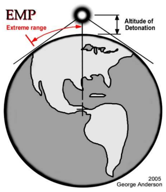
Protecting Our Power Grid

From EMP and Solar Weather Threats

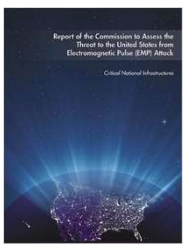
EMPRIMUS *Presented to the Minnesota State House Energy Committee on 2/7/2018 by Gale Nordling, CEO, Emprimus*



The Issue

There are two electromagnetic pulse effects that threaten the quality of our power and the stability of our power grid – those caused by nature (Solar Storms-GMD) and those caused by humans (EMP).

Naturally occurring solar storms currently impact customers by creating harmonics that damage equipment and cause $billions of business losses each year (see p2). In addition, within the past 25 years, numerous larger solar storms have damaged utility transformers, and have caused short-term blackouts to regional power grids, resulting in huge regional economic loss. A severe solar storm, similar to those recorded in 1921 and 1859 (well before our developed electrical grid), could result in large-scale, extended blackouts of our bulk power grid, causing societal chaos.



Background

The EMP & GMD issues were brought to public light through the Congressional EMP Commission Report, initially released in 2004 (unclassified summary), and then a more detailed unclassified report released in 2008. Since then, the threats have been studied by many government agencies, the electric utility industry, and private industry. For many years, the Department of Defense has been protecting (hardening) some of its critical facilities, but it still relies on the bulk electric grid for the significant majority of its power. All of our local and state first-responders rely on our power grid for communications and effective response.

Action To Date

As mentioned, many agencies and organizations (public and private) have been working on the various issues and solutions to protect the grid, and legislation has been introduced at both Federal and State levels in different forms. Since no specific leadership for protecting the grid as a whole has emerged, several individual states either have introduced, or currently are, introducing legislation to protect their citizens.

In 2011, the National Association of Regulatory Utility Commissioners (NARUC), through a Board Resolution, recommended that member States (PUC), ***"recognize and consider…design features rendering infrastructure less susceptible to the threat of damage from severe space weather and EMP…"***

The current Bill being contemplated by the 2018 Minnesota Legislature, **HF 2695,** will address the concerns for the power grid in the State of Minnesota that are raised in the EMP Commission's report, as well as the 2011 NARUC recommendations.

Solutions Exist

EMP - The shielding and filtering technologies to harden the facilities and controls systems used in power substations are known and have been proven over many years of use in mission critical installations.

GMD – Neutral blocking systems/devices to protect large transformers and other utility equipment have been installed and are operating successfully in the grid. ***Why is Action Important? Over***

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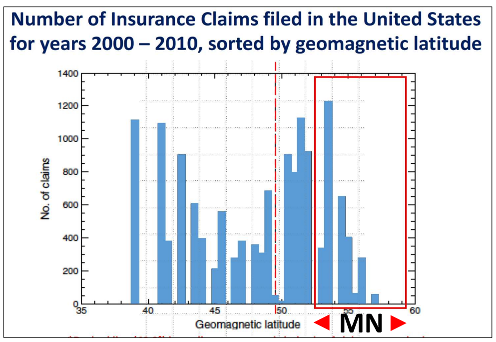
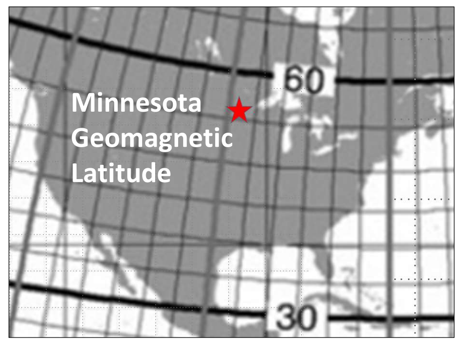
2015 Zurich Report

Current Economic Impact To Minnesota Businesses

In 2014 and 2015, Zurich Insurance released reports of a study conducted by Lockheed, Zurich, and NOAA that assessed the economic losses suffered by businesses in the United States. Over a 10 year period they correlated claims with low-level ordinary solar storms, and found that equipment damage and business interruption were estimated to be several billion dollars per year. While they did not present an estimate of economic loss state-by-state, they did include a graph of losses by geomagnetic latitude (shown below). Minnesota lies within a range of geomagnetic latitudes that suffer $$$Millions of business losses annually.





EMP and Low-Level GMD are not being addressed by the Utilities, NERC, or FERC

Why Is It Important For Minnesota To Take Action?

As in other states, the resilience of our power grid is, first and foremost, an urgent consumer right-to-know issue. Every Minnesota citizen and business is a direct 24/7consumer of the electric energy delivered to us via our sole source - our power grid. As participants in today's just-in-time, universally electrified society and economy, we are all at risk. As citizens and customers, we have the right to know and understand the degree of real risk to our grid's vulnerability from a growing range of threats, both natural and those due to terroristic actions, and what steps are being taken by our state's energy suppliers to defend it and assure its continued reliability.

Protecting Our Power Grid

from EMP and Solar Weather Threats

Gale Nordling, CEO, Emprimus

Presentation to the

Minnesota State House Energy Committee

February 7, 2017

EMPRIMUS

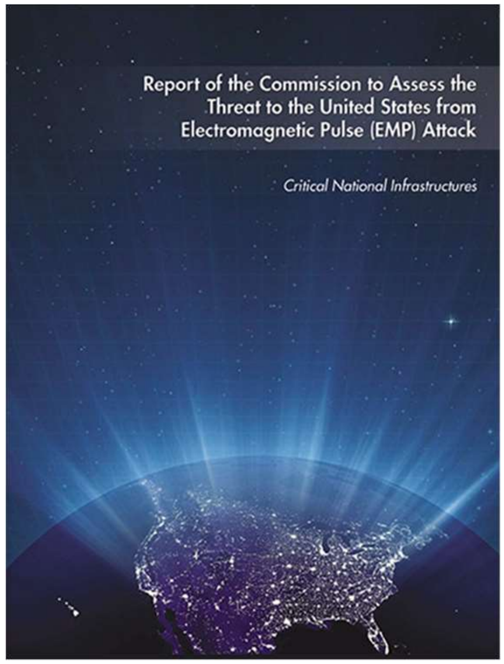
Introduction to EMPRIMUS™

Minnesota R&D Company focused on the development of equipment and systems that will protect our critical electric power grid and computer infrastructure from the threats of:

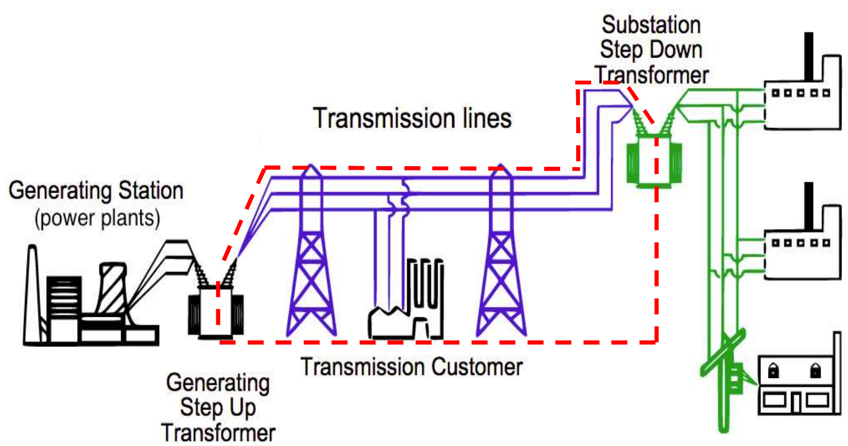
- *Solar Storms (GMD)*
- *Nuclear Electromagnetic Pulse (EMP)*
- *Intentional Electromagnetic Interference (IEMI)*

Congressional EMP Commission Report

- *Est. by NDAA-2001: 2004 Commission Report – Mostly Classsified*
- *ReEst. by NDAA-2006: 2008 Full Report Released*
  - *Long Term Power Loss - "Consequences Likely to be Catastrophic to Civilian Society"*
  - *EMP and GMD*
  - *15 Unclassified Recommendations*
- *Little Accomplished to date*



AC Power Distribution System



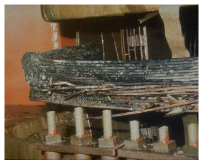
Quasi DC Current
Geomagnetically or E3 Induced

Impact of EMP and GMD on Power Grid

$$$$$

Current Impact – Annual Low-level GMD*

- ***Several $Billion Annual Business Loss***



1989 Salem, NJ

2003 South Africa

Potential Impact from EMP & Severe GMD

- ***Irreparable Damage to Transformers & other equipment***
- ***Grid Voltage Collapse***
- ***Long Term Power Outage***
- ***"Catastrophic" Consequences to Society***
  EMP Commission Report

- ***2014 & 2015 publication by C. J. Schrijver et.al. at Lockheed Martin, Zurich and NOAA**

Current Business Losses - Low Level Solar Storms

Several $Billion in business losses ***each year*** in the United States (2000-2010) due to common low-level solar storms.

Caused by Induced Poor Quality Power - i.e. GIC related Harmonics

AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE

Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

C. J. Schrijver, R. Dobbins, W. Murtagh, and S. M. Petrinec

Abstract

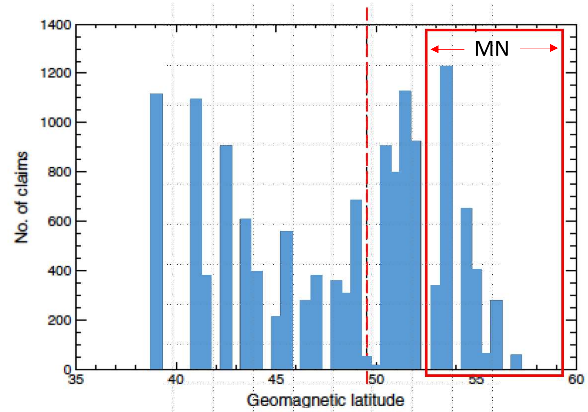
1. Introduction

Electrical Claims and Space Weather: Zurich, June 2015

Insurance Study By Lockheed/Zurich/NOAA: C. J. Schrijver, R. Dobbins, W. Murtagh, and S.M. Petrinec Space Weather Journal, 2014

Current Business Losses - Low Level Solar Storms

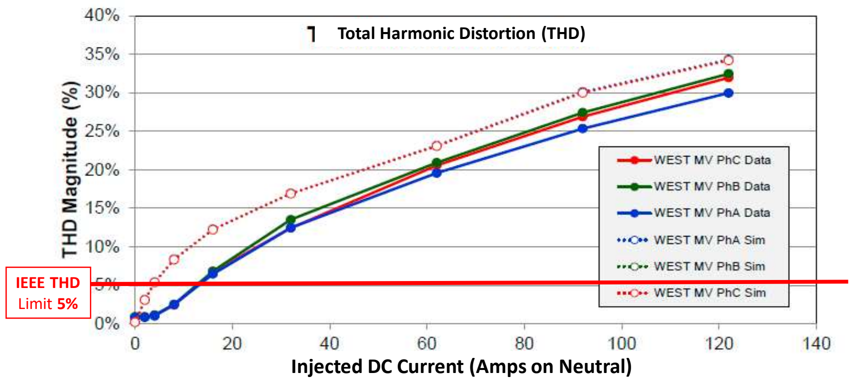
Number of Insurance Claims filed in the United States for years 2000 – 2010, sorted by geomagnetic latitude



*Dashed line (49.3°) is median geomagnetic latitude of claims researched
Box shows Minnesota range of latitude

"**Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment**", Figure 2, Lockheed/Zurich/NOAA, Space Weather Journal, 2014

Secondary Harmonic Trends



- **Above 5 Amps DC <u>per phase</u> the IEEE 519 Std. of 5% Total Harmonic Distortion <u>was exceeded</u>.** *This data helps explain why small amounts of GIC (DC current) on our AC power grid cause major customer problems each year. As Total Harmonic Distortion increases, business interruptions increase as well as the risk of damage to customer equipment.*

*Graph from the U.S. Defense Threat Reduction Agency (DTRA) test results measured on the Idaho National Laboratories Grid in 2012.

Minnesota GIC Risk

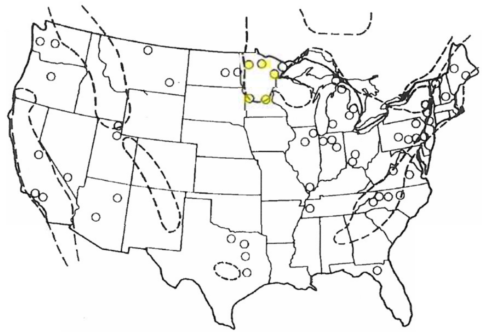


Figure 1. Locations of GIC Recorders on Power Systems from 1969-1972 (Indicated by Circles). Dotted Lines Outline Areas of Igneous Rock Geology.

As shown in figure 2 (from references 2 and 3), solar cycle 20 had an abnormally low number of geomagnetically disturbed days from 1969-1972. Even so, there were 111 geomagnetic storms of intensity K-5 or greater from March 1, 1969 through September 29, 1972 as measured by the planetary K index, K_p. Table 1 summarizes the K_p levels for that time period, however, it must be noted that the data in table 1 are global statistics, and should not be interpreted to mean that all of those geomagnetic disturbances were concentrated over the U.S. or Canada.

TABLE 2
GIC Recorded in Transformer Neutrals
March 1969 - September 1972 (39 months)
Sequenced by Maximum GIC

NO.	COMPANY	SUBSTATION	MAX. GIC NEUTRAL AMPS	AVE. NO. GIC INDIC./MO.	AVE. GIC PER INDIC. AMPS
1	Newfoundland and Labrador Power	Corner Brook	100 +	39.00	16.50
2	Philadelphia Electric Co.	Whitpain No. 1	98	3.92	9.89
3	Philadelphia Electric Co.	Whitpain No. 3	86	4.95	9.28
4	Philadelphia Electric Co.	Peachbottom	76	6.35	10.25
5	Consolidated Edison Co.	Pleasant Valley	68	1.82	13.40
6	Virginia Electric Power	Elmont	68	4.22	7.97
7	Minnesota Power	Arrowhead	58	6.91	7.65
8	Pennsylvania Power and Light	Juniata No. 2	48	3.83	8.37
9	Otter Tail Power Co.	Bemidji	44	4.18	6.38
10	Pennsylvania Power and Light	Juniata No. 1	44	3.75	11.42
11	Central Maine Power Co.	Bucksport	32	2.41	6.73
12	Central Main Power Co.	Wyman Hydro	32	3.35	7.11
13	Consolidated Edison Co.	Sprain Brook	32	1.30	7.78
14	Minnesota Power	Silver Bay	28	4.29	7.11
15	Texas Electric Service	Everman	24	2.34	6.33
16	Southern California Edison	Sylmar	22	2.40	7.84
17	Otter Tail	Winger	20	2.89	5.66
18	Niagara Mohawk Power	Rotterdam	18	0.91	7.11
19	Metropolitan Edison Co.	Hosensack	16	3.76	5.70
20	Metropolitan Edison Co.	N. Temple	16	0.55	4.36
21	Northern States Power	Black Dog	16	1.81	6.25
22	Northern States Power	Minnesota Valley	16	1.47	8.40

One of the geomagnetic storms that occurred during the period covered by tables 1 and 2 was a K-8 storm on August 4, 1972. Figure 3 is a map showing where disturbances were noted on power systems during that storm, and figure 4 is an example of the GIC recorded during the storm, at the Arrowhead Substation of Minnesota Power [5].

EPRI Report on Geomagnetically Induced Currents Conference - 1992

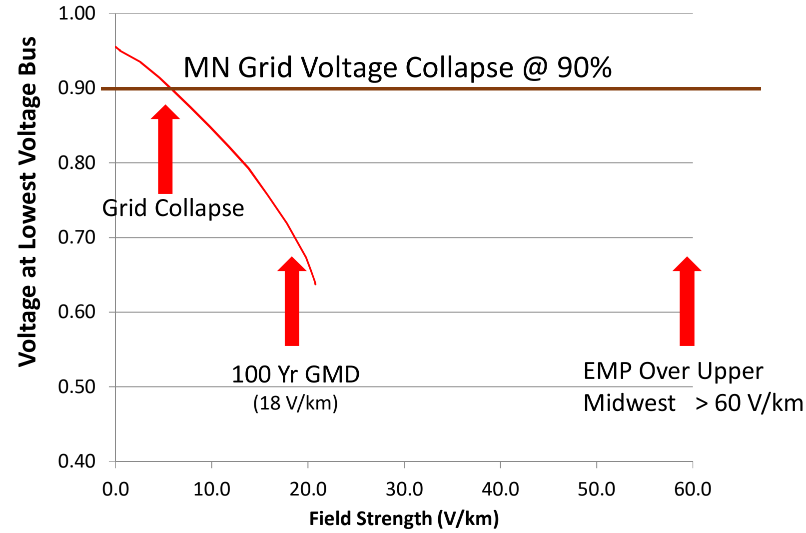
GIC Must Be Blocked

Operational Procedures Alone Are Inadequate

"Utility operating procedures when a GMD event is anticipated, do not reduce the GIC in the network or reduce GIC related harmonics. Therefore, operating procedures do not reduce the potential for misoperation of relays, transformer damage or generator rotor damage. GIC must be blocked or significantly reduced to ensure the stability and reliability of the grid."

**HV Power Transformer Neutral Blocking Device (NBD) Operating Experience in Wisconsin*
D. Wojtczak, F. R. Faxvog, M. B. Marz, G. Fuchs, W. Jensen, S. R. Dahman

Minnesota Grid Collapse for Severe GMD



MN Grid Voltage Collapse Predicted for GMD & EMP Event

Solutions are Available

Electromagnetic Pulse (EMP) Components

E1 Fast, Brief, Intense	**Shielding** **Filtering**	
E2 Intermediate (Lightning)	**Lightning** **Arresters**	
E3/GMD Slow, Long, Inductive	**Neutral** **Blocking**	

NARUC (National Association of Regulatory Utility Commissioners)

- **July, 2011 Board Resolution**
  supporting:

  "Protection of Utility Infrastructure against Electromagnetic Pulse Effects"

> ***"NARUC member States recognize and consider…design features rendering infrastructure less susceptible to the threat of damage from severe space weather and EMP…"*** ***NARUC Board, July, 2011***

- **2011 Report:**
  Resilience in Regulated Utilities

- **2014 Report:**
  Resilience for Black Sky Days

Utility Industry Action to Date

- ***1983 MN. Power / U of M / EPRI developed GMD Capacitor Solution – Not Implemented***
- ***1992 EPRI Reiterated Capacitor on Neutral Solution – Not Implemented***
- ***State Utility Tariffs Protect Utilities from Liability***
- ***Utilities (NERC) Write Own Regulations / FERC Approves or Rejects***
- ***2016 NERC developed GMD Standard considered low by many experts, working on EMP Standard***
- ***Some hardening occurring***

No Efforts Being Made to Protect Against Low Level Solar Storms

Customers Bear Losses From GMD

Minnesota Tarriff

- Sheet 6.4 section 1.4 - Continuity of Service

- The Company … *does not guarantee an uninterrupted or undisturbed supply of electric service.* ***The Company shall not be responsible for any loss or damage resulting from the interruption or disturbance of service for any cause other than gross negligence of the Company.*** *The Company shall not be liable for any loss of profits or other consequential damages resulting from the use of service or any interruption or disturbance of service.*

State Legislative Action

- **Many States Active**
  - ***Maine: Bill Passed, 2013***
  - ***Texas – Bill Introduced 2016 & 2017 (Current)***
  - ***Arizona, Kentucky, Texas, Florida, Virginia, South Carolina, Colorado - Discussions***

Minnesota Bill: HF2695

Study MN Grid Vulnerability to Geomagnetic Disturbances (GMD) and Electromagnetic Pulse (EMP)

- ***Potential Disturbances that may impact MN grid***
- ***Existing system for predicting solar storms***
- ***Steps Utilities, private and public sectors can take to minimize grid vulnerability***
- ***How to maintain and restore communications systems after grid damage***
- ***Emergency planning efforts/concerns regarding grid damage***

Suggest Adding "Low Level and Severe" GMD

Janney Report – January 18 - 2018

Janney

Grid Resiliency From Electromagnetic Threats; the Infrastructure Plan Provides an Opportunity for Substantial Investment

"Given most utilities are likely to reduce rates to customers due to the recent lowering of the corporate federal tax rate…tax savings could be redeployed into ..resiliency investments."

Current Tarriff Structures Being Challenged

Definition of Gross Negligence

Presentation to the

Minnesota State House Energy Committee

February 7, 2017

EMPRIMUS

Michael Gaugler 215-665-1359 mgaugler@janney.com

January 18, 2018

INFRASTRUCTURE

Grid Resiliency From Electromagnetic Threats; the Infrastructure Plan Provides an Opportunity for Substantial Investment

- Given a confluence of events (the U.S. government's plans for a $1 trillion infrastructure investment and the geopolitical tensions currently being experienced as they relate to North Korea's nuclear program), we've examined the investment needs and opportunity for hardening of the United States electrical grid against Geomagnetic Disturbances (GMD) and Electromagnetic Pulse (EMP) events. What we found is that hardening against such attacks is possible, but will require significant leadership and coordination among federal agencies, state public utility commissions, grid operators and electric utilities.
- Reliable estimates of the total cost to ensure resiliency from electromagnetic pulse and geomagnetic events are wide-ranging. One offered to Congress from a special commission assembled to address this issue in 2004 recommended spending $10B to $20B (in 2004 USD) over a 20 year period, for a total investment ranging from $200B to $400B, but other estimates are as low as $10B to $30B. Given that solutions to achieve significant resiliency already exist and could be considered "shovel-ready", our view is that interested stakeholders should immediately press the political establishment to provide some level of funding for this endeavor. Given most utilities are likely to reduce rates to customers due to the recent lowering of the corporate federal tax rate from 35% to 21%, perhaps tax savings could be redeployed into the aforementioned resiliency investments. Other options could be special utility programs such as those used to address natural gas distribution pipe replacement for safety purposes, which have been successful in recent years.
- Grid reliability investment could easily be targeted to U.S.-based corporations, benefitting shareholders, workers, tax collections and the U.S. economy. The U.S. already possesses a handful of transformer manufacturers, and utilities/transmission operators and construction companies could substantially benefit. These would be highly skilled, high-paid jobs, the very type the current U.S. government administration is targeting to create more of. The benefits would be spread across the entire country, in both red and blue states, particularly those with dense population centers.
- Hardening will likely require a phased approach, based on 1) the natural replacement cycle of equipment, 2) focusing initially on protecting the largest, most important transformers, 3) investments in Regional Transmission Operators (RTO's) and Independent System Operators (ISO's), 4) communication hardening, and 5) generators and their "black-start" capability. Our report provides a brief overview of the grid, the threats to it, and partial potential investment opportunities for companies within (and a select group outside) our coverage universe focused in the Northeast and Mid-Atlantic regions.

RESEARCH ANALYST CERTIFICATIONS AND IMPORTANT DISCLOSURES ARE ON PAGES 16 - 17 OF THIS REPORT

REPORT OVERVIEW

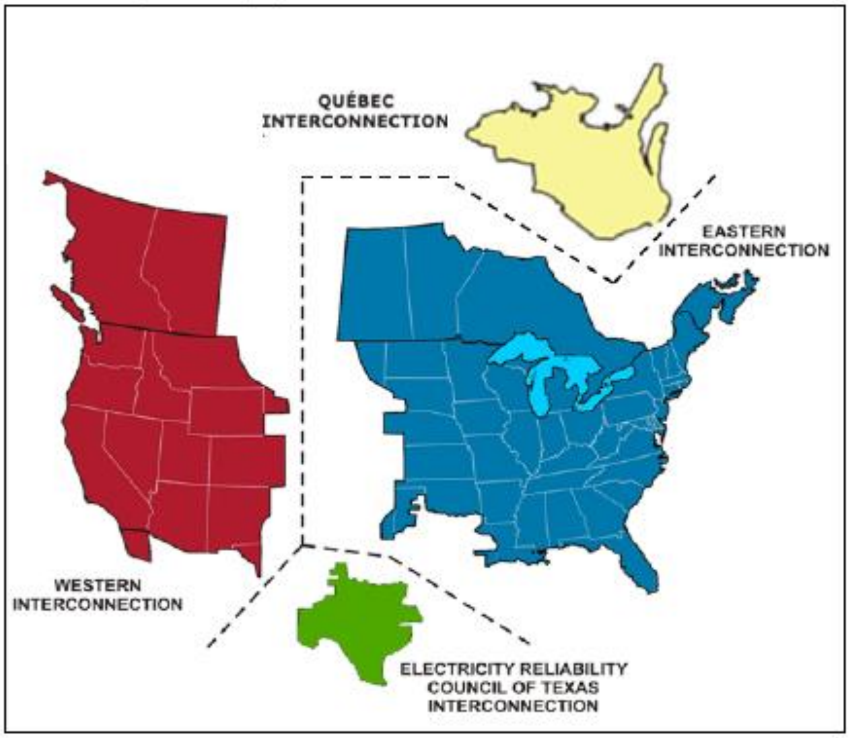
We see the potential for significant capital investment opportunities across the U.S./North American electrical grid. We believe a confluence of events, including a renewed focus by the U.S. government on infrastructure improvement (and commitment that could approach $1 trillion USD), the United States resolve to prevent the further spread of nuclear weapons across the world, and greater public awareness of electromagnetic threats could converge to create a real commitment to grid resilience and reliability beyond those already identified and receiving funding for (weather events and cyber-attacks). We also believe the FERC's recent rejection of the DOE's notice of proposed rulemaking (NOPR), which would have rewarded large-scale "black start" assets like coal-fired and nuclear generators with on-site fuel stockpiles could result in additional reliability focus (and pressures) on a grid increasingly reliant on markets where natural gas continues to take market share. While FERC has tasked the Independent System Operators (ISO's)/ Regional Transmission Operators (RTO's) to examine resiliency/reliability outside potential electromagnetic threats, the unintended consequence of the approach could result in more attention on transformer and digital protective relays (DPR) weaknesses. This topic has been broached at the federal level fairly recently; former Representative Henry Waxman (D-CA-33) introduced House Resolution 4298 (Grid Reliability and Infrastructure Defense Act) on 3/28/2014 that would have, among other things "directed FERC to order the Electric Reliability Organization (ERO) to submit reliability standards requiring owners or operators of large transformers to ensure their adequate availability to restore promptly the reliable operation of the bulk-power system in the event that any such transformer is destroyed or disabled as a result of a reasonably foreseeable physical or other attack or a geomagnetic storm event". Other bills during the 113^{th} Congress were attempted (H.R. 2417 and S.2158) with similar goals; none became law.

We also note that should the investments we've outlined in this report become reality, it would provide high-paying jobs across the country and in some cases benefit "red" or "purple" states where many equipment suppliers are located, blue states where high population density demands more transmission/distribution infrastructure. Our purpose in this report is to 1) provide a brief overview of the electrical grid for background informational purposes and more importantly, the equipment specifically threatened, 2) identify the solutions and potential costs to rectify the problem, 3) identify the potential investment opportunity for companies within (and in some cases out of) our coverage universe, and 4) provide reinforcement to the opinion that no infrastructure at the civilian level is more important than the electrical grid, which provides the energy for such vital services as water/wastewater treatment, residential heating/cooling, medical facilities, national defense and transportation networks. Resilience against electromagnetic threats will ultimately depend upon the commitment to the endeavor; costs could range from $10B to protect only the most critical equipment to perhaps as high as $400B, which would take many years to complete, but could envelop regular equipment cycle upgrades.

THE GRID: A BRIEF OVERVIEW

The combined transmission and distribution network in North America (the United States, Canada and a small adjacent portion of Mexico) is known and commonly referred to as "the grid." Within the grid are four distinct power grids, known as interconnections. The Eastern Interconnection includes the eastern two-thirds of the continental United States and Canada from the Great Plains to the Eastern Seaboard. The Western Interconnection includes the western one-third of the continental United States, the Canadian provinces of Alberta and British Columbia, and a portion of Baja California Norte in Mexico. The Texas Interconnection comprises most of the State of Texas, and the Canadian province of Quebec is the fourth North American interconnection. The grid systems in Hawaii and Alaska are not connected to the grids in the lower 48 states. Exhibit #1 displays the four distinct power grids (interconnections).

Exhibit 1: North American Interconnection Map



Source: U.S. Department of Energy

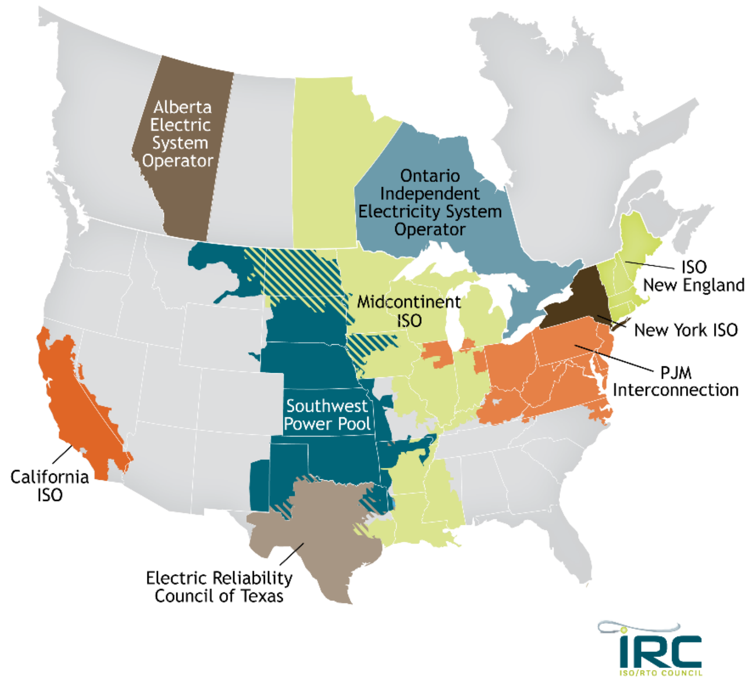
There are currently (7) Independent System Operators (ISO) within North America:

- CAISO – California ISO
- NYISO – New York ISO
- ERCOT – Electric Reliability Council of Texas; also a Regional Reliability Council
- MISO – Midcontinent Independent System Operator
- ISO-NE – ISO New England
- AESO – Alberta Electric System Operator
- IESO – Independent Electricity System Operator

There are currently (4) Regional Transmission Operators (RTO) within North America:

- PJM – PJM Interconnection
- MISO – Midcontinent Independent System Operator; also and RTO
- SPP – Southwest Power Pool; also a Regional Reliability Council
- ISONE – ISO New England; also an RTO

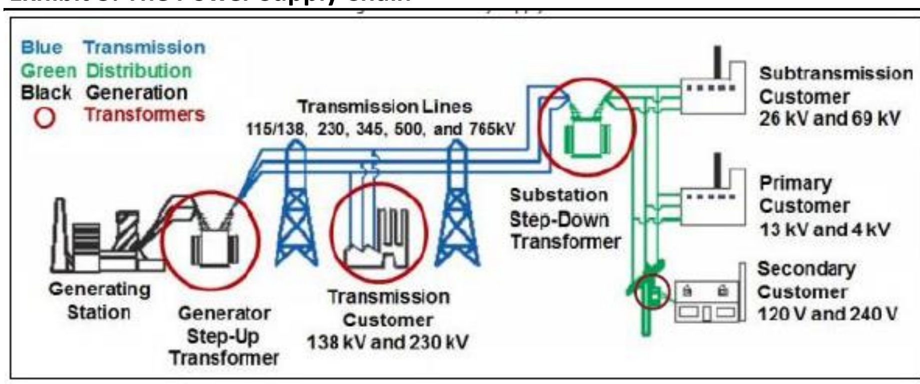
Exhibit 2: ISO/RTO Map



Source: ISO/RTO Council

The energy grid of the United States is comprised of generation, transmission and distribution that integrates 9,000+ electric generating units moving electricity across 200,000+ miles of high-voltage transmission lines rated at 230kV or greater. Generating stations use "step-up" transformers to increase voltage for transmission purposes; as electricity approaches its regional destination, substations use "step-down" transformers to decrease voltage, which is then distributed to end users such as industrial, commercial and residential end users. High voltage transformers comprise 3% of the total in transformer substations, but they carry 60-70% of the country's electricity. A basic diagram of how electricity is generated, transmitted and distributed is presented in Exhibit #3.

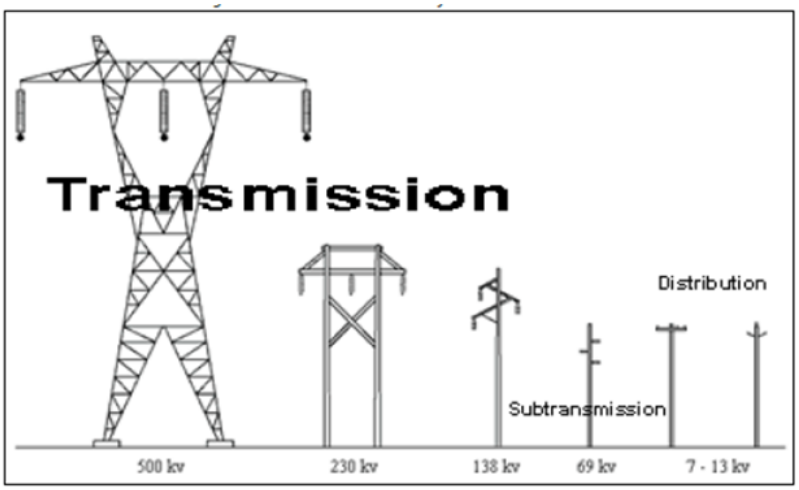
Exhibit 3: The Power Supply Chain



Sources: Federal Energy Regulatory Commission, U.S. Department of Energy

Transmission networks are defined as transmission lines that interconnect with each other that are separated from local distribution lines. Typical transmission lines operate at 765, 500, 345, 230, and 138 kV; the higher the voltage being transmitted, the larger the support structures and span lengths need to be, as shown in Exhibit #4.

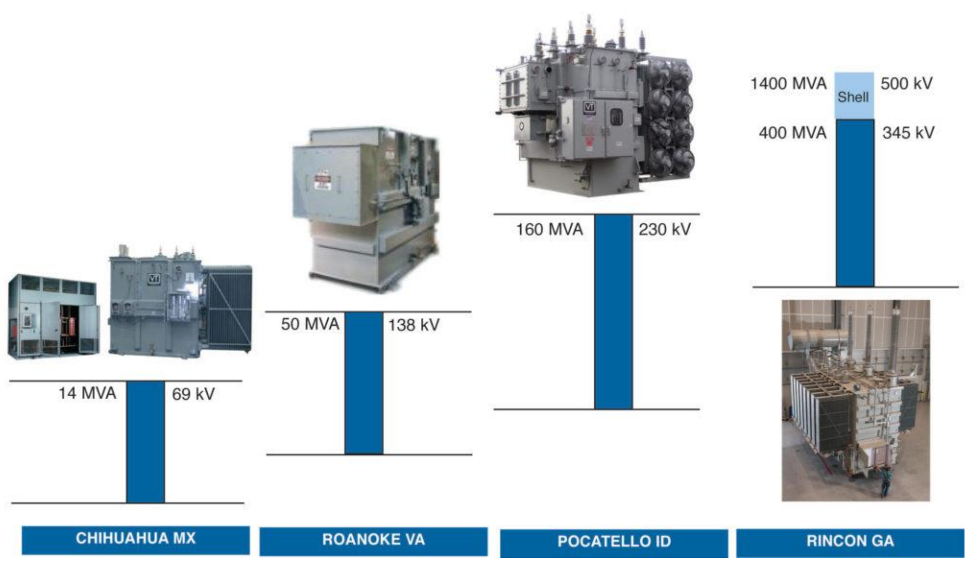
Exhibit 4: Transmission/Distribution Sizes (kV)



Source: U.S. Department of Labor, OSHA

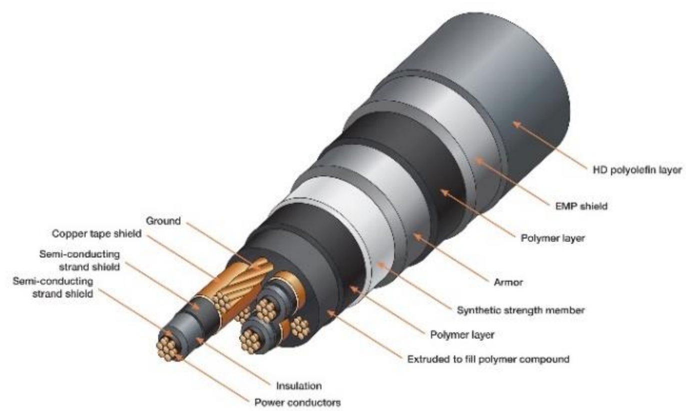
Within the transmission/distribution system interface points are equipment and components. For our purposes in the discussion of protection of equipment deemed "critical" from electromagnetic damage, we focus only on transformers, Digital Protective Relays (DPR's) and control cables (Exhibits #5, #6 & #7).

Exhibit 5: Various Transformer Sizes



Source: Virginia Transformer

Exhibits 6 (Digital Protective Relay) and 7 (EMP Shielded Cable)

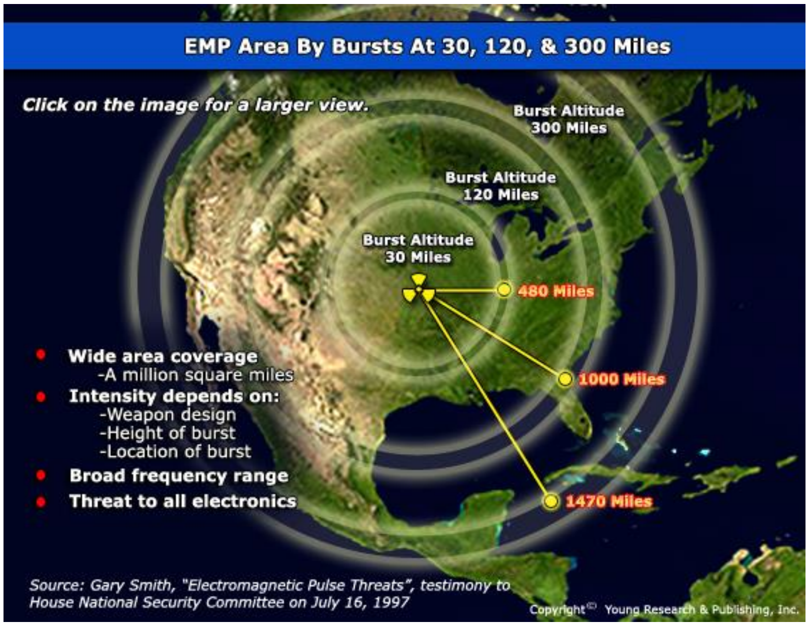


Sources: ABB, Aetna Insulated Wire

HOW DO ELECTROMAGNETIC EVENTS IMPACT GRID EQUIPMENT?

There are two specific grid threats we believe need to be addressed: intentional electromagnetic pulse (EMP) and geomagnetic disturbances (GMD) caused by solar flares. Recent geopolitical developments between North Korea and several other countries over its nuclear weapons program (and the threats those weapons pose) on a global basis has reignited the discussion over intentional electromagnetic threats. With respect to the North Korean situation, the focus is on the detonation of a nuclear warhead at high altitude that could send a HEMP (High-altitude Electromagnetic Pulse, or HEMP) into the North American airspace, causing catastrophic failure of critical electrical equipment (transformers and digital protective relays). The damage from a HEMP comes in 3 waves that can be spread across thousands of miles, referred to as E1, E2 and E3. "E1" has a duration of nano-seconds, but can damage many electronic components, from those found in vehicles with electronic fuel injection to computers and communication devices. The "E2" wave duration is slightly longer than E1, and resembles a lightning strike. The "E3" wave duration is longer, and has been proven in previous testing to damage large transmission equipment (transformers). Exhibit #8 illustrates how the altitude of a detonation can impact the range of effectiveness of an EMP.

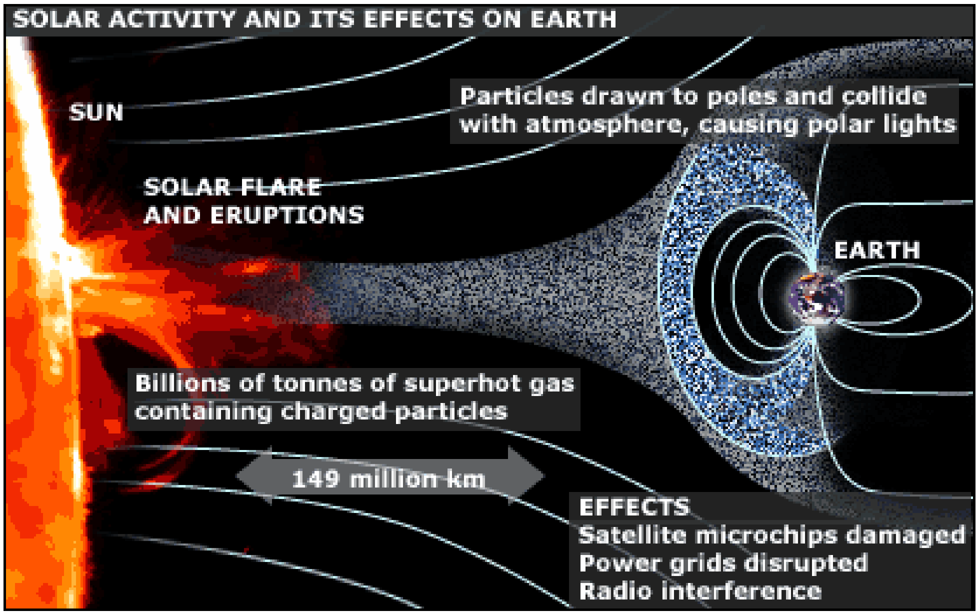
Exhibit 8: EMP Coverage by Burst Range, in Miles



Source: Young Research & Publishing, Inc.

Geomagnetic disturbances caused by solar flares can also inflict catastrophic damage on relays and transformers, and has does so. Examples include a severe geomagnetic storm caused by the sun's solar flare activity on March 13, 1989 that shut down Hydro-Quebec's electricity transmission system for 9 hours across Quebec, Canada. The aurora borealis that's typically only visible at the Earth's North and South Poles was visible as far south as Texas and Florida in the United States during that event. The most serious geomagnetic solar storm to hit the Earth is believed to have occurred on September 11th & 12th, 1859. Commonly referred to as the "Carrington Event" after the British astronomer that observed and recorded the event, the severity of the impact (if seen in modern day society) would likely disrupt and damage global electrical grids and electronics/communications. Reaction times are extremely limited; a solar flare's effect reaches Earth in approximately 8 minutes. The only known solution to prevent widespread disruption/damage would be a complete shutdown of electrical grids prior to the disturbance, which is highly unlikely. In the Quebec event in 1989, its speculated that the heavy rock formations upon which the transmission system is built upon provided some shielding and lessened the severity. Exhibit #9 displays the mechanics of how geomagnetic disturbances impact the Earth.

Exhibit 9: Geomagnetic Pathways/Impacts



Source: aviaton.stackexchange.com

WHAT STATE OF READINESS IS THE U.S. GRID IN TO WITHSTAND INTENTIONAL ELECTROMAGNETIC THREATS?

Put simply, it's not. Since the first atomic tests, the U.S. government (and the developed countries of the world) have been aware of the damaging impacts from electromagnetic pulses and geomagnetic disturbances. The U.S. military appears somewhat prepared; its E-4B fleet stationed at Offutt AFB, Nebraska (the Advanced Airborne Command Posts) are hardened to the point that they are expected to operate in the event of a nuclear-derived EMP event (the E-4B is built on a Boeing 747 platform; we believe it worthwhile to note that Boeing's Counter-electronic High Power Microwave Advanced Missile Project (CHAMP), in conjunction with the U.S. Air Force Research Laboratory (AFRL) Directed Energy Electorate, Kirtland Air Force Base, New Mexico has successfully tested flight-based weapons as far back as 2012 that produced EMP-like effects on electronics). The first studies related to HEMP impacts occurred on July 9, 1962 by the Atomic Energy Committee and the Nuclear Safety Agency of the Department of Defense of the United States of America (codenamed "Starfish Prime"). The extensive damage to the Johnson Attol, located in the Pacific Ocean is worthy of mentioning, given that it not only damaged electronic equipment, communications and overhead power lines, but disabled street lighting in the Hawaiian Islands.

The equipment in use in 1962 (in terms of complexity) was much simpler in design and operation than that in use today, which could make recovery from an event much more difficult. We count roughly 20 large entities in the United States studying this issue, including the following: Department of Homeland Security (DHS), EMP Commission of Congress, North American Electric Reliability Corp (NERC), Department of Energy (DOE), Department of Defense (DoD), Critical Infrastructure Partnership Advisory Council (CIPAC), Electric Infrastructure Security Council (EICS), U.S. Strategic Command (USSTRATCOM), Defense Threat Reduction Agency (DTRA), Defense Logistics Agency (DLA), Air Force Weapons Laboratory, Federal Bureau of Investigation (FBI), Sandia National Laboratories, Lawrence Livermore National Laboratories (LINL), Oak Ridge National Laboratory, Los Alamos National Laboratories, Federal Emergency Management Agency (FEMA), National Academy of Science, Federal Energy Regulatory Commission (FERC), Electric Power Research Institute (EPRI), National Aeronautics and Space Administration (NASA), and U.S. Northern Command, to name some (but not all) of researching participants on this topic. It seems fairly easy (to us) to understand why the grid has not been protected after 55 years of "research"; too many agencies without what we can determine to be a "clear leader" with a mandate to "get it done". Given the ultimate responsibility for the reliability of the grid rests with the FERC, we believe that regulatory body would be best suited to examine the options and provide guidance to implement a final solution (with assistance from the aforementioned agencies and state public utility commissions, as needed).

DO SOLUTIONS EXIST TO INSULATE THE U.S. GRID FROM HEMP (OR SIMILAR) EVENTS?

Solutions do exist to provide protection for critical infrastructure based in the United States/North America from intentional electromagnetic threats. Some solutions are rather simple, others require expensive, complex fixes. Starting with the E1 wave, equipment such as vehicular electronics, computers and cell phones not shielded can be rendered inoperable. Shielding for these types of equipment at the most simplistic level would be the use of "Faraday Shields" commonly referred to as "Faraday Cages". Faraday Shields can range in size from buildings to small boxes. The common element is that all interior spaces are shielded from damaging electromagnetic influences, which can be accomplished with grounding (insulation in these instances needs to be complete between the shielded surface (typically metallic) and interior electronic components). A simple metal box, completely sealed with foam insulation affixed to all interior surfaces is a most simplistic method of protecting electronic devices (the access point to the box must be sealed as well; common aluminum tape is one solution). In terms of utility-scale equipment, grounded metallic cages surrounding equipment can direct _some types_ of electromagnetic energy around critical equipment and allow the energy to dissipate to ground. An example of a Faraday-shielded power facility is displayed in Exhibit #10.

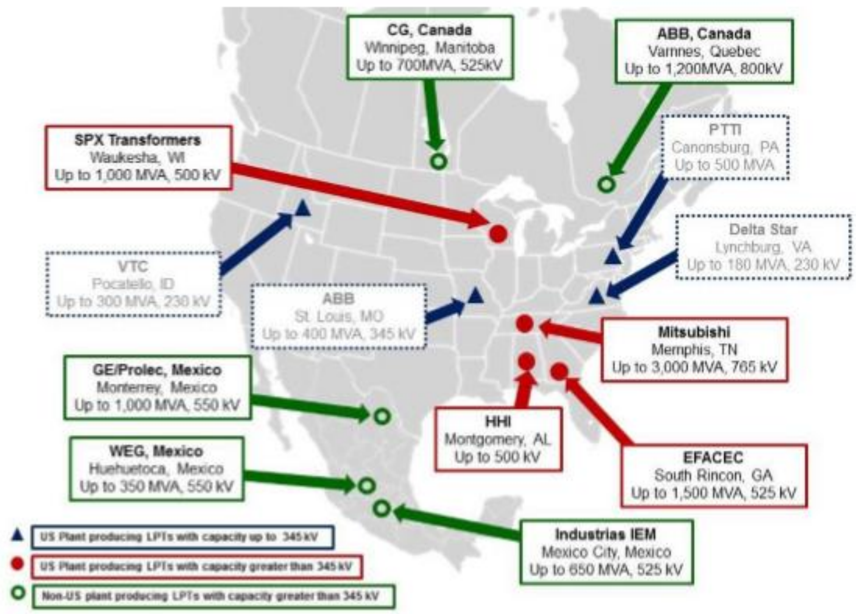
Exhibit 10: Faraday Shielded Enclosure

Source: Wikipedia

Faraday shielding is among the easiest and most commonly suggested solutions to preventing GMD/EMP-related damage to equipment, regardless of what threat is being guarded against. Control centers for ISO/RTO's can be shielded by locating equipment to interior rooms with no windows and doors capable of sealing against threats. That said, ISO/RTO control centers (and DPR's and transformers) have another problem; cables entering these buildings/equipment act as a collector for EMP energy. At the DPR level, housing equipment within Faraday-type cabinets and ensuring EMP-resistant cabling (Exhibit #7) is used on all connections entering the cabinet from the exterior would provide significant protection for DPR and DPR-related equipment.

Our research indicates that among the equipment hardest (and most expensive) to replace, transformers present the greatest problem. Unlike DPR's and associated equipment (which provide an opportunity to store extra equipment on-site in Faraday-shielded containments), transformers have long lead times to manufacture, number in the tens of thousands, can be difficult to transport and site, and a complete failure of all transformers would take years to rectify, given spare transformers are expensive to maintain in a utility's inventory and what is limited manufacturing capability in the United States. Exhibit #11 displays a map included in the 2014 Department of Energy update detailing U.S. manufacturers.

Exhibit 11: North American Transformer Manufacturing Locations



Source: U.S. Department of Energy

SUMMARY/OPINION

The topics of protection against EMP and solar derived geomagnetic storms have been under study by multiple agencies, including some specifically created just for the aforementioned task for several decades. The "research" and expenditure of funds continues onward, and yet we weren't able to identify any specific substantial investments made into actual grid protection from these threats. A key reference material we utilized to gain basic technical knowledge of the issues (and solutions) necessary to protect the grid were found in a recent book published by Wiley & Sons in early 2017 titled "*Protection of Substation Critical Equipment Against Intentional Electromagnetic Threats*" written by Vladimir Gurevich. The author's background in electrical engineering is extensive, both in the private sector and academia. Basic preventive actions suggested by V. Gurevich (preventing the Geo-magnetically Induced Currents (GIC) from entering systems via overhead power lines (OPL) by using a series capacitance battery inserted into the OPL wires or by blocking the GIC from entering the neutral inputs in transformers by inserting capacitors into the neutral earth circuit in series, Faraday shielding around critical equipment and EMP-resistant cabling) have been known and detailed solutions for many years, and that work should begin immediately, starting with the 5,000 largest high-voltage transformers currently in service. We estimate the entire 5,000 could be outfitted with state-of-the-art, field-tested and proven technology such as SolidGround™ GIC/EMP neutral blockers for approximately $3.75B. Additional protection could then be added incrementally to the remaining ground-mounted transformers over a period of years.

With the United States considering a $1 trillion infrastructure plan, our view is that some of those funds should be directed to the electric utility industry to immediately begin hardening the grid against all electromagnetic threats, with a focus on the most expensive, critical (and difficult) component to replace, the largest transformers. Allocating funds just to the 5,000 largest transformers would represent less than 1% of the anticipated infrastructure spend; it would also dovetail nicely into the President's recently-released "National Security Strategy of the United States of America" on 12/18/17, which mentions "the vulnerability of U.S. critical infrastructure to cyber, physical, and electromagnetic attacks" as something that needs to be addressed.

In terms of the beneficiaries of a funded push toward grid resiliency against electromagnetic threats, electric utilities and transmission operators would need to spend additional CAPEX, which would increase rate base. Significant work, performed over many years, would be necessary to harden existing assets with significant useful life remaining. This could benefit electrical suppliers and contractors. The jobs required to complete these tasks are typically high wage, requiring post-secondary education. The total costs to harden the grid depends largely on the level of threat being protected against and what equipment is being hardened; for a HEMP-related event, Mr. Gurevich suggests equipment designed to block GIC in the neutral circuits of transformers can cost more than $300,000 (an example of this type of equipment provided by ABB costing $500K (plus $250K to install/commission) is shown in Exhibit #12.

Exhibit 12: GIC/EMP Protection Equipment

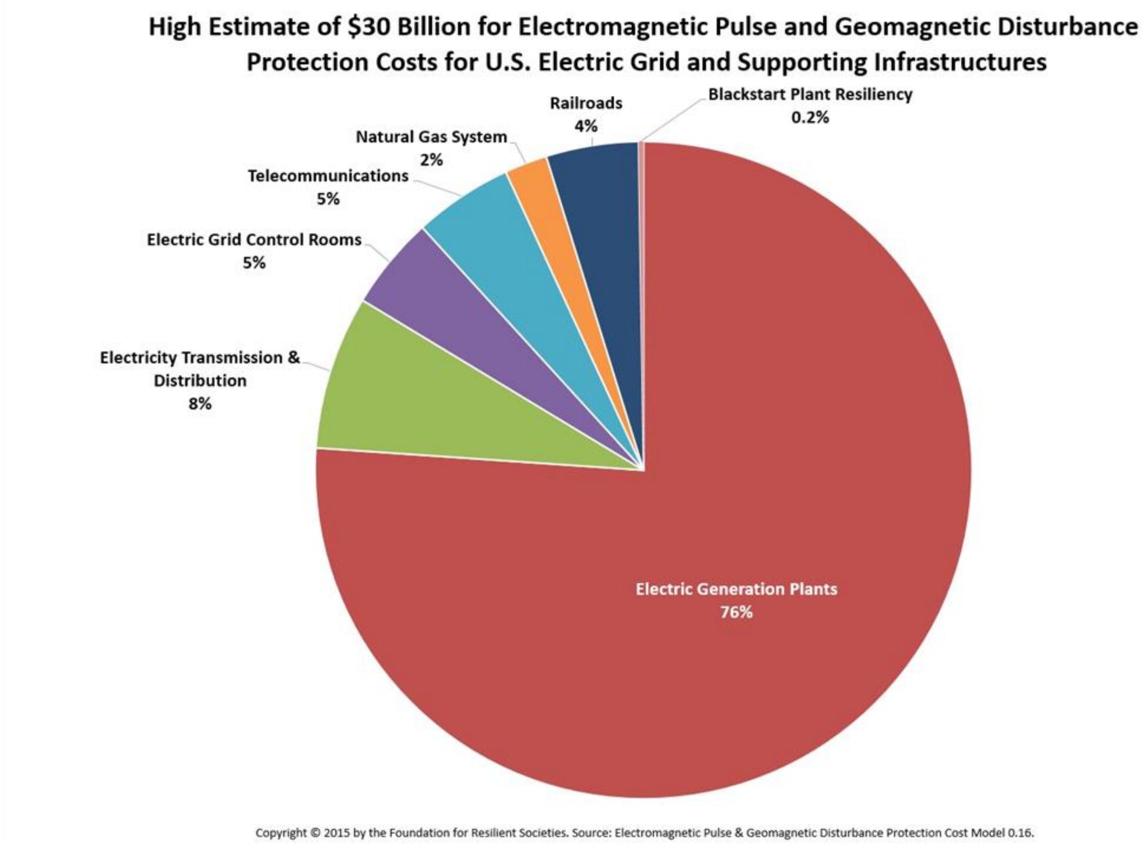
Source: ABB

Multiplying $750,000 by 50,000 or 70,000 ground-mounted transformers generates CAPEX costs of $37.5B to $52.5B and we note this estimate doesn't include costs necessary for the protection of DPR's by 1) Faraday shielding, most likely by locating equipment in specialized cabinets, 2) rewiring those relays with HEMP-resistant cable, or 3) the cost of locating critical spare parts at DPR and transformer locations in Faraday-shielded containers. Also not factored would be the cost of either procuring (and storing) specialized vehicles that would run after an event, or procurring the spare parts (and storing them in Faraday-shielded containers) so repair personnel can reach critical equipment in the field (vehicles made with electronics, typically those manufactured after 1985, would be susceptible to failure). One critical point we believe necessary to make is that naturally-occurring geomagnetic storms have a longer duration than EMP events, and pose (in our opinion) a greater threat to electrical grid stability given they are constantly damaging electrical equipment (a study by Zurich Insurance details several billion in losses each year from common low-level solar storms). Given the industry is experiencing billions of losses annually that exceeds the approximate cost to protect the largest 5,000 transformers, it would seem a logical course of action to protect this most critical of grid equipment (the savings from insurance claims alone should cover the protection equipment costs in either year 1 or year 2).

One other aspect we believe is worth mentioning is the potential legal liability utilities could face in a blackout scenario from GMD/EMP events. We've seen utilities come under pressure for lacking in natural disaster prepardedness (California for wildfires, Florida for hurricanes) given these are regularly occurring and forseeable natural events. While EMP's would likely not fall into that category, GMD's certainly would, and a severe disruption could result in substantial legal claims against utilities for a variety of reasons from all types of customers. The cost of some minimal investment by utilities could provide some level of protection against potential future litigation and financial liabilities.

Our research on official estimates of the total cost to protect the grid turned up several "opinions"; The Edison Electric Institute (an electric utility industry organization) states that cost estimates to protect the grid have not shown to be reliable or accurate http://www.eei.org/issuesandpolicy/cybersecurity/Documents/Electromagnetic%20Pulses%20%28EMPs%29%20-%20Myths%20vs.%20Facts.pdf. Perhaps the most extensive work done on the issue of assigning potential costs to grid reliability has been done by the Foundation for Resilent Societies http://www.resilientsocieties.org/research.html. They've produced both a high and low estimate; we display the high estimate ($30B) in Exhibit #13.

Exhibit 13: Resilient Societies High Estimate



Source: Resilient Societies

The Resilient Societies estimate is available in excel format at the web site; we note that it incorporates into its forecasts only "several thousand" protected transformers; it appears to us that its estimates accepts some level of disruption within the grid among transmission/distribution equipment. We know that the number of sizable transformers within the grid is substantial; for selected utilities within the Mid-Atlantic/Northeast, it totals in excess of 18,000. The ultimate cost for grid protection depends upon how secure the society wants it to be.

Congress has moved to renew funding for The Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack as part of the National Defense Authorization Act. In a Bloomberg article dated 12/22/17 https://www.bloomberg.com/news/articles/2017-12-22/hardening-power-grids-for-nuclear-and-emp-attacks-by-north-korea, New Jersey Board of Public Utilities President Richard Mroz was quoted that the costs to prevent widespread failures would be "astronomical", and that placing transformers or substations in shielded cages would cost hundreds of millions of dollars, while the protection of critical assets just for the State of New Jersey could reach into the billions of dollars. Based on our research, President Mroz's estimates would appear to be conservative in terms of protecting transformers, but certainly correct in terms of overall costs for the State of New Jersey (we've compiled some estimates for utilities operating in New Jersey and the Northeast/Mid-Atlantic region later on in this report). In his book "A Nation Forsaken: EMP, the Escalating Threat of an American Catastrophe" author F. Michael Maloof, on page 79 indicates that the 2004 report presented to Congress from the aforementioned Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack as recommending spending $10B to $20B annually over 20 years ($200B to $400B, again in 2004 dollars). We reviewed the publicly-available documents from the Commission's work in 2004, and could not find the cost estimates mentioned, but again, based on our research into the topic, those figures (which were based on 2004 dollar purchasing power) could be fairly accurate if the United States decides to protect its entire grid from EMP/GIC events. If the costs are exceptionally high, perhaps a phased in approach (starting with the largest transformers) over many years under special programs such as those used to replace natural gas distribution pipe could be similarly utilized. Utilities also have a windfall from the recent reduction in U.S. income tax rates; perhaps that could be another avenue for covering costs associated with grid resiliency against GMD/EMP.

For companies within our coverage universe, **Eversource Energy (ES, BUY, $71 Fair Value estimate)** lists its transformers in its annual 10K report as totaling 538,032 (this includes the small transformers on utility poles). For our purposes, we're most interested in the ground-mounted transformers ranging in size from 69kV to 345kV, which we view as critical equipment and would be most likely to receive resiliency investment in the beginning of a comprehensive program. Based on FERC Form 1 filings, we estimate those transformers to total 1,421. Our estimated CAPEX just for transformer EMP/GIC resiliency is $1.1B; we note this estimate doesn't include the remaining small transformers on the utility poles, which we estimate to be approximately 537,000 (we believe hardening of those units could be done incrementally during routine normal maintenance and cycle replacement, as it occurs). Our estimate also doesn't include DPR protection, which is not calculable based on publicly available information we could find. We also note that transformer protection (at $750K per unit) represents 98% of last year's electric utility CAPEX, which would be a sizable investment for the company, but not so much that the company's state utility regulators should reject. We can envision a $1B - $2B total CAPEX opportunity for Eversource Energy; our remaining coverage universe (and a selected group of electric utilities that we do not cover) is displayed in Exhibit #14 (the tables use the estimated cost of ABB's SolidGround™ solution of $750K per transformer; Mr Gurevich offered a $300K per transformer cost assumption, but we were unable to determine if that estimate included transportation/installation costs). As we examined the data, we noted that transformer upgrades could provide a significant CAPEX lift for several utilities, including Eversource Energy, Avangrid, National Grid (not covered) and First Energy (not covered).

Exhibit 13: Coverage Universe CAPEX Estimates

Coverage Universe

Avangrid (AGR, BUY, $55 F.V.)	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
Central Maine Power	323	$750,000	$ 242,250,000	$ 294,000,000	82%
United Illuminating	66	$750,000	$ 49,500,000	$ 194,000,000	26%
New York State Electric & Gas	1149	$750,000	$ 861,750,000	$ 274,000,000	315%
Rochester Electric & Gas	321	$750,000	$ 240,750,000	$ 261,000,000	92%
Totals	**1859**		**$ 1,394,250,000**	**$1,023,000,000**	**136%**

Eversource Energy (ES, BUY, $71 F.V.)	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
CL&P	412	$750,000	$ 309,000,000	$ 338,000,000	91%
WMECO	92	$750,000	$ 69,000,000	$ 99,000,000	70%
PSNH	284	$750,000	$ 213,000,000	$ 119,000,000	179%
NSTAR *(estimate)*	633	$750,000	$ 474,750,000	$ 532,692,000	89%
Totals	**1421**		**$ 1,065,750,000**	**$1,088,692,000**	**98%**

Unitil (UTL, BUY, $50 F.V.)	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
Energy Services	38	$750,000	$ 28,500,000	$ 33,800,000	84%
Fitchburg	16	$750,000	$ 12,000,000	$ 9,900,000	121%
Totals	**54**		**$ 40,500,000**	**$ 43,700,000**	**93%**

UGI Corp (UGI, BUY, $56 F.V.)	# of Transformers	Cost	Total Est. CAPEX	2017 CAPEX	% FY17 CAPEX
UGI Utilities	**22**	$750,000	**$ 16,500,000**	**$ 11,000,000**	**150%**

Chesapeake Utilities (BUY, $88 F.V.)	
Florida Public Utilities	**no FERC F-1 filings)**

Off-Coverage Selected Electric Utilities

National Grid	# of Transformers	Cost	Total Est. CAPEX	FY17 CAPEX	% 2017 CAPEX
Massachusetts Electric	386	$750,000	$ 289,500,000	$ 263,583,000	110%
Niagara Mohawk	1240	$750,000	$ 930,000,000	$ 543,138,000	171%
Narragansett Electric	217	$750,000	$ 162,750,000	$ 308,433,000	53%
Totals	**1843**		**$ 1,382,250,000**	**$1,115,154,000**	**124%**

Consolidated Edison	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
ConEd	1764	$750,000	$ 1,323,000,000	$2,392,000,000	55%
Orange & Rockland	105	$750,000	$ 78,750,000	$ 143,000,000	55%
Totals	**1869**		**$ 1,401,750,000**	**$2,535,000,000**	**55%**

Exelon	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
PECO	1191	$750,000	$ 893,250,000	$ 687,333,000	130%
BGE	476	$750,000	$ 357,000,000	$ 849,000,000	42%
Pepco	430	$750,000	$ 322,500,000	$ 605,000,000	53%
ComEd	1411	$750,000	$ 1,058,250,000	$2,722,000,000	39%
Delmarva Power	336	$750,000	$ 252,000,000	$ 353,000,000	71%
Atlantic City Electric	213	$750,000	$ 159,750,000	$ 300,000,000	53%
Totals	**4057**		**$ 3,042,750,000**	**$5,516,333,000**	**55%**

First Energy	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
Jersey Central Power & Light	1696	$750,000	$ 1,272,000,000	$ 371,062,000	343%
Met-Ed	462	$750,000	$ 346,500,000	$ 132,701,000	261%
Penn Power	267	$750,000	$ 200,250,000	$ 97,894,000	205%
West Penn Power	424	$750,000	$ 318,000,000	$ 162,320,000	196%
Ohio Edison	1380	$750,000	$ 1,035,000,000	$ 141,398,000	732%
The Cleveland Illuminating Compa	591	$750,000	$ 443,250,000	$ 115,147,000	385%
Toledo Edison	148	$750,000	$ 111,000,000	$ 39,612,000	280%
Mon Power	329	$750,000	$ 246,750,000	$ 231,825,000	106%
Potomac Edison	177	$750,000	$ 132,750,000	$ 97,894,000	136%
Totals	**5474**		**$ 4,105,500,000**	**$1,389,853,000**	**295%**

PP&L	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
PPL Electric Utilities	717	$750,000	$ 537,750,000	$1,107,000,000	49%
Louisville Gas & Electric	225	$750,000	$ 168,750,000	**$ 165,322,000**	102%
Kentucky Utilities	764	$750,000	$ 573,000,000	$ 428,564,000	134%
Totals	**1706**		**$ 1,279,500,000**	**$1,700,886,000**	**75%**

Public Service Electric & Gas	# of Transformers	Cost	Total Est. CAPEX	2016 CAPEX	% 2016 CAPEX
Totals	**847**	$750,000	**$ 635,250,000**	**$2,865,000,000**	**22%**

Sources: FERC F-1 filings, Company reports

Reference Sources:

1) Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, 2004
2) Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, 2008
3) Threat Posed by Electromagnetic Pulse (EMP) Attack – Committee on Armed Services House of Representatives: 110th Congress, Second Session, July 10, 2008
4) Large Power Transformers and the U.S. Electric Grid – Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability – U.S. Department of Energy, 2012
5) Maloof, F. Michael: A Nation Forsaken, EMP: the Escalating Threat of an American Catastrophe, Wind Books, 2013
6) Gurevich, Vladimir; Protection of Substation Critical Equipment Against Intentional Electromagnetic Threats, Wiley, 2017
7) Trump, Donald J: National Security Strategy of the United States of America; December 2017
8) EMPrimus; SolidGround™ GIC & EMP Neutral Blocker presentation, January 9, 2018

IMPORTANT DISCLOSURES

Research Analyst Certification

I, Michael Gaugler, the Primarily Responsible Analyst for this research report, hereby certify that all of the views expressed in this research report accurately reflect my personal views about any and all of the subject securities or issuers. No part of my compensation was, is, or will be, directly or indirectly, related to the specific recommendations or views I expressed in this research report.

Chesapeake Utilities Corporation currently is, or during the past 12 months was, a Janney Montgomery Scott LLC client. Janney Montgomery Scott LLC, provided investment banking related services.

Unitil currently is, or during the past 12 months was, a Janney Montgomery Scott LLC client. Janney Montgomery Scott LLC, provided investment banking related services.

Janney Montgomery Scott LLC currently acts as a market-maker in the securities of Unitil.

Janney Montgomery Scott LLC managed or co-managed a public offering of securities for Chesapeake Utilities Corporation and Unitil in the past 12 months.

Janney Montgomery Scott LLC received compensation for investment banking services from Chesapeake Utilities Corporation in the past 12 months.

Janney Montgomery Scott LLC intends to seek or expects to receive compensation for investment banking services from Avangrid, Inc., Chesapeake Utilities Corporation, Eversource Energy, UGI Corporation and Unitil in the next three months.

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			IB Serv./Past 12 Mos.*	
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NEUTRAL [N]	117	50.65	22	18.80
SELL [S]	3	1.30	0	0.00

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AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE
10.1002/2014SW001066

Key Points:
- We present a first analysis of the effects of space weather on insurance claims
- Geomagnetic variability couples into the low-voltage power network
- GIC effects lead to malfunctions in electrical and electronic devices

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Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment

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Abstract Geomagnetically induced currents are known to induce disturbances in the electric power grid. Here we perform a statistical analysis of 11,242 insurance claims from 2000 through 2010 for equipment losses and related business interruptions in North American commercial organizations that are associated with damage to, or malfunction of, electrical and electronic equipment. We find that claim rates are elevated on days with elevated geomagnetic activity by approximately 20% for the top 5% and by about 10% for the top third of most active days ranked by daily maximum variability of the geomagnetic field. When focusing on the claims explicitly attributed to electrical surges (amounting to more than half the total sample), we find that the dependence of claim rates on geomagnetic activity mirrors that of major disturbances in the U.S. high-voltage electric power grid. The claim statistics thus reveal that large-scale geomagnetic variability couples into the low-voltage power distribution network and that related power-quality variations can cause malfunctions and failures in electrical and electronic devices that, in turn, lead to an estimated 500 claims per average year within North America. We discuss the possible magnitude of the full economic impact associated with quality variations in electrical power associated with space weather.

1. Introduction

Large explosions that expel hot, magnetized gases on the Sun can, should they eventually envelop Earth, effect severe disturbances in the geomagnetic field. These, in turn, cause geomagnetically induced currents (GICs) to run through the surface layers of the Earth and through conducting infrastructures in and on these, including the electrical power grids. The storm-related GICs run on a background of daily variations associated with solar (X)(E)UV irradiation that itself is variable through its dependence on both quiescent and flaring processes.

The strongest GIC events are known to have impacted the power grid on occasion [see, e.g., *Kappenman et al.*, 1997; *Boteler et al.*, 1998; *Arslan Erinmez et al.*, 2002; *Kappenman*, 2005; *Wik et al.*, 2009]. Among the best known of such impacts is the 1989 Hydro-Québec blackout [e.g., *Bolduc*, 2002; *Béland and Small*, 2004]. Impacts are likely strongest at middle to high geomagnetic latitudes, but low-latitude regions also appear susceptible [*Gaunt*, 2013].

The potential for severe impacts on the high-voltage power grid and thereby on society that depends on it has been assessed in studies by government, academic, and insurance industry working groups [e.g., *Space Studies Board*, 2008; *FEMA and NOAA*, 2010; *Kappenman*, 2010; *Hapgood*, 2011; *JASON*, 2011]. How costly such potential major grid failures would be remains to be determined, but impacts of many billions of dollars have been suggested [e.g., *Space Studies Board*, 2008; *JASON*, 2011].

Noncatastrophic GIC effects on the high-voltage electrical grid percolate into financial consequences for the power market [*Forbes and St. Cyr*, 2004, 2008, 2010] leading to price variations on the bulk electrical power market on the order of a few percent [*Forbes and St. Cyr*, 2004].

Schrijver and Mitchell [2013] quantified the susceptibility of the U.S. high-voltage power grid to severe, yet not extreme, space storms, leading to power outages and power-quality variations related to voltage sags and frequency changes. They find, “with more than 3σ significance, that approximately 4% of the

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disturbances in the U.S. power grid reported to the U.S. Department of Energy are attributable to strong geomagnetic activity and its associated geomagnetically induced currents."

The effects of GICs on the high-voltage power grid can, in turn, affect the low-voltage distribution networks and, in principle, might impact electrical and electronic systems of users of those regional and local networks. A first indication that this does indeed happen was reported on in association with tests conducted by the Idaho National Laboratory (INL) and the Defense Threat Reduction Agency (DTRA). They reported [*Wise and Benjamin*, 2013] that "INL and DTRA used the lab's unique power grid and a pair of 138kV core form, 2 winding substation transformers, which had been in-service at INL since the 1950s, to perform the first full-scale testing to replicate conditions electric utilities could experience from geomagnetic disturbances." In these experiments, the researchers could study how the artificial GIC-like currents resulted in harmonics on the power lines that can affect the power transmission and distribution equipment. These "tests demonstrated that geomagnetic-induced harmonics are strong enough to penetrate many power line filters and cause temporary resets to computer power supplies and disruption to electronic equipment, such as uninterruptible power supplies."

In parallel to that experiment, we collected information on insurance claims submitted to Zurich North America (NA) for damage to, or outages of, electrical and electronic systems from all types of industries for a comparison with geomagnetic variability. Here we report on the results of a retrospective cohort exposure analysis of the impact of geomagnetic variability on the frequency of insurance claims. In this analysis, we contrast insurance claim frequencies on "high-exposure" dates (i.e., dates of high geomagnetic activity) with a control sample of "low-exposure" dates (i.e., dates with essentially quiescent space weather conditions), carefully matching each high-exposure date to a control sample nearby in time so that we may assume no systematic changes in conditions other than space weather occurred between the exposure dates and their controls (thus compensating for seasonal weather changes and other trends and cycles).

For comparison purposes, we repeat the analysis of the frequency of disturbances in the high-voltage electrical power grid as performed by *Schrijver and Mitchell* [2013] for the same date range and with matching criteria for threshold setting and for the selection of the control samples. In section 2 we describe the insurance claim data, the metric of geomagnetic variability used, and the grid-disturbance information. The procedure to test for any impacts of space weather on insurance claims and the high-voltage power grid is presented and applied in section 3. We summarize our conclusions in section 4 where we also discuss the challenges in translating the statistics on claims and disturbances into an economic impact.

2. Data

2.1. Insurance Claim Data

We compiled a list of all insurance claims filed by commercial organizations to Zurich NA relating to costs incurred for electrical and electronic systems for the 11 year interval from 1 January 2000 through 31 December 2010. Available for our study were the date of the event to which the claim referred, the state or province within which the event occurred, a brief description of the affected equipment, and a top-level assessment of the probable cause. Information that might lead to identification of the insured parties was not disclosed.

Zurich NA estimates that it has a market share of approximately 8% in North America for policies covering commercially used electrical and electronic equipment and contingency business interruptions related to their failure to function properly during the study period. Using that information as a multiplier suggests that overall some 12,800 claims are filed per average year related to electrical/electronic equipment problems in North American businesses. The data available for this study cannot reveal impacts on uninsured or self-insured organizations or impacts in events of which the costs fall below the policy deductable.

The 11 year period under study has the same duration as that characteristic of the solar magnetic activity cycle. Figure 1 shows that the start of this period coincides with the maximum in the annual sunspot number for 2000, followed by a decline into an extended minimum period in 2008 and 2009, ending with the rise of sunspot number into the start of the next cycle.

The full sample of claims, regardless of attribution, for which an electrical or electronic system was involved includes 11,242 entries. We refer to this complete set as set *A*.

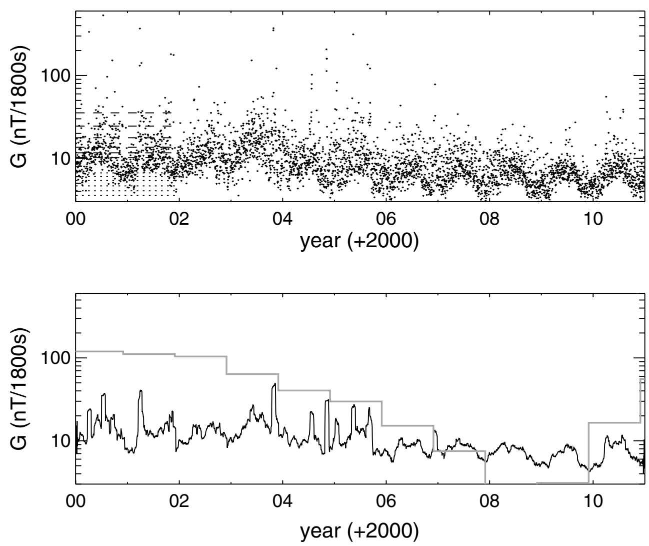


Figure 1. (top) Daily values $G \equiv \max(|dB/dt|)$ based on 30 min intervals (dots; nT/1800s) characterizing geomagnetic variability for the contiguous United States versus time (in years since 2000). The 27 day running mean is shown by the solid line in the bottom panel. The levels for the 98, 95, 90, 82, 75, and 67 percentiles of the entire sample are shown by dashed lines (sorting downward from the top value of G) and dotted lines (sorting upward from the minimum value of the daily geomagnetic variability as expressed by $G \equiv \max(|dB/dt|)$). (bottom) The grey histogram shows the annual mean sunspot number.

Claims that were attributed to causes that were in all likelihood not associated with space weather phenomena were deleted from set A to form set B (with 8151 entries remaining after review of the Accident Narrative description of each line item). Such omitted claims included attributions to water leaks and flooding, stolen or lost equipment, vandalism or other intentional damage, vehicle damage or vehicular accidents, animal intrusions (raccoons, squirrels, birds, etc.), obvious mechanical damage, and obvious weather damage (ice storm damage, hurricane/windstorm damage, etc.). The probable causes for the events making up set B were limited to the following categories (sorted by the occurrence frequency, given in percent): Misc: Electrical surge (59%); Apparatus, Miscellaneous Electrical - Breaking (30%); Apparatus, Miscellaneous Electrical - Arcing (4.1%); Electronics - Breaking (1.6%); Apparatus, Miscellaneous Electrical - Overheating (1.4%); Transformers - Arcing (0.9%); Electronics - Arcing (0.6%); Transformers - Breaking (0.5%); Generators - Breaking (0.4%); Apparatus, Electronics - Overheating (0.3%); Generators - Arcing (0.2%); Generators - Overheating (0.2%); and Transformers - Overheating (0.1%).

Figure 2 shows the number of claims received as a function of the mean geomagnetic latitude for the state within which the claim was recorded. Based on this histogram, we divided the claims into categories of comparable size for high and low geomagnetic latitudes along a separation at 49.°5 north geomagnetic latitude to enable testing for a dependence on proximity to the auroral zones. We note that we do not have access to information about the latitudinal distribution of insured assets, only on the claims received. Hence, we can only assess any dependence of insurance claims on latitude in a relative sense, comparing excess relative claim frequencies for claims above and below the median geomagnetic latitudes, as discussed in section 3.

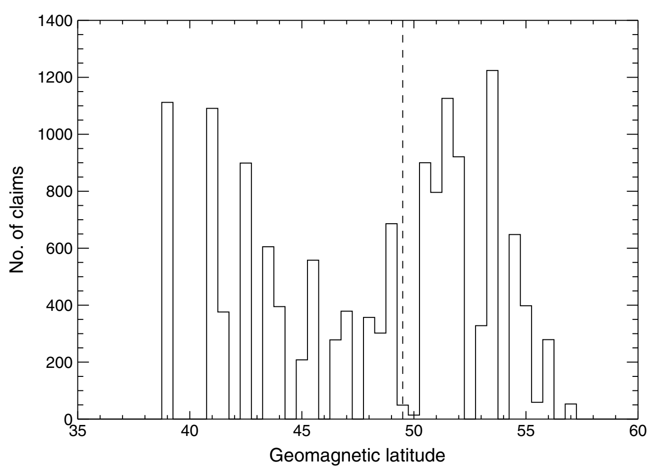


Figure 2. Number of insurance claims sorted by geomagnetic latitude (using the central geographical location of the state) in 0.5° bins. The dashed line at 49.5° is near the median geomagnetic latitude of the sample (at 49.3°), separating what this paper refers to as high latitude from low-latitude states.

2.2. Geomagnetic Data

Geomagnetically induced currents are driven by changes in the geomagnetic field. These changes are caused by the interaction of the variable, magnetized solar wind with the geomagnetic field and by the insolation of Earth's atmosphere that varies globally with solar activity and locally owing to the Earth's daily rotation and annual revolution in its orbit around the Sun. A variety of geomagnetic activity indices is available to characterize geomagnetic field

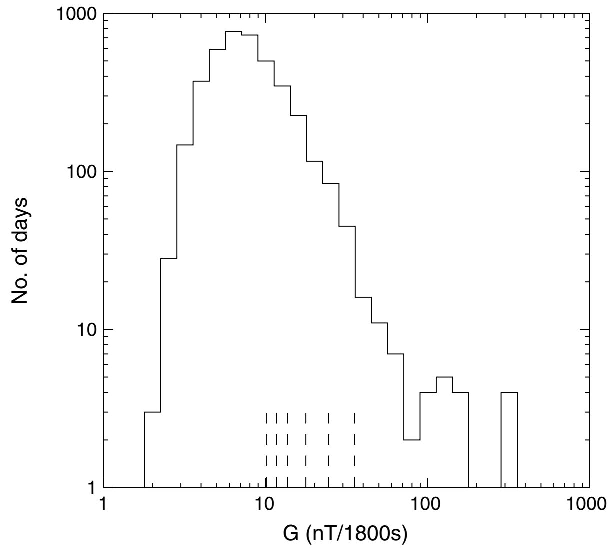


Figure 3. Histogram of the number of days between 1 January 2000 and 31 December 2010 with values of $G \equiv \max(|dB/dt|)$ in logarithmically spaced intervals as shown on the horizontal axis. The 98, 95, 90, 82, 75, and 67 percentiles (ranking G from low to high) are shown by dashed lines.

variability [e.g., *Jursa*, 1985]. These indices are sensitive to different aspects of the variable geomagnetic-ionospheric current systems as they may differentially filter or weight storm-time variations (*Dst*), disturbance-daily variations (Ds), or solar quiet daily variations (known as the *Sq* field), and may weight differentially by (geomagnetic) latitude. Here we are interested not in any particular driver of changes in the geomagnetic field but rather need a metric of the rate of change in the strength of the surface magnetic field as that is the primary driver of geomagnetically induced currents.

To quantify the variability in the geomagnetic field, we use the same metric as *Schrijver and Mitchell* [2013] based on the minute-by-minute geomagnetic field measurements from the Boulder (BOU) and Fredericksburg (FRD) stations (available via http://ottawa.intermagnet.org): we use these measurements to compute the daily maximum value, G, of $|dB/dt|$ over 30 min intervals, using the mean value for the two stations. We selected this metric recognizing a need to use a more regional metric than the often-used global metrics but also recognizing that the available geomagnetic and insurance claim data have poor geographical resolution so that a focus on a metric responsive to relatively low-order geomagnetic variability was appropriate. We chose a time base short enough to be sensitive to rapid changes in the geomagnetic field but long enough that it is also sensitive to sustained changes over the course of over some tens of minutes. For the purpose of this study, we chose to use a single metric of geomagnetic variability, but with the conclusion of our pilot study revealing a dependence of damage to electrical and electronic equipment on space weather conditions, a multiparameter follow up study is clearly warranted, ideally also with more information on insurance claims, than could be achieved with what we have access to for this exploratory study.

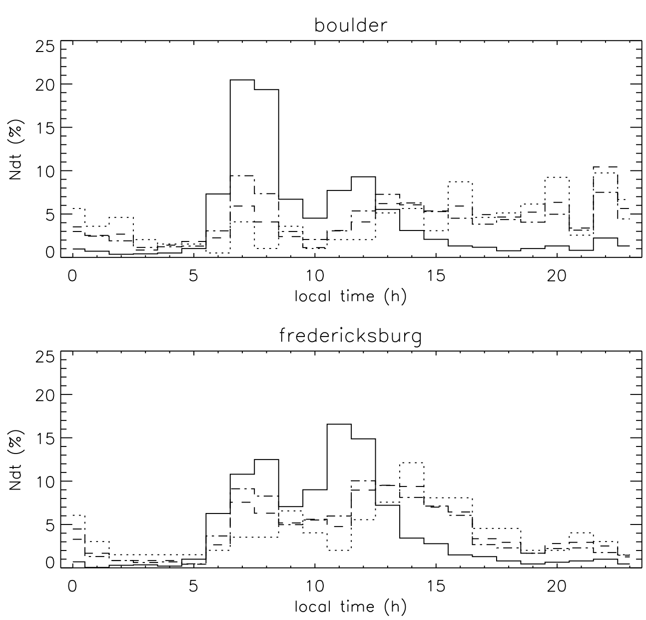
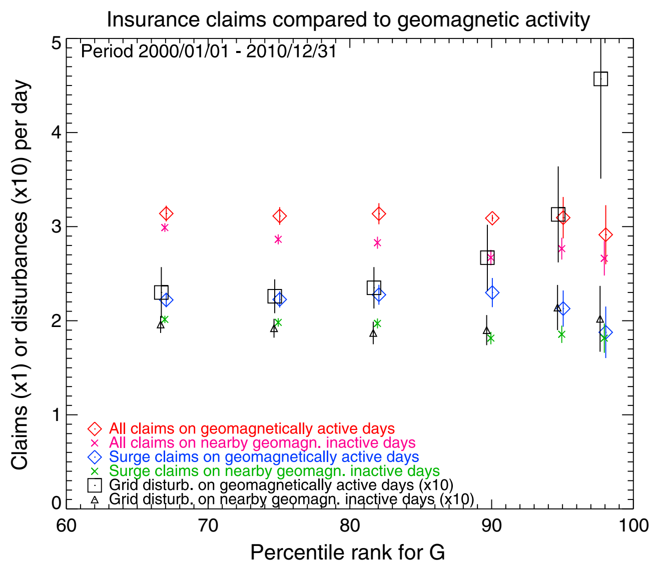


Figure 4. Normalized histograms of the local times for which the values of $G \equiv \max(|dB/dt|)$ reach their daily maximum: (top) Boulder and (bottom) Fredericksburg. The solid histogram shows the distribution for daily peaks for all dates with G values in the lower half of the distribution, i.e., for generally quiescent conditions. The dotted, dashed, and dash-dotted histograms show the distributions for dates with high G values, for thresholds set at the 95, 82, and 67 percentiles of the set of values for G, respectively.

The BOU and FRD stations are located along the central latitudinal axis of the U.S. The averaging of their measurements somewhat emphasizes the eastern U.S. as do the grid and population that uses that. Because the insurance claims use dates based on local time we compute the daily G



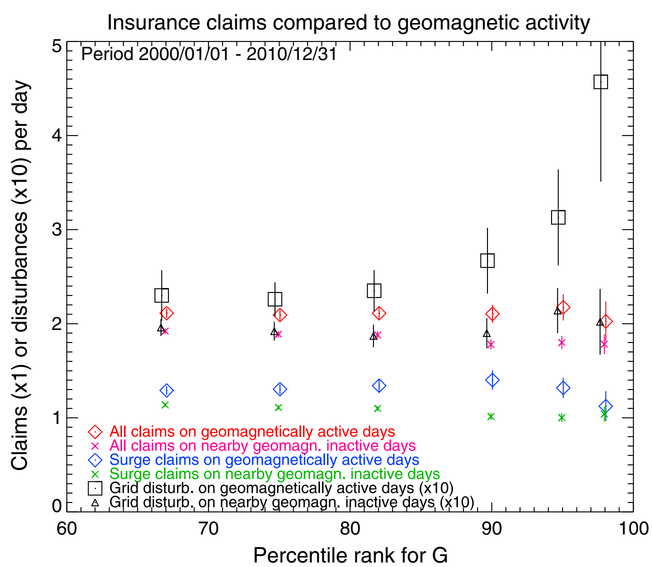


Figure 5. (top) Claims per day for the full sample of insurance claims (set *A*) and (bottom) for the sample from which claims likely unrelated to any space weather influence have been removed (set *B*). Each panel shows mean incident claim frequencies $n_i \pm \sigma_c$ (diamonds) for the most geomagnetically active dates, specifically for the 98, 95, 90, 82, 75, and 67 percentiles of the distribution of daily values of $G \equiv \max(|dB/dt|)$ sorted from low to high (shown with slight horizontal offsets to avoid overlap in the symbols and bars showing the standard deviations for the mean values). The asterisks show the associated claim frequencies $n_c \pm \sigma_c$, for the control samples. The panels also show the frequencies of reported high-voltage power grid disturbances (diamonds and triangles for geomagnetically active dates and for control dates, respectively), multiplied by 10 for easier comparison, using the same exposure-control sampling and applied to the same date range as that used for the insurance claims.

values based on date boundaries of U.S. central time. Figure 3 shows the distribution of values of *G*, while also showing the levels of the percentiles for the rank-sorted value of *G* used as threshold values for a series of subsamples in the following sections.

Figure 4 shows the local times at which the maximum variations in the geomagnetic field occur during 30 min intervals. The most pronounced peak in the distribution for geomagnetically quiet days (solid histogram) occurs around 7–8 o'clock local time, i.e., a few hours after sunrise, and a second peak occurs around local noon. The histograms for the subsets of geomagnetically active days for which *G* values exceed thresholds set at 67, 82, and 95 percentiles of the sample are much broader, even more so for the Boulder station than for the Fredericksburg station. From the perspective of the present study, it is important to note that the majority of the peak times for our metric of geomagnetic variability occurs within the economically most active window from 7 to 18 hours local time; for example, at the 82 percentile of geomagnetic variability in *G*, 54% and 77% of the peak variability occur in that time span for Boulder and Fredericksburg, respectively.

From a general physics perspective, we note that periods of markedly enhanced geomagnetic activity ride on top of a daily background variation of the ionospheric current systems (largely associated with the "solar quiet" modulations, referred to as the *Sq* field) that is induced to a large extent by solar irradiation of the atmosphere of the rotating Earth, including the variable coronal components associated with active-region gradual evolution and impulsive solar flaring. We do not attempt to separate the impacts of these drivers in this study, both because we do not have information on the local times for which the problems occurred that lead to the insurance claims and because the power grid is sensitive to the total variability in the geomagnetic field regardless of cause.

The daily *G* values are shown versus time in Figure 1, along with a 27 day running mean and (as a grey histogram) the yearly sunspot number. As expected, the *G* value shows strong upward excursions particularly

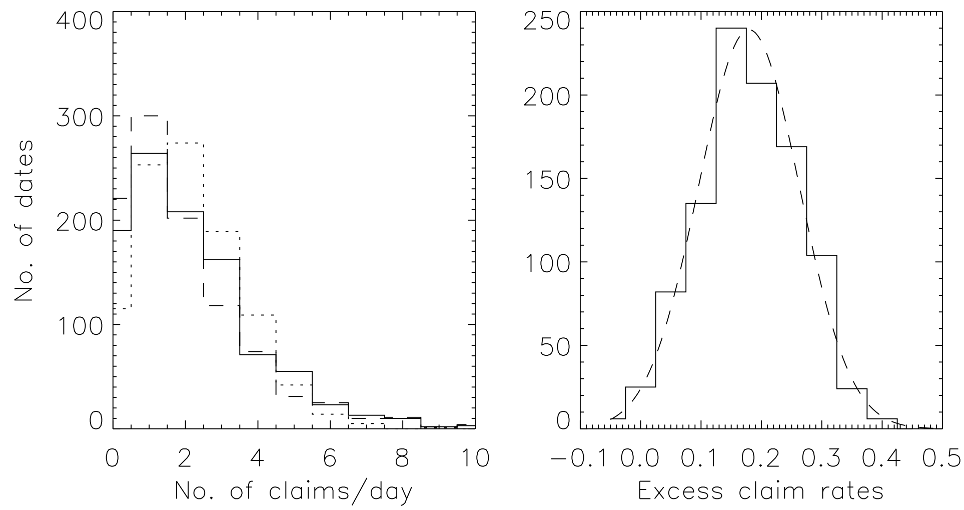


Figure 6. (left) Distribution of the number of claims per geomagnetically active day for set *B* for the top 25% of *G* values (solid) compared to that for the distribution of control dates (divided by 3 to yield the same total number of dates; dashed). For comparison, the expected histogram for a random Poisson distribution with the same mean as that for the geomagnetically active days is also shown (dotted). (right) Distribution (solid) of excess daily claim frequencies during geomagnetically active days (defined as in Figure 6 (left)) over those on control dates determined by repeated random sampling from the observations (known as the bootstrap method), compared to a Gaussian distribution (dashed) with the same mean and standard deviation.

during the sunspot maximum. Note the annual modulation in *G* with generally lower values in the northern hemispheric winter months than in the summer months.

2.3. Power Grid Disturbances

In parallel to the analysis of the insurance claim statistics, we also analyze the frequencies of disturbances in the U.S. high-voltage power grid. *Schrijver and Mitchell* [2013] compiled a list of "system disturbances" published by 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). This information is compiled by NERC for a region with over 300 million electric power customers throughout the USA and in Ontario and New Brunswick in Canada, connected by more than 340,000 km of high-voltage transmission lines delivering power generated in some 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." We use the complete set of disturbances reported from 1 January 2000 through 31 December 2010 regardless of attributed cause. We refer to *Schrijver and Mitchell* [2013] for more details.

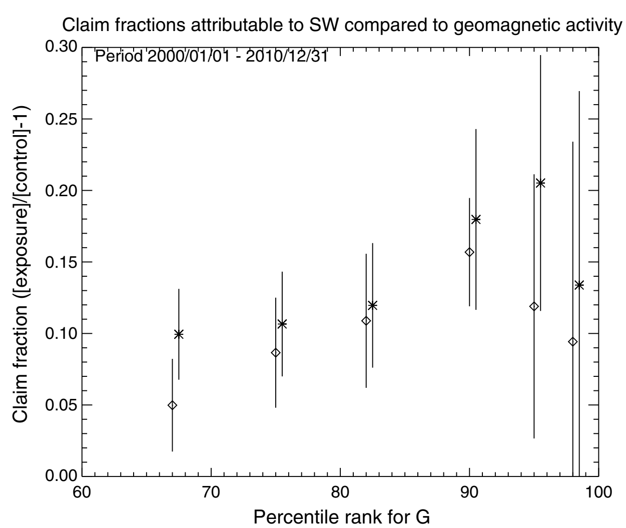


Figure 7. Relative excess claim frequencies statistically associated with geomagnetic activity (difference between claim frequencies on geomagnetically active dates and the frequencies on control dates as shown in Figure 5, i.e., $(n_i - n_c)/n_c$) for the full sample (*A*; diamonds) and for the sample (*B*; asterisks) from which claims were removed attributable to apparently nonspace weather-related causes.

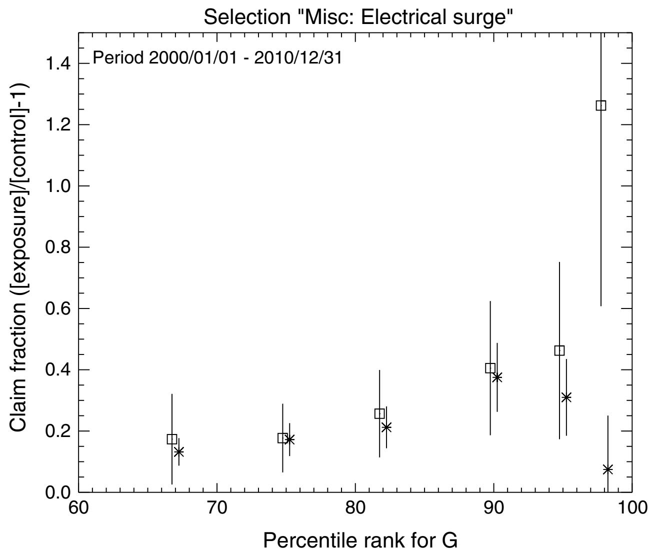


Figure 8. Same as Figure 7 but for sample *B* limited to those claims attributed to "Misc.: Electrical surge" (asterisks) (for 57% of the cases in that sample), compared to the fraction of high-voltage power grid disturbances statistically associated with geomagnetic activity (squares).

3. Testing for the Impact of Space Weather

In order to quantify effects of geomagnetic variability on the frequency of insurance claims filed for electrical and electronic equipment, we need to carefully control for a multitude of variables that include trends in solar activity, the structure and operation of the power grid (including, for example, scheduled maintenance and inspection), various societal and technological factors changing over the years, as well as the costs and procedures related to the insurance industry, and, of course, weather and seasonal trends related to the insolation angle and the varying tilt of the Earth's magnetic field relative to the incoming solar wind throughout the year.

There are many parameters that may influence the ionospheric current systems, the quality and continuity of electrical power, and the malfunctioning of equipment running on electrical power. We may not presume that we could identify and obtain all such parameters or that all power grid segments and all equipment would respond similarly to changes in these parameters. We therefore do not attempt a multiparameter correlation study but instead apply a retrospective cohort exposure study with tightly matched controls very similar to that applied by *Schrijver and Mitchell* [2013].

This type of exposure study is based on pairing dates of exposure, i.e., of elevated geomagnetic activity, with control dates of low geomagnetic activity shortly before or after each of the dates of exposure, selected from within a fairly narrow window in time during which we expect no substantial systematic variation in ionospheric conditions, weather, the operations of the grid, or the equipment powered by the grid. Our results are based on a comparison of claim counts on exposure dates relative to claim counts on matching sets of nearby control dates. This minimizes the impacts of trends (including "confounders") in any of the potential factors that affect the claim statistics or geomagnetic variability, including the daily variations in quiet-Sun irradiance and the seasonal variations as Earth orbits the Sun, the solar cycle, and the structure and operation of the electrical power network. This is a standard method as used in, e.g., epidemiology. We refer to *Wacholder et al.* [1992, and references therein] for a discussion on this method particularly regarding ensuring of time comparability of the "exposed" and control samples, to *Schulz and Grimes* [2002] for a discussion on the comparison of cohort studies as applied here versus case-control studies, and to *Grimes and Schulz* [2005] for a discussion of selection biases in samples and their controls (specifically their example on pp. 1429–1430).

We define a series of values of geomagnetic variability in order to form sets of dates including different ranges of exposure, i.e., of

Table 1. Probability (*p*) Values Based on a Kolmogorov-Smirnov Test That the Observed Sets of Claim Numbers on Geomagnetically Active Dates and on Control Dates Are Drawn From the Same Parent Distribution, for Date Sets With the Geomagnetic Activity Metric *G* Exceeding the Percentile Threshold in the Distribution of Values

	All Claims		Attributed to Electrical Surges	
Percentile	Set *A*	Set *B*	Set *A*	Set *B*
67	2×10^{-10}	2×10^{-19}	1×10^{-27}	0
75	3×10^{-7}	4×10^{-14}	8×10^{-20}	4×10^{-35}
82	0.0004	2×10^{-7}	1×10^{-13}	6×10^{-24}
90	0.010	0.0002	1×10^{-7}	8×10^{-13}
95	0.05	0.013	0.0001	2×10^{-7}
98	0.33	0.06	0.003	0.0001

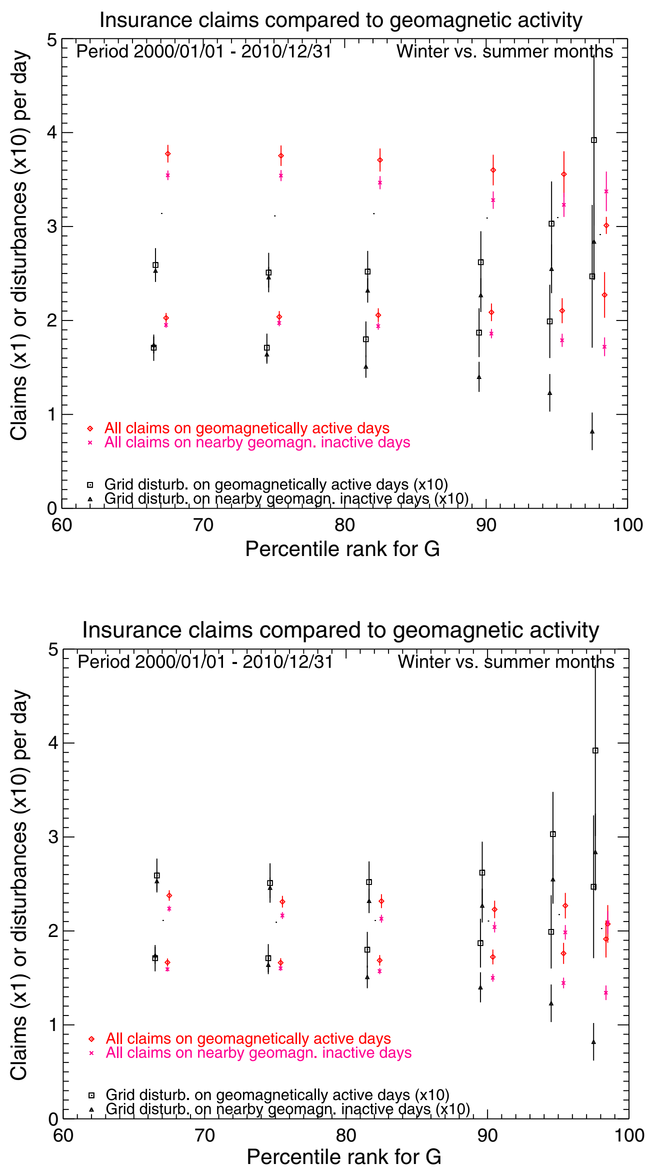


Figure 9. As Figure 5 but separating the winter half year (October through March) from the summer half year (April through September), for (top) the full sample of insurance claims (set *A*) and (bottom) the sample from which claims likely unrelated to any space weather influence have been removed (set *B*). Values for the summer months are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the winter months are offset to the right. Values for the winter season are systematically higher than those for summer months.

geomagnetic variability, so that each high-exposure date is matched by representative low-exposure dates as controls. We create exposure sets by selecting a series of threshold levels corresponding to percentages of all dates with the most intense geomagnetic activity as measured by the metric *G*. Specifically, we determined the values of *G* for which geomagnetic activity, sorted from least active upward, includes 67%, 75%, 82%, 90%, 95%, and 98% of all dates in our study period. For each threshold value we selected the dates with *G* exceeding that threshold (with possible further selection criteria as described below). For each percentile set, we compute the mean daily rate of incident claims, n_i, as well as the standard deviation on the mean, σ_i, as determined from the events in the day-by-day claims list.

In order to form tightly matched control samples for low "exposure," we then select three dates within a 27 day period centered on each of the selected high-activity days. The 27 day period, also known as the Bartels period, is that characteristic of a full rotation of the solar large-scale field as viewed from the orbiting Earth; *G* values within that period sample geomagnetic variability as induced during one full solar rotation. This window for control sample selection is tighter than that used by *Schrijver and Mitchell* [2013] who used 100 day windows centered on dates with reported grid disturbances. For the present study we selected a narrower window to put even stronger limits on the potential effects of any possible long-term trends in factors that might influence claim statistics or geomagnetic variability. We note that there is no substantive change in our main conclusions for control windows at least up to 100 days in duration.

The three dates selected from within this 27 day interval are those with the lowest value of *G* smoothed with a 3 day running mean. We determine the mean claim rate, n_c, for this control set and the associated standard deviation in the mean, σ_c.

Figure 5 shows the resulting daily frequency of claims and the standard deviations in the mean, $n_i \pm \sigma_i$, for the selected percentiles, both for the full sample *A* (top) and for sample *B* (bottom) from which claims were omitted that were attributed to causes not likely associated directly or indirectly with geomagnetic

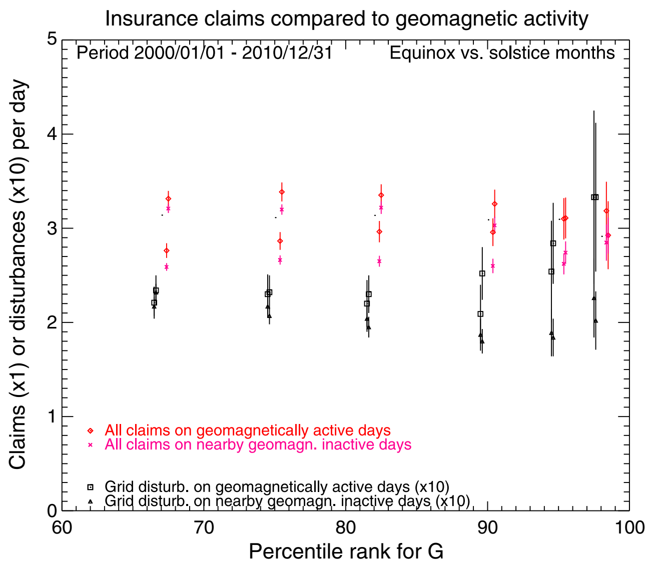


Figure 10. As Figure 9 but separating the months around the equinoxes (February–April and August–October) from the complementing months around the solstices, for the full sample of insurance claims (set *A*). Values for the equinox periods are shown offset slightly toward the left of the percentiles tested (98, 95, 90, 82, 75, and 67), while values for the solstice months are offset to the right. Mean claim frequencies for the solstice periods are systematically higher than those for equinox periods, but the frequencies for high-*G* days in excess of the control sample frequencies are slightly larger around the equinoxes than around the solstices.

activity. For all percentile sets, we see that the claim frequencies n_i on geomagnetically active days exceed the frequencies n_c for the control dates.

The frequency distributions of insurance claims are not Poisson distributions, as can be seen in the example in Figure 6 (left): compared to a Poisson distribution of the same mean, the claims distributions on geomagnetically active dates, $N_{B,a,75}$, and for control days, $N_{B,c,75}$, are skewed to have a peak frequency at lower numbers and a raised tail at higher numbers; a Kolmogorov-Smirnov (KS) test suggests that the probability that $N_{B,c,75}$ is consistent with a Poisson distribution with the same mean is 0.01 for this example. The elevated tail of the distribution relative to a Poisson distribution suggests some correlation between claim events, which is of interest from an actuarial perspective as it suggests a nonlinear response of the power system to space weather that we cannot investigate further here owing to the signal-to-noise ratio of the results given our sample.

For the case shown in Figure 6 for the 25% most geomagnetically active dates in set *B*, a KS test shows that the probability that $N_{B,a,75}$ and $N_{B,c,75}$ are drawn from the same parent distribution is of order 10^{-14}, i.e., extremely unlikely.

The numbers that we are ultimately interested in are the excess frequencies of claims on geomagnetically active dates over those on the control dates and their uncertainty. For the above data set, we find and excess daily claims rate of $(n_{B,i} - n_{B,c}) \pm \sigma_B = 0.20 \pm 0.08$. The uncertainty σ_B is in this case determined by repeated random sampling of the claim sample for exposure and control dates and subsequently determining the standard deviation in a large sample of resulting excess frequencies (using the so-called bootstrap method). The distribution of excess frequencies (shown in Figure 6 (right)) is essentially Gaussian, so that the metric of the standard deviation gives a useful value to specify the uncertainty. We note that the value of σ_B is comparable to the value $\sigma_{a,c} = (\sigma_a^2 + \sigma_b^2)^{1/2}$ derived by combining the standard deviations for the numbers of claims per day for geomagnetically active dates and the control dates, which in this case equals $\sigma_{a,c} = 0.07$. Thus, despite the skewness of the claim count distributions relative to a Poisson distribution as shown in the example in Figure 6 (left), the effect of that on the uncertainty in the excess claim rate is relatively small. For this reason, we show the standard deviations on the mean frequencies in Figures 5–11 as a useful visual indicator of the significance of the differences in mean frequencies.

Figure 7 shows the relative excess claim frequencies, i.e., the relative differences $r_e = (n_i - n_c)/n_c$ between the claim frequencies on geomagnetically active dates and those on the control dates, thus quantifying the claim fraction statistically associated with elevated geomagnetic activity. The uncertainties shown are computed as $\sigma_e = (\sigma_i^2/n_i^2 + \sigma_c^2/n_c^2)^{1/2}\, r_e$, i.e., using the approximation of normally distributed uncertainties, warranted by the arguments above. We note that the relative rate of claims statistically associated with space weather is slightly higher for sample *B* than for the full set *A* consistent with the hypothesis that the claims omitted from sample *A* to form sample *B* were indeed preferentially unaffected by geomagnetic activity. Most importantly, we note that the rate of claims statistically associated with geomagnetic activity increases with the magnitude of that activity.

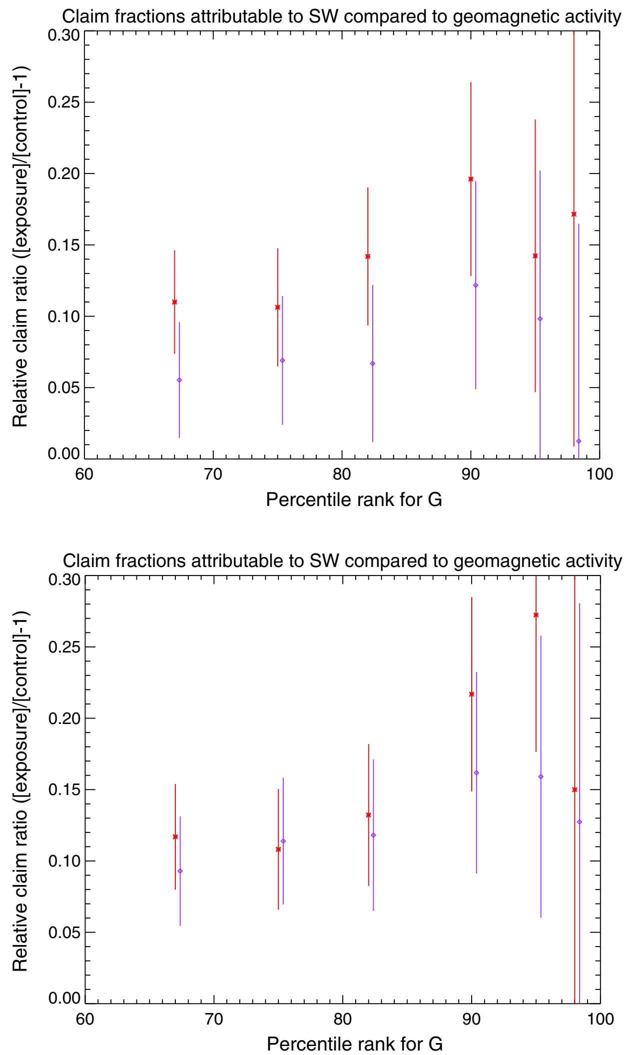


Figure 11. Relative excess claim frequencies $(n_i - n_c)/n_i$ on geomagnetically active dates relative to those on control dates for geomagnetic latitudes below 49.5°N (asterisks, red) compared to those for higher latitudes (diamonds, purple; offset slightly to the right) for the percentiles tested (98, 95, 90, 82, 75, and 67). (top) The results for the full sample (*A*) and (bottom) for sample *B* from which apparently nonspace weather-related events were removed (see section 2.1).

About 59% of the claims in sample *B* attribute the case of the problem to "Misc.: Electrical surge", so that we can be certain that some variation in the quality or continuity of electrical power was involved. Figure 8 shows the relative excess claim rate $(n_i - n_c)/n_c$ as function of threshold for geomagnetic activity. We compare these results with the same metric, based on identical selection procedures, for the frequency of disturbances in the high-voltage power grid (squares). We note that these two metrics, one for interference with commercial electrical/electronic equipment and one for high-voltage power, agree within the uncertainties, with the possible exception of the infrequent highest geomagnetic activity (98 percentile) although there the statistical uncertainties on the mean frequencies are so large that the difference is less than 2 standard deviations in the mean values.

To quantify the significance of the excess claim frequencies on geomagnetically active days, we perform a nonparametric Kolmogorov-Smirnov (KS) test of the null hypothesis that the claim events on active and on control days could be drawn from the same parent sample. The resulting *p* values from the KS test, summarized in Table 1, show that it is extremely unlikely that our conclusion that geomagnetic activity has an impact on insurance claims could be based on chance, except for the highest percentiles in which the small sample sizes result in larger uncertainties. We note that the *p* values tend to decrease when we eliminate claims most likely unaffected by space weather (contrasting set *A* with *B*) and when we limit either set to events attributed to electrical surges: biasing the sample tested toward issues more likely associated with power grid variability increases the significance of our findings that there is an impact of space weather.

Figure 9 shows insurance claims differentiated by season: the frequencies of both insurance claims and power grid disturbances are higher in the winter months than in the summer months, but the excess claim frequencies statistically associated with geomagnetic activity follow similar trends as for the full date range. The same is true when looking at the subset of events attributed to surges in the low-voltage power distribution grid.

Figure 10 shows a similar diagram to that of Figure 9 (top), now differentiating between the equinox periods and the solstice periods. Note that although the claim frequencies for the solstice periods are higher than those for the equinox periods, that difference is mainly a consequence of background (control) frequencies:

the fractional excess frequencies on geomagnetically active days relative to the control dates are larger around the equinoxes than around the solstices.

Figure 11 shows the comparison of claim ratios of geomagnetically active dates relative to control dates for states with high versus low geomagnetic latitude, revealing no significant contrast (based on uncertainties computed as described above for Figure 7).

4. Discussion and Conclusions

We perform a statistical study of North American insurance claims for malfunctions of electronic and electrical equipment and for business interruptions related to such malfunctions. We find that there is a significant increase in claim frequencies in association with elevated variability in the geomagnetic field, comparable in magnitude to the increase in occurrence frequencies of space weather-related disturbances in the high-voltage power grid. In summary,

1. The fraction of insurance claims statistically associated with geomagnetic variability tends to increase with increasing activity from about 5 to 10% of claims for the top third of most active days to approximately 20% for the most active few percent of days.
2. The overall fraction of all insurance claims statistically associated with the effects of geomagnetic activity is $\approx$ 4%. With a market share of about 8% for Zurich NA in this area, we estimate that some 500 claims per year are involved overall in North America.
3. Disturbances in the high-voltage power grid statistically associated with geomagnetic activity show a comparable frequency dependence on geomagnetic activity as do insurance claims.
4. We find no significant dependence of the claim frequencies statistically associated with geomagnetic activity on geomagnetic latitude.

For our study, we use a quantity that measures the rate of change of the geomagnetic field regardless of what drives that. Having established an impact of space weather on users of the electric power grid, a next step would be to see if it can be established what the relative importance of various drivers is (including variability in the ring current, electrojet, substorm dynamics and solar insolation of the rotating Earth), but that requires information on the times and locations of the impacts that is not available to us.

The claim data available to us do not allow a direct estimate of the financial impacts on industry of the malfunctioning equipment and the business interruptions attributable to such malfunctions: we do not have access to the specific policy conditions from which each individual claim originated, so we have no information on deductable amounts, whether (contingency) business interruptions were claimed or covered or were excluded from the policy, whether current value or replacement costs were covered, etc. Moreover, the full impact on society goes well beyond insured assets and business interruptions, of course, as business interruptions percolate through the complex of economic networks well outside of direct effects on the party submitting a claim. A sound assessment of the economic impact of space weather through the electrical power systems is a major challenge, but we can make a rough order-of-magnitude estimate based on existing other studies as follows.

The majority (59% in sample *B*) of the insurance claims studied here are explicitly attributed to "Misc.: electrical surge," which are predominantly associated with quality or continuity of electrical power in the low-voltage distribution networks to which the electrical and electronic components are coupled. Many of the other stated causes (see section 2.1) may well be related to that, too, but we cannot be certain given the brevity of the attributions and the way in which these particular data are collected and recorded. Knowing that in most cases the damage on which the insurance claims are based is attributable to perturbations in the low-voltage distribution systems, however, suggests that we can look to a study that attempted to quantify the economic impact of such perturbations on society.

That study, performed for the Consortium for Electric Infrastructure to Support a Digital Society [*Lineweber and McNulty*, 2001], focused on the three sectors in the U.S. 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 U.S. gross domestic product.

Lineweber and McNulty [2001] obtained information from a sampling of 985 out of a total of about 2 million businesses in these three sectors. The surveys assessed impact by "direct costing" by combining statistics on grid disturbances and estimates of costs of outage scenarios via questionnaires completed by business officials. 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 or costs).

For a typical year (excluding, for example, 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 U.S. from all electric power disturbances results in impacts ranging from $119 billion/yr to $188 billion/yr (for about year 2000 economic conditions).

Combining the findings of that impact quantification of all problems associated with electrical power with our present study on insurance claims suggests that, for an average year, the economic impact of power-quality variations related to elevated geomagnetic activity may be a few percent of the total impact or several billion dollars annually. That very rough estimate obviously needs a rigorous follow up assessment, but its magnitude suggests that such a detailed, multidisciplinary study is well worth doing.

Acknowledgments
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State of Minnesota
HOUSE OF REPRESENTATIVES
NINETIETH SESSION
H. F. No. 2695

05/19/2017 Authored by Pugh, Newberger, Lohmer, Runbeck, Miller and others
The bill was read for the first time and referred to the Committee on Job Growth and Energy Affordability Policy and Finance

A bill for an act

relating to energy; requiring a study on the vulnerability of the electrical grid to solar storms; appropriating money.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF MINNESOTA:

Section 1. **STUDY; ELECTRICAL GRID VULNERABILITY TO GEOMAGNETIC DISTURBANCES AND ELECTROMAGNETIC PULSE.**

(a) The Public Utilities Commission and the Department of Public Safety must conduct a joint study on the vulnerability of Minnesota's electrical grid to geomagnetic disturbances caused by solar storms and electromagnetic pulse, including how any vulnerability may be reduced. Information must be gathered from a variety of stakeholders, including but not limited to (1) electric utilities, (2) the Midcontinent Independent System Operator, (3) scientists and others with expertise in the field of solar disturbances, electromagnetic pulses, and the impact of each on the electrical grid, and (4) emergency hazard planners.

(b) At a minimum, the report must contain information regarding:

(1) potential disturbances that may impact Minnesota's electrical grid as a result of solar storms and electromagnetic pulse;

(2) the existing system for predicting solar storms;

(3) steps utilities and the private and public sectors could take to minimize grid vulnerability to geomagnetic disturbances and electromagnetic pulse;

(4) how to maintain and restore communications systems after grid damage from geomagnetic disturbances and electromagnetic pulse; and

(5) how current emergency planning efforts may incorporate concerns regarding grid damage and long-term power outage resulting from geomagnetic disturbances and electromagnetic pulse.

(c) By February 15, 2018, the Public Utilities Commission and the Department of Public Safety must submit a report to the chairs and ranking minority members of the senate and house of representatives committees with jurisdiction over energy policy and public safety.

(d) For the purposes of this section, "solar storms" means the ejection of particles, plasma, flares, or electromagnetic radiation from the sun's surface or corona that travel through space and reach the surface of the earth, where the ejection may damage the electric power grid and other critical infrastructure.

(e) For the purposes of this section, "electromagnetic pulse" means one or more pulses of electromagnetic energy capable of disabling, disrupting, or destroying an electric transmission and distribution system.

EFFECTIVE DATE. This section is effective the day following final enactment.

Sec. 2. **APPROPRIATION.**

$50,000 in fiscal year 2018 is appropriated from the general fund to the Public Utilities Commission to complete the study described in section 1.