# ESTIMATING THE ECONOMIC IMPACT OF DISTURBANCES IN THE U.S. ELECTRIC GRID ASSOCIATED WITH GEOMAGNETIC ACTIVITY

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## Keywords

Electric Power Grid, Space Weather, Geomagnetic Activity, Economic Impact

## Abstract

Large solar explosions are responsible for space weather that can impact technological infrastructure on and around Earth. Here, we study the impacts of geomagnetic activity on the U.S. electric power grid from 1992 to 2010. We find, with more than 3σ significance, that approximately 4% of the disturbances in the U.S. power grid reported to the U.S. Department of Energy are attributable to high levels of geomagnetic activity. The combination of our results with an economic assessment study by the electric power industry suggests that the average cost to the U.S. economy of non-catastrophic grid disturbances in which space weather conditions are a contributing factor exceeds $3 billion per year. The magnitude of this apparent economic impact warrants extensive follow-up studies to validate, understand, and mitigate against the weak but significant contribution of space weather in power grid disturbances.

## 1. Introduction

Explosions powered by the Sun's magnetic field ("flares" and "coronal mass ejections" or CMEs) are among the principal causes of "space weather" [see, e.g., Space Studies Board, 2008]. These electromagnetic storms can affect our infrastructure in space, interfere with communications and GPS signals, and couple through the geomagnetic field into the large-scale high-voltage electric grid [e.g., Boteler et al., 1998; Boteler and Jansen van Beek, 1999]. Despite the known impact of severe space weather on the power grid [e.g., Space Studies Board, 2008; FEMA, 2010; Kappenman, 2010; Hapgood, 2011; JASON, 2011] - including the 1989 Hydro-Québec blackout [Béland and Small, 2004] - relatively few studies of the general correlation are available; case studies of individual events [such as by Kappenman et al., 1997; Kappenman, 2005] and compilations of events for comparison with the solar cycle [for example by Boteler et al., 1998] generally focus on large storms and large impacts.

There is a recognized hazard of catastrophic outages that may be caused by geomagnetic superstorms larger than what we have experienced in recent decades [Space Studies Board, 2008; FEMA, 2010; Kappenman, 2010; Hapgood, 2012]. Such superstorms may cause trillions of dollars of damage [Space Studies Board, 2008], although it is acknowledged that such estimates are rather uncertain [JASON, 2011]. Other studies assessing the economic impact on a statistical basis, find significant correlations between magnetometer data,

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geomagnetic induced currents (GICs), electric grid effects, and the conditions of the electric power grid market [Forbes and St. Cyr , 2004, 2008, 2010]. These correlations are associated with market price variations on the order of a few percent [Forbes and St. Cyr, 2004].

The main cause of GICs is the interaction of the geomagnetic field with the magnetic field carried within CMEs and the surrounding background magnetized solar wind that is modulated by them. With speeds of 400 − 2500 km/s, it takes some 1 − 4 d for CMEs to propagate from the Sun to the Earth, with a typical transit time of 2 − 3 d. Correlations between the strength of CMEs, and the magnitude of their impact in geospace continue to be studied, both observationally and in numerical analyses [e.g., Newell et al., 2007; Schrijver, 2009; Andreeova et al., 2011]. A multitude of factors may play a role, including properties of the solar events themselves and of the solar wind through which the events travel to Earth [e.g., Russell and McPherron, 1973; Pulkkinen, 2007; Schrijver and Siscoe, 2010]. Furthermore, the magnitude of GICs depends on the location and time of day (through the geomagnetic position relative to the Sun-Earth line) at impact, on the structure within the CME as it passes by Earth (inducing electric fields dependent on the direction and the rate of change of the magnetic field), on the ground conductivities in a wide area around any particular site for depths from sea level down to in excess of 100 km, and on the evolving architecture of the electric power grid into which the induced electric field couples.

The intensities of GICs scale with the rate of change of the geomagnetic field. As our study addresses the reliability of the U.S. power grid, we chose to use a measure of geomagnetic variability characteristic of the central U.S. latitudes. We verified that a commonly-used metric for large-scale geomagnetic variability, the Kp index, yields statistically identical results. In fact, we show that even using criteria based on the solar events that ultimately drive space weather results in consistent statistics, so that our findings are quite insensitive to the metric used to quantify space weather conditions in which the U.S. power grid operates. Combination of our results with a study executed by the electric power industry enables us to estimate the overall impact of flare-related grid disturbances on the U.S. economy.

## 2. Disturbances in the U.S. power grid

As input to this study we use a compilation of “system disturbances” published annually by both the North American Electric Reliability Corporation (NERC: available since 1992) and by the Office of Electricity Delivery and Energy Reliability of the Department of Energy (DOE; available since 2000). NERC compiles this information for an electric power market that serves over 300 million people throughout the U.S. and in Ontario and New Brunswick in Canada, jointly delivering power through more than 340,000 km of high-voltage transmission lines, linking 18,000 power plants within the U.S. [JASON, 2011].

The reported disturbances include, among others, “electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of the bulk electric systems, and fuel problems.” The NERC reporting changed from “selected disturbances” to a more comprehensive listing starting in 2003 (following a grid collapse on August 14, 2003, affecting almost 50 million customers). The DOE lists add information for 2008, 2010, and 2011. To avoid a strongly inhomogeneous data set, we exclude the DOE data for 2011 because of a marked change in the types of events being reported on; for example, there are 79 events marked ’Vandalism’ in 2011, which is 300× the average rate for that class of event reported in the 19 preceding years.

We extracted the information on all 1216 disturbances listed in the NERC-DOE reports, including the identified main cause, and the impact on power and number of customers affected (the latter two are often incompletely specified in the disturbance reports). Hence, our master list of attributed “causes” includes a variety of weather conditions (storms, ice, lightning, etc.), operator errors, equipment failures, transmission line faults, etc.

## 3. Geomagnetic activity and electric power grid disturbances

As no direct attributions to space weather conditions have been made for the events from the NERC-DOE reports studied here, we anticipate at most a weak effect by space weather on the power grid that may be strongly modulated by other processes affecting the grid's condition. Given enough independent controlling variables, such as the evolving connectivities within the power grid, the patterns of weather conditions, and the grid loads and their changes with time around the country, one might develop a multivariate dependent variable model, but insufficient information is available to us at present: the detailed supply, demand, and weather conditions are not included in the NERC-DOE reports, and no information is available on the probability that no reportable grid disturbances ensued from other operator errors, cases of vandalism, or cyber attacks, for example. Moreover, as we find below that only a few dozen disturbances in the sample of over 1,000 reported disturbances are attributable to enhanced space weather, we cannot study separate grid areas while maintaining statistical significance of the results. Such regional studies are natural follow-up studies of this work, and those can focus not on the statistical demonstration of susceptibility, as we do here, but on the detailed physics of the electromagnetic coupling of GICs into the power grid.

The power grid is generally operated with enough power being generated to meet customer demand, with a relatively small overcapacity available to accommodate changes in demand or to compensate for external perturbations, such as lightning strikes and other weather conditions. Thus, whereas one might argue that, for example, disturbances attributed to a lightning strike or to an ice storm or to a heat wave might need to be removed from the sample in a study looking to quantify the potential effects of space weather, it may well be that the grid disturbance ensued only because other factors, possibly including space weather, put the system in a state of increased susceptibility. Taking this perspective, we argue that the only disturbances that one might exclude a priori are those that are attributed to 'planned maintenance' (provided these did not cause unforeseen disturbances elsewhere) or to 'fuel shortages' at the generating plants. Even cases flagged as 'operator errors' should not be excluded a priori because the reports do not specify if the operators were responding to changing grid conditions or merely to a truly local need to change the operation of a grid segment. One may even ask if 'vandalism' might be more or less effective in causing a grid disturbance depending on system load and on the conditions of the geomagnetic field. In view of the low numbers of events in the above sets, and to avoid the inadvertent introduction of biases in the process, we elected to work with the full set of reported grid disturbances.

We may assume that weather conditions, fuel prices, and vandalism, for example, are not correlated with conditions on the Sun and in geospace, but that these and other conditions form a background that varies independently of space weather. In view of the above, we adopt the following avenue of research: we compare the frequency of grid disturbances under severe space weather conditions with that under light space weather conditions, with the grid in otherwise similar conditions. The second group is the control group containing grid disturbances that are much less, if not entirely unaffected by space weather. The contrast between these two samples enables us to estimate the impact of space weather.

To characterize the geomagnetic activity that may couple into the U.S. power grid, we use data from the Boulder (BOU) and Fredericksburg (FRD) stations. With the minute-by-minute data in hand, we compute the maximum value of $|dB/dt|$ for 30-min. intervals, for the average of the two stations that are located along the central latitudinal axis of the U.S., somewhat emphasizing the eastern U.S. as do the grid and population.

As the space weather effects on the U.S. power grid over our 19-y interval are relatively weak, we use a superposed epoch analysis to determine the magnitude of the effects. Figure 1 shows the average grid disturbance frequencies for days with geomagnetic activity, as

Table 1. *Average daily frequency of grid disturbances relative to days with high geomagnetic activity: $g_a$ within the day of high geomagnetic activity as measured by |dB/dt|(30m); $g_i$ for a day ending a 3-day period with the lowest average |dB/dt(30m)| within 25 days of a day with high |dB/dt(30m)|; $g_r$ for a day selected at random between 5 and 50 days before or after high |dB/dt(30m)|. The conditional criterion for days with high |dB/dt(30m)| is defined in the first column for each of the three rows. The final column shows the total number of dates, $N_d$ with high |dB/dt(30m)| corresponding to the 2, 5, and 10 percentile levels. Uncertainties and subsampling criteria are as defined in Table 2.*

| Selection criterion for reference dates | $g_a$ (enhanced geomagn. act.) | $g_i$ (low nearby geomagn. activity | $g_r$ (nearby random date) | $N_d$ |
|---|---|---|---|---|
| All disturbances (1216 cases) | | | | |
| \|*dB/dt*(30m)\|>36.1 | 0.230 ± 0.041 | 0.058 ± 0.020 | 0.136 ± 0.031 | 139 |
| \|*dB/dt*(30m)\|>24.5 | 0.184 ± 0.023 | 0.107 ± 0.018 | 0.143 ± 0.023 | 347 |
| \|*dB/dt*(30m)\|>18.5 | 0.167 ± 0.016 | 0.089 ± 0.012 | 0.147 ± 0.016 | 694 |
| WET: attributed to weather/external/technical causes (743 cases) | | | | |
| \|*dB/dt*(30m)\|>36.1 | 0.137 ± 0.031 | 0.043 ± 0.018 | 0.079 ± 0.024 | |
| \|*dB/dt*(30m)\|>24.5 | 0.115 ± 0.018 | 0.055 ± 0.013 | 0.077 ± 0.016 | |
| \|*dB/dt*(30m)\|>18.5 | 0.099 ± 0.011 | 0.050 ± 0.009 | 0.080 ± 0.010 | |

Table 2. *Average daily frequency of grid disturbances relative to days with major flaring: $f_a$ from 2 to 5 days after a major flare; $f_i$ for inactive intervals, i.e., 4-d intervals following the first 7-d intervals of no M or X flaring prior to dates with major flaring; $f_r$ for a randomly-selected 4-d interval between 5 and 50 days before or after 'major flaring'. The conditional criterion for days with 'major flaring' is defined in the first column for each of the three rows. The final two columns show the total number of dates, $N_d$, and the total number of flares on such dates, $N_f$. Uncertainties in $f_a$ and $f_i$ assume Gaussian statistics; for $f_r$ the standard deviation of a sample of 100 random realizations is given. Data are shown for all grid disturbances (top) and for grid disturbances attributed to weather, technical or external causes (bottom); the complementary set of disturbances of unclear attribution is not shown.*

| Selection criterion for reference dates | $f_a$ (2-5d after M or X flaring) | $f_i$ (nearby interval without M/X flares) | $f_r$ (nearby random date) | $N_d$ ,$N_f$. |
|---|---|---|---|---|
| All disturbances (1216 cases) | | | | |
| Multiple X flares | 0.328 ± 0.072 | 0.063 ± 0.031 | 0.210 ± 0.071 | 116, 36 |
| At least one X flare | 0.179 ± 0.020 | 0.116 ± 0.015 | 0.154 ± 0.022 | 116,136 |
| At least one M flare | 0.151 ± 0.006 | 0.126 ± 0.005 | 0.148 ± 0.007 | 1054, 1897 |
| WET: attributed to weather/external/technical causes (743 cases) | | | | |
| Multiple X flares | 0.140 ± 0.047 | 0.031 ± 0.022 | 0.120 ± 0.056 | |
| At least one X flare | 0.071 ± 0.012 | 0.050 ± 0.010 | 0.085 ± 0.017 | |
| At least one M flare | 0.077 ± 0.004 | 0.068 ± 0.004 | 0.083 ± 0.005 | |

measured by |*dB/dt*(30m)|, in the top 2, 5, and 10 percentiles in panels a, b, and c, respectively, for 4-week periods centered on those most active dates. There is a clear peak on the central dates relative to their surrounding periods, revealing a dependence of the U.S. power grid reliability on space weather conditions. Often, solar active regions exhibit series of flaring and coronal mass ejections over periods of multiple days, sometimes up to a full two weeks as a flare-productive region crosses the disk. Hence, for a comparison of the geomagnetically active dates with a reference date of low geomagnetic activity, the curves shown in Figure 1 do not provide suitable information to set a baseline level for grid disturbances in periods of low geomagnetic activity.

In Table 1, we list the average grid disturbance rates, $g_a$, for dates corresponding to the top $p$ = 2, 5, and 10 percentiles of geomagnetic activity, respectively. These numbers need to be compared to disturbance rates in the absence of strong geomagnetic activity. In order to ensure that the grid and its load are in a statistically comparable state, we look at conditions in 50-d windows centered on dates with high $|dB/dt(30\text{m})|$. Selecting a random date within these windows, but more than 5-d away from the reference dates, yields the disturbance rates $g_r$. These are lower than the rates $g_a$ for days of high geomagnetic activity, but this selection criterion does not, of course, avoid dates of significant geomagnetic activity. Hence, as the reference level, we select dates for the last day of the 3-d interval of the lowest average $|dB/dt(30\text{m})|$ within each of the 50-d intervals. This yields disturbance rates $g_i$ for geomagnetically inactive days.

For each value of the percentiles, $p$, we can estimate the number of grid disturbances in excess of those occurring in conditions of low geomagnetic activity by computing $N_p = (g_a - g_i)(p/100)n_d$ (where $n_d$ is the number of days in our 19-y study interval): $N_p$ =24 ± 6, 27 ± 10, 54 ± 13, respectively, for $p$ = 2, 5, 10. For higher $p$ values, more disturbances may be associated with geomagnetic activity, but the uncertainties on the values of $N_d$ rapidly increase (for $p$ = 25, for example, the uncertainty in $N_{25}$ embraces $N_{10}$ within one standard deviation), so that with the present data, we leave it at our finding that at least $N_{10} \approx 50$ disturbances are attributable to enhanced geomagnetic activity during the period of our study.

In order to assess whether our choice of metric for geomagnetic variability would significantly bias the results, we repeated our analysis for another commonly used index to characterize the interaction of the geomagnetic field with the variable solar wind, namely the Kp index. Kp is measured in subauroral mid-latitude stations characteristic of activity in central regions of Europe and the northern US, which is to be contrasted to the higher latitudes used for the AE index or the more global distribution of stations used for the Dst index. The Kp index is determined from the variability of the Earth's magnetic field, as measured by a network of ground-based magnetometers, on a 3-h basis, expressed relative to quiet-day variability on a scale from 0 to 9. Using daily averages of Kp, we find results that are statistically consistent with those based on $|dB/dt(30\text{m})|$; we omit that table for brevity.

As a final test, we compare the compiled data base on disturbances in the electric power grid to the catalog of solar flares maintained by NOAA, selecting only large flares of GOES classes M and X (based on the logarithmic 1 − 8Å peak brightness, such that an X1 flare is ten times brighter than an M1 flare, and close to ten times more energetic overall [Veronig et al., 2002]). For the period 1992-2010 there were 1897 M- and X-class flares on 1054 distinct dates. Nearly half of all M-class flares and over 90% of X-class flares are associated with CMEs [see the review by Schrijver, 2009, and references therein] and thus most such flares affect the dynamics of the heliospheric field, and thereby can couple into the geomagnetic field if directed towards the Earth.

We determined the grid disturbance frequencies $f_a, f_r, f_i$ using three distinct selection criteria: (1) $f_a$ for intervals 2-5 d after major solar flaring (allowing for a range of CME propagation times and a 1 − 2 d period of ensuing geomagnetic activity as the CME passes Earth), (2) $f_r$ for 4-d intervals randomly selected within 50-d of major solar flaring (in order to remain reasonably within similar conditions for the grid otherwise) but not within 5-d of that flaring, and (3) $f_i$ for the first 4-d intervals prior to the selected reference dates of major solar flaring that end 7-d intervals of no major solar flaring, thus selecting periods of relatively quiescent conditions in geospace. When selecting dates for all X- or M-class flares, Table 2 shows $f_a$ = 0.151 ± 0.006 disturbances/day and $f_i$ = 0.126 ± 0.005 (with the uncertainties based on the numbers of events and assuming Poisson statistics). We thus find a substantial increase in

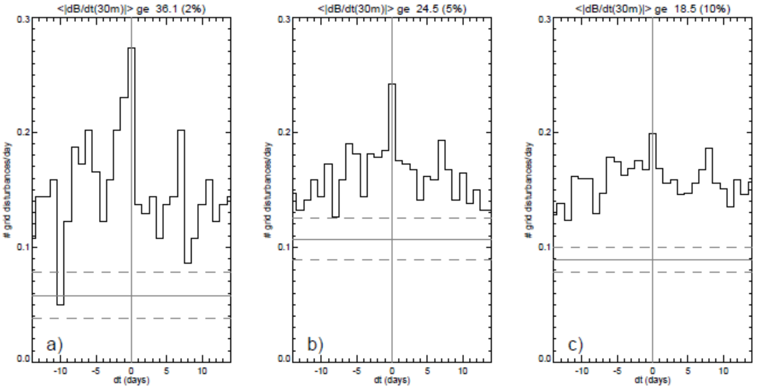

Figure 1. *Superposed epoch statistics of U.S. grid disturbances for days of geomagnetic activity as measured by the maximum dB/dt in 30-min. intervals, averaged for the U.S. BOU and FRD stations (|dB/dt(30m)|) for the top 2, 5, and 10 percent of dates between 1992 and 2010, respectively. In each panel, the horizontal grey line and the dashed lines adjacent to it show the disturbance rates under quiescent space-weather conditions (i.e., the values of* $g_i$*, see Section 3 and Table 1) and their standard deviations, respectively.*

the frequency of grid disturbances in the days following major flaring relative to quiescent intervals, at a significance of about 4.5σ.

Note that $f_r$ is not significantly different from $f_a$: with 1054 days of X or M flaring mostly concentrated around cycle maximum, randomly selected dates within 50-d from a flare frequently yield dates only days after another major flare. When we select only days with at least one X-class flare, the chance of such overlaps is lowered: in this case $f_a$ exceeds $f_r$ by about 2σ, while $f_a$ exceeds $f_i$ by 3.6σ. Dates with more than one X flare show an even more pronounced difference, but uncertainties for the relatively small sample are large.

To estimate the total number $N_T$ of grid disturbances added to the background grid variability by solar activity, we multiply $f_a - f_i$ by the number of independent dates found within the set of 4-d periods 2-d after major flaring, yielding $N_T = 50 \pm 16$, or 4.1 ± 1.3% of all disturbances.

Tables 1 and 2 also contain information on the grid disturbance frequencies when separating them into two broad categories. One category (WET) contains clear attributions to weather (including hot and cold weather, wind, ice, and lightning; 637 entries), external factors (fires, sabotage, earthquakes, collisions, etc.; 63), and technical issues (fuel shortages, maintenance, etc.; 43 entries). The complementary list (U, with 473 entries – not shown explicitly) contains causes such as 'line fault', 'operator error', 'public appeal', 'voltage reduction', 'load shed', 'equipment failure', etc., for which no clear correlation with weather, external, or technical issues is listed. The contrasts between $g_a$ and $g_i$ for days with geomagnetic activity in the top percentiles for the both types of events are statistically comparable to those of the full sample. The same is true for the contrast between the conditional grid disturbance frequencies given flare activity, i.e., $f_a / f_i$ for high, medium, and moderate flaring activity.

In conclusion, we find a statistically significant enhancement in the frequency of power grid disturbances on days of high geomagnetic activity, regardless of which measure for geomagnetic activity we use: a metric for 30-min. variability centered on the U.S. (for which the results are shown graphically in Figure 2), a metric for the 3-h (Kp) variability for high latitudes around the globe, or when looking at intervals following days of major solar flaring. This enhancement means that at least ≈ 4% of reported grid disturbances are attributable in whole or in part to enhanced geomagnetic activity. We note that although significant, the fraction of grid disturbances that we find attributable to GIC effects is relatively small, so that the overall number of disturbances attributable to space weather is small even during periods of severe solar activity: even on days with the most extreme geomagnetic activity, only

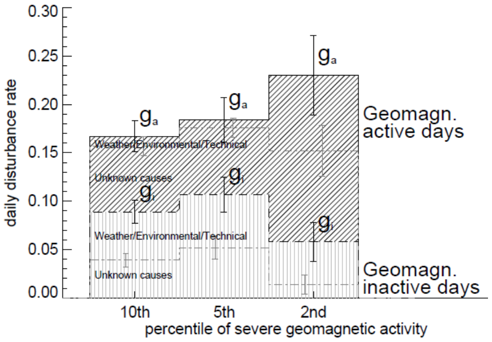

Figure 2. *Graphical rendition of the grid disturbance rates under different levels of geomagnetic activity, as listed in Table 1. The three columns show the results for geomagnetic activity in the 10th, 5th, and 2th upper percentile of geomagnetic activity as measured by |dB/dt(30m)|, respectively. The difference between geomagnetically active and nearby inactive days is shown by dark shading.*

$\approx ((0.23 \pm 0.04) - (0.06 \pm 0.02)) = 0.17 \pm 0.05$ disturbances per day would expected in association with severe space weather (using numbers from Table 1).

## 4. Estimating the cost of power grid disturbances associated with space weather

Estimating the economic impact of grid disturbances involves a multitude of factors: power losses may occur outside of productive hours or may interrupt the continuous process manufacturing sector; grid disturbances affect residential and industrial customers differentially (with particular sensitivity in the digital economy sector and in the continuous processing sector); and they may require substantial periods before full industrial productivity or service can resume. A DOE report [US Dep. of Energy, 2003; Lineweber and McNulty, 2001] puts the costs of “power outages and power quality disturbances” to the overall economy between $25 billion and $180 billion annually.

In order to estimate the economic impact of electric power disturbances associated with solar flaring, we here rely on a study reported on by the Electric Power Research Institute (EPRI) [Electric Power Research Institute, 2003], and executed for the Consortium for Electric Infrastructure to Support a Digital Society” (CEIDS) [Lineweber and McNulty, 2001]. That study looked at all disturbances in the electric power supply including, ”power outages (the complete absence of voltage, whether for a fraction of a second of several hours)” and ”power quality phenomena (all other deviations from perfect power, including voltage sags, surges, transients, and harmonics).” The study assessed the economic impact of all such disturbances which reach well beyond the period of the disturbance itself because of the time it takes to resume full productivity or service. Electric power disturbances also lead to damage to equipment or to spoiled or lost materials. All of those costs were included in the study.

The study focused on the three most sectors in the US economy that are particularly influenced by electric power disturbances: the digital economy (including telecommunications), the continuous process manufacturing (including metals, chemicals, and paper), and the fabrication and essential services sector (which includes transportation and water and gas utilities). These three sectors contribute approximately 40% of the US Gross Domestic Product (GDP).

The report states that “whereas [t]he electric utility industry has long been aware that power disturbances can cause economic losses for business customers”…”[r]eliable, national data to back up this assertion and quantify the losses [...] have been surprisingly scarce.” This lack of information was one of the prime motivators of that study.

The report is based on information collected in questionnaires from a sampling of 985 out of a total of about 2 million businesses in these three sectors. The surveys assessed impact using ”direct costing” by combining statistics on grid disturbances and estimates of costs of outage scenarios. Information was gathered on grid disturbances of any type or duration, thus resulting in a rather complete assessment of the economic impact. The resulting numbers were corrected for any later actions to make up for lost productivity (actions with their own types of benefits and costs).

The study found that businesses are affected by 3.9 electric power outages in a typical year, with 49% of these less than 3min. in duration (which are ”often not recorded in the ’official’ outage statistics maintained by utilities and public utility commissions” according to Lineweber and McNulty [2001]). The frequency of electric power quality problems for businesses is, on average, 8.3 per year.

For a typical year (excluding, e.g., years with scheduled rolling blackouts due to chronic shortages in electric power supply), the total annual loss to outages in the sectors studied is estimated to be $46 billion, and to power quality phenomena almost $7 billion. Extrapolating from there to the impact on all businesses in the US from all electric power disturbances, Lineweber and McNulty [2001] find a range from $119 billion/year to $188 billion/year.

If we assume that the set of grid disturbances associated with severe space weather in our sample is comparable in properties to sample of all disturbances as studied by Lineweber and McNulty [2001], then our finding that ≈ 4% of electric grid disturbances are attributable to space weather suggests that the full economic impact may be as high as $5 billion up to $7.5 billion per year. If we conservatively assume that our correlations do not apply to the disturbances of less than 3min. (which are ”often not recorded in the ’official’ outage statistics maintained by utilities and public utility commissions” according to Lineweber and McNulty [2001]), then we can use the cost estimates of the longer outages only (thus ignoring the 13% impact of power-quality effects) that are associated with 1.10 times the cost of an average outages including the short-duration ones, so that the overall economic impact would lie in the range of $3 billion up to $5 billion per year (equivalent to 0.02% to 0.03% of GDP).

## 5. Discussion

Except in rare cases, solar energetic events and resulting geomagnetic activity are not presently recognized as contributing to power grid disturbances. In fact, no grid disturbance was thus attributed over the 19-y period studied in the NERC-DOE reports. This is to be contrasted to our finding (significant in excess of 4 standard deviations) that over the 19-y period of our study, ≈ 50 grid disturbances reported to NERC and DOE had strong geomagnetic and solar activity as a contributing factor.

The present lack of recognition of geomagnetic activity as a contributing agent in grid disturbances may reflect that, in contrast to extreme storms, moderate to severe space weather conditions do not by themselves cause such disturbances but instead increase the susceptibility of the electric power grid to a variety of other perturbations. These other perturbations may be identified as the cause of the disturbance, but our study leads us to conclude that sometimes geomagnetic activity is a contributing factor. One may think of parallels such as the activity of skiers that contributes to the triggering of avalanches particularly if conditions of snowfall and weather are right; or one may consider the effect of being engaged in cell phone calls on the likelihood of vehicular accidents in demanding traffic conditions. We conjecture that in the grid disturbances that we find to be influenced by geomagnetic activity, this activity may be the equivalent of the presence of a skier or of being on the phone in the above analogies. The U.S. power grid is, after all, a highly complex coupled system in which initially localized problems can cascade into disturbances of any size (characterized on the large end of the spectrum by a scale-free power-law distribution typical of nonlinear systems [Carreras et al., 2003; Talukdar et al., 2003]), compounded by the fact that GICs induced by space weather extend over a large fraction of the footprint of the U.S. electric power grid and thus can have effects in various locations simultaneously.

The estimated economic impact of the order of multiple billion dollars per average year stemming solely from electric power grid disturbances associated with pronounced solar and geomagnetic activity warrants the investigation and implementation of mitigation strategies and the support of a space weather research program as well the continued development of a space weather forecasting system. Such an investment would also help us to better understand what protection society would need if faced with more severe space weather than experienced in recent decades, or from more extensive cascading effects in our ever-more coupled technological infrastructure.

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## References

Andreeova, K., T. I. Pulkkinen, M. Palmroth, and R. McPherron, Geoefficiency of solar wind discontinuities, Journal of Atmospheric and Solar-Terrestrial Physics, 73 , 112– 122, 2011, doi:10.1016/j.jastp.2010.03.006.

Béland, J., and K. Small, Space weather effects on power transmission systems: the cases of Hydro-Qu´ebec and Transpower New Zealand Ltd, in Effects of space weather on technological infrastructure, edited by I. A. Daglis, pp. 287–299, Kluwer Academic Publishers, The Netherlands, 2004.

Boteler, D. H., and G. Jansen van Beek, August 4, 1972 revisited: a new look at the geomagnetic disturbance that caused the L4 cable system outage, Geophys. Res. Lett., 26 , 577–580, 1999.

Boteler, D. H., R. J. Pirjola, and H. Nevanlinna, The effects of geomagnetic disturbances on electrical systems at Earth's surface, Adv. Space Res., 22 , 17–27, 1998.

Carreras, B., V. Lynch, D. Newman, and I. dobson, Blackout mitigation assessment in power transmission lines, System Sciences, 2003, doi:10.1109/HICSS.2003.1173911, doi10.1109/HICSS.2003.1173911.

DOE. (2012). Office of Electricity Delivery and Energy Reliability. http://energy.gov/oe/office-electricity-delivery-and-energy-reliability and http://www.oe.netl.doe.gov/OE417 annual summary.aspx. Last Accessed June 2012.

Electric Power Research Institute, Electricity sector framework for the future. Vol. I. Achieving a 21st Century transformation, EPRI, Palo Alto, CA, 2003.

FEMA, M., NOAA, Managing critical disasters in the transatlantic domain - the case of a geomagnetic storm, FEMA, Washington, DC, 2010.

Forbes, K. F., and O. C. St. Cyr, Space weather and the electricity market: an initial assessment, Space Weather , 2 , S10,003, 2004, doi:10.1029/2003SW000005.

Forbes, K. F., and O. C. St. Cyr, Solar activity and economic fundamentals: evidence from 12 geographically disparate power grids, Space Weather, 6, S10,003, 2008, doi:10.1029/2007SW000350.

Forbes, K. F., and O. C. St. Cyr, An anatomy of space weather's electricity market impact: case of the PJM power grid and the performance of its 500 kV transformers, Space Weather , 8 , S09,004, 2010, doi:10.1029/2009SW000498.

Hapgood, M., Lloyd's 360◦ risk insight: Space Weather: Its impacts on Earth and the implications for business, Lloyd's, London, UK, 2011.

Hapgood, M., Prepare for the coming space weather storm, Nature, 484, 311–313, 2012, doi:10.1038/484311a.

INTERMAGNET. (2012). Station data. http://ottawa.intermagnet.org/apps/dl data def e.php. Last accessed June 2012.

JASON, Impacts of severe space weather on the electric grid (JSR-11-320), The MITRE Corporation, McLean, VA, 2011.

Kappenman, J., Geomagnetic storms and their impacts on the US power grid (Tech. Rep. Meta-R-319 , Metatech Corp., Goleta, CA, 2010.

Kappenman, J. G., An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun-Earth connection events of 2931 October 2003 and a comparative evaluation with other contemporary storms, Space Weather , 3 , 2005, doi:10.1029/2004SW000128.

Kappenman, J. G., L. J. Zanetti, and W. A. Radasky, Geomagnetic storm forecasts and the power industry, Eos Trans. AGU, 78 , 37, 1997.

Lineweber, D., and S. McNulty, The cost of power disturbances to industrial and digitaeconomy companies, PRIMEN, Madison, WI, 2001.

NERC. (2012). http://www.nerc.com and http://www.nerc.com/page.php?cid=5|66. Last Accessed June 2012.

Newell, P., T. Sotirelis, K. Liou, C. I. Meng, and F. J. Rich, A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables, JGR, 112 , 2007, doi:10;1029/2006JA012015.

Pulkkinen, T., Space Weather: Terrestrial Perspective, Living Reviews in Solar Physics, 4 , 1, 2007.

Russell, C. T., and R. L. McPherron, Semiannual variation of geomagnetic activity., JGR, 78 , 92–108, 1973, doi:10.1029/JA078i001p00092.

Schrijver, C., and G. Siscoe, Heliophysics. Space storms and radiation: Causes and Effects, Cambridge University Press, Cambridge, U.K., 2010.

Schrijver, C. J., Driving major solar flares and eruptions: A review, Advances in Space Research, 43, 739–755, 2009, doi:10.1016/j.asr.2008.11.004.

Space Studies Board, Severe space weather events - understanding societal and economic impacts, National Academy Press, Washington, D.C., U.S.A., 2008.

Talukdar, S., J. Apt, M. Ilic, L. Lave, and M. Morgan, Cascading failures: survival vs. prevention, The Electricity Journal , 16, Issue 9 , 25–31, 2003.

US Dep. of Energy, Grid 2030: A national vision for electricity's second 100 years, DOE: Office of electric transmission and distribution, Washington, DC, 2003.

Veronig, A., M. Temmer, A. Hanslmeier, W. Otruba, and M. Messerotti, Temporal aspects and frequency distributions of solar soft X-ray flares, A&A, 382 , 1070–1080, 2002, doi:10.1051/0004-6361:20011694.

## Biographies

**Carolus J. Schrijver** received his doctorate at the University of Utrecht on the topic of solar and stellar magnetic activity. After postdoctoral appointments at the University of Colorado and the European Space Agency, and a fellowship of the Royal Netherlands Academy of Sciences, he now is senior fellow at the Lockheed Martin Advanced Technology Center. His research focuses on the magnetic activity of the Sun, the coupling of the Sun's magnetic field into the heliosphere, the manifestations of magnetic activity of other Sun-like stars, and the impact of solar variability on society. He co-authored the first textbook on solar and stellar magnetic activity and defined and continues in the leadership of the Heliophysics Summer School resulting in a textbook series on heliophysics as an integrated science.

**Sarah D. Mitchell** went to the University of Michigan for her BSE in Aerospace Engineering and San Jose State University for a dual MBA and MSE in Engineering Management. She began her career as a Research Programmer for the Cassini-Huygens program followed by becoming a Systems and Test Engineer for several solar science instrument programs at Lockheed Martin's Solar and Astrophysics Laboratory. Sarah served as the Flight Operations Manager for the Solar Dynamics Observatory AIA and HMI instruments and eventually the On-orbit Program Manager for the AIA instrument.