact on normal consumer spending, and there are other factors such as food spoilage, and regional economic collapse from business closures. All of this would likely represent a substantial fraction of the Nation's annual gross domestic product.
[74] See Appendix G of the SNRA draft Unclassified Documentation of Findings for references and additional discussion of the SNRA Psychological Distress metric.
[75] The elicitations were performed in 2011 for the first iteration of the SNRA, which included space weather as a National-level Event. These elicitations were not repeated in 2015.

The Significant Distress Index is calculated from these inputs using a formula proposed by experts consulted for the SNRA project: $N_{SD} = C_{EF} \times (5\ Fat + Inj + \frac{1}{2} D)$, where N_{SD} represents the number of persons significantly distressed, C_{EF} is the expert assessed Event Familiarity Factor, *Fat* is the number of fatalities, *Inj* is the number of injuries and/or illnesses, and *D* is the number of persons displaced (Social Displacement).

- In words, this formula suggests that there are 5 significantly distressed persons for each life lost; 1 for each person injured; and 1 for each 2 people displaced. This formula was constructed to reflect the empirical finding that the most severe stressor of a disaster is losing a loved one, followed by injury, followed by displacement.

The Event Familiarity Factor is intended to capture the extent to which the event entails an ongoing threat with uncertainty regarding long-term effects, is unfamiliar, or that people dread, exacerbating psychological impacts. This factor, ranging from 1.0 for familiar events to 1.3 for unfamiliar events, was provided by subject matter experts for each national-level event included in the SNRA: Space Weather was given a C_{EF} of 1.0.

- Uncertainty was captured by applying the index formula to the low, best, and high estimates of these three human impact metrics.

The numerical outputs of this index formula were used to assign events to bins of a risk matrix for a semi-quantitative analysis of psychological risk in the SNRA.[76]

Environmental Impacts

In 2011, the U.S. Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event in the 2011 SNRA. Estimates are based on the following assumptions:

- Experts were elicited to provide estimates in the environmental impact category based on assumptions. Actual environmental/ecological harm that occurs as a result of the events described in a given scenario may vary considerably, and will depend on numerous variables (e.g., chemical or biological agents, contamination extent, persistence, toxicity—both chronic and acute toxicity—and infectivity).
- EPA defined environmental consequence (impact)[77] as the potential for adverse effects on living organisms associated with pollution of the environment by effluents, emissions, wastes, or accidental chemical releases; energy use; or the depletion of natural resources.
- Experts identified the best estimate for environmental impacts as “de minimus” or none. Experts indicated environmental/ecological effects would likely depend on duration of outages. For one day to a few days, the damage would be relatively minimal/de minimus (this is in the scope of typical power outages due to snowstorms, rain, and other natural disasters). If the outage persisted for weeks, then there is the potential for backup systems to fail. If backup systems (such as diesel fuel delivery) failed, then the lack of power to treatment plants and chemical plants could have a massive impact. A space weather event would most likely affect a large geographic area in addition to having the potential for a longer duration.

[76] Please reference the 2015 detailed findings for Psychological Distress in this document.

[77] The 2011 SNRA referred to impacts as ‘consequences’ because of prior usage in quantitative risk assessment (Kaplan and Garrick [1981, March], On the quantitative definition of risk: *Risk Analysis* 1(1) 11-32). Except where it will cause confusion, ‘impact’ is used synonymously in this document because of pre-existing connotations of the word ‘consequence’ within FEMA.

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