Extreme Space Weather Final Report

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I. Defining the Problem

Measuring Outcomes

There are three stages of solar storms: (1) high-energy electromagnetic rays ionize the Earth's upper atmosphere, (2) proton 'storms' collide with the Earth's magnetosphere, and (3) coronal mass ejections (CMEs) react violently with the magnetosphere (*Solar Storms, Flares, CMEs, Geomagnetic Storms, Vulnerable Grid*). Severe space weather events impacting Earth have seldom occurred throughout history—including in 2003, 1989, 1940, and most notably, in 1859 (the "Carrington event"). However, experts often say that an extreme solar storm is not a matter of "if" but rather an issue of "when." Our reliance on advanced technology and infrastructure has made us particularly vulnerable to geomagnetically induced current (GIC) exposure (i.e. disturbances) caused by solar storms in the upper layers of the Earth's atmosphere. Disruptions caused by solar storms can hinder the functionality of essential systems, including electric grids, radio communications, satellites, aviation, and Global Positioning Systems (GPS). Considering the United States' increasing dependence on electricity, our team will concentrate on analyzing the effects of severe geomagnetic storms on electric grid systems in the United States (US). According to the National Oceanic and Atmospheric Administration (NOAA), the potential consequences of a severe geomagnetic storm include: widespread voltage control and protective system problems, complete voltage collapse or blackouts, and damaged transformers (*NOAA Space Weather Scales*).

An extreme geomagnetic disturbance that affects Earth can generate GICs which disrupt the electric grid of a major US city, such as New York City.[1] We discuss the likelihood of an extreme geomagnetic storm in Section II using objective probabilities. In this section, we focus on understanding the potential economic impacts on an electric grid after a worst-case scenario, "one in 100-year" storm. Although we initially intended to calculate the expected monetary value of losses, to do so would require a multitude of simplifying assumptions and access to a wide variety of data. An additional challenge comes from the fact that the estimates may be far from exact due to limited historical data on geomagnetic storms affecting modern electric grids. Therefore, we synthesized findings from existing studies.

On March 13, 1989, one of the most impactful geomagnetic storms in recent history caused a nine-hour blackout in Québec, Canada and impacted the electric grid in parts of the US The collapse of the Hydro-Québec power system was caused by a GIC, and it ultimately affected 842,000 people in the province and 6 million people in North America. The equipment damage had a total cost of $6.5 million and the net cost of Hydro-Québec's failure was estimated to be $13.2 million (Bolduc, 2002). Although Hydro-Québec was a well-documented event that had widespread effects, it was not as destructive as the Carrington event. For comparison, Eastwood et al. reported an estimate of $0.6 to $2.6 trillion as the total economic cost of a Carrington-sized storm (2017).[2] This estimate was based on assumptions of "extended power outages lasting from 16 days to one to two years, and minimum transformer replacement lead times of five months" (Eastwood et al., 2017). Repairing or replacing an extra high-voltage (EHV) transformer can cost

[1] In the proposal, we highlighted Pacific Gas and Electric as a relevant stakeholder for evaluation. The lack of highly susceptible electric grids in their system warranted the change to The Consolidated Edison Company (ConEd). ConEd is a large utility company servicing the New York City metropolitan area (which is heavily populated). Note that this region is extremely susceptible to outages due to extreme geomagnetic disturbances.

[2] Such an event would affect roughly 20 to 40 million people.

millions of dollars, and it can take anywhere from several months to a year (Kirkham et al., 2011, p. 5; Thompson, 2014).

Multiple existing studies have sought to estimate the costs of geomagnetic storms. However, it is important to note that there are limitations on the level of preciseness that can be achieved. These studies have widely varying estimates because they assume different levels of severity of the geomagnetic storms and different durations of recovery and repair. Some look at insurance claims whereas others look at the indirect effects of power outages on supply chains and the US GDP. Experts' estimates of the duration of the effects of an electrical collapse range from a few hours to a decade, depending on whether extra high voltage transformers sustain permanent damage (and thus need to undergo weeks or months of replacement) or whether transmissions systems only collapse for a few hours to a few days without harming electricity generating facilities (Oughton, Skelton, Horne, Thomson, & Gaunt, 2017).

One approach taken in some of these studies was to examine the risks through the lens of insurance. One group studied insurance claims and arrived at an estimate for a more moderate scenario: "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" (Schrijver, Dobbins, Murtagh, & Petrinec, 2014). In a 2016 study, Oughton and colleagues reported that the amount of US GDP lost over a five-year period following an extreme space weather event would be about $136 billion for the baseline scenario and $613 billion for the pessimistic scenario (Oughton et al., 2017). Another metric that the researchers used to estimate the economic impacts of an extreme space weather event was the US insurance industry's losses, which ranged from $55.0 to $333.5 billion from the first scenario to the third scenario. They commented, "at the low end, this is roughly double the insurance payouts of either Hurricane Katrina or Superstorm Sandy, and similar to the total insured losses from all catastrophes in 2015" (Oughton et al., 2017).

In a 2017 study, Oughton and colleagues emphasized the importance of looking not only at direct costs but also at indirect costs of an extreme space weather event. The researchers took indirect supply chain losses into account when arriving at cost estimates for four hypothetical scenarios (based on the percent of the US population that would be left without power). For the first scenario, in which 8 percent of the population would be affected, they estimated a daily economic loss of about $6.2 billion and an additional indirect loss of $0.8 due to interruptions in the global supply chain. For the second scenario, where 23 percent of the population would be affected, Oughton and colleagues estimated a daily US loss of $16.5 billion and additional international loss of $2.2 billion. For a 44 percent scenario, they estimated a $37.7 billion loss within the US and $4.8 billion loss globally. For the fourth scenario, where 66 percent of the population would be affected, the daily economic losses were estimated at $41.5 billion for the US, and $7 billion globally (Oughton et al., 2017). Each of the scenarios was based on a range of geomagnetic latitudes; the second scenario, which includes regions within 2.75° of the 50° latitude would affect key states like New York, Illinois, Pennsylvania, Ohio, and Michigan (Oughton et al., 2017, p.74). In Figure 1, we can see that the state of New York is red on the Daily Customer Disruptions and Daily Direct Loss maps. Based on the scales shown below, this means New York's daily customer disruptions are estimated to be close to 20 million, and its daily direct loss is estimated to be around 3 billion USD (Figure 1).

Scenario Variant	U.S. Population Affected	U.S. Direct Loss ($bn)	U.S. Indirect Downstream Loss ($bn)	U.S. Indirect Upstream Loss ($bn)	Global Indirect Downstream Loss ($bn)	Global Indirect Upstream Loss ($bn)	Global Total Macroeconomic Loss ($bn)
S1	8%	$3.2	$1.6	$1.4	$0.5	$0.3	$7
S2	44%	$19.7	$9.3	$8.7	$2.7	$2.1	$42.4
S3	23%	$8.6	$4.2	$3.7	$1.3	$0.9	$18.7
S4	66%	$28.2	$6.1	$7.2	$4	$3	$48.5

Table 1: Loss by Scenario Variant
Note. From Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, *15*(1), 65–83. doi: 10.1002/2016sw001491

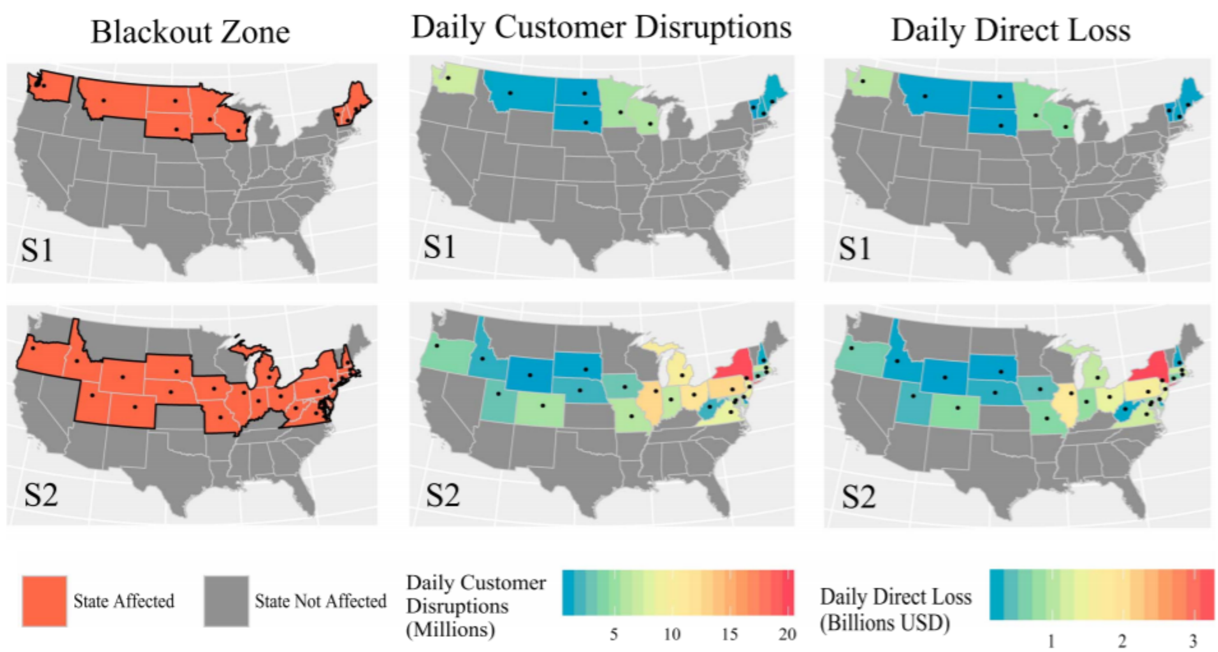

Figure 1: Blackout zone, daily customer disruptions (millions), and daily direct lost ($bn)
Note. From Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, *15*(1), 65–83. doi: 10.1002/2016sw001491

Regulation and Governance

Although extreme space weather events that affect Earth are less frequent than other natural disasters, they can be much more catastrophic due to the scope of the threat they pose; in other words, while a hurricane or tornado directly impacts a relatively small geographical area, a severe geomagnetic storm can theoretically disrupt electrical grid systems around the world. We are left to ponder an interesting risk governance problem, as extreme space weather appears to pose a low frequency, high impact risk. The federal government has already invested significant resources toward supporting citizens in preparing for the devastating consequences of a severe geomagnetic storm. In 2019, the US government dedicated a "combined total of nearly $350 million to activities related to space weather," according to the Congressional Budget Office.

In 1997, the US Presidential/Congressional Commission on Risk Assessment and Risk Management outlined their "Framework for Environmental Health Risk Management," which included six stages: "define the *problem* and put it into context, analyze the *risks*, examine *options* for addressing the risks, make *decisions* about which options to implement, take *actions* to implement the decision, and conduct an *evaluation* of the action's results" (Omenn, 1997, p. 3). An important tenet of the framework is that it involves continued iterations based on new information and collaborating with stakeholders. Multiple US offices have responsibilities relating to space weather risks, and they each contribute to specific stages within this risk policy framework. The Space Weather Operations, Research, and Mitigation (SWORM) Working Group was formed to coordinate how various departments and offices address space weather risks, and it is involved in all stages of the framework. It set three main objectives: "1. Enhance the Protection of National Security, Homeland Security, and Commercial Assets and Operations against the Effects of Space Weather; 2. Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts; and 3. Establish Plans and Procedures for Responding to and Recovering from Space Weather Events" (Droegemeier, 2019). In other words, SWORM aims to analyze and communicate the risks, strategize on how to manage and respond to those risks, and ultimately protect the nation's security and assets from the effects of extreme space weather events. These goals align nicely with the steps outlined in the Presidential/Congressional Commission's framework.

The first stage involves "defining the problem and putting into context" (Omenn, 1997, p. 3). Congress and presidents are quite influential in this stage, where the scope of the problem gets defined and high-level goals are set for years to come. Congress called for the White House Office of Science and Technology Policy (OSTP) to "improve national preparedness for space weather events and to coordinate federal space weather activities of the NSWP Council" 2010, passing the baton of space weather policy to the White House. Executive orders issued by presidents set the agenda for how to address the problem at large. For instance, E.O. 13865 called for the federal government to "foster sustainable, efficient, and cost-effective approaches" (Lipiec and Humphreys, 2020).

The Department of Commerce is responsible for providing forecasts and research, which aligns with the risk analysis stage of the risk management framework. One responsibility of the Secretary of Commerce is to "prepare and issue predictions of electromagnetic wave propagation conditions and warnings of disturbances in such conditions" (Lipiec and Humphreys, 2020, p. 7).

The Department of Defense has responsibilities that seem to fall within the "risks" and "evaluation" stages; it is expected to "conduct R&D and testing to understand the effects of EMPs on Department of Defense systems and infrastructure, improve capabilities to model and simulate the environments and effects of EMPs, and develop technologies to protect Department of Defense systems and infrastructure" (Lipiec and Humphreys, 2020, p. 8). Along with their responsibility to analyze the risks as they "rapidly characterize, attribute, and provide warning of EMPs" (Lipiec and Humphreys, 2020, p. 8), they are also expected to evaluate the effectiveness of risk management actions by "review[ing] and updat[ing] existing EMP-related standards for Department of Defense systems and infrastructure, as appropriate" (p. 8).

The Department of Homeland Security has responsibilities that align with the "options," and "decisions" phases. According to Executive Order 13865, the Secretary of Homeland Security is expected to "use the results of risk assessments to better understand and enhance resilience to the effects of EMPs across all critical infrastructure sectors, including coordinating the identification of national critical functions and the prioritization of associated critical infrastructure at greatest risk to the effects of EMP" (Lipiec and Humphreys, 2020, p. 12). It evaluates options for enhancing resilience and then makes decisions when prioritizing areas of focus.

The Department of Energy has responsibilities that align with the "decisions" and "actions" phases. In particular, it is "responsible for coordinating recovery in case of damage or disruption to the electric grid" (Lipiec & Humphreys, 2020, p. 10). Under the Department of Energy, the Federal Energy Regulatory Commission (FERC) enforces infrastructure reliability standards by "develop[ing] 'corrective action plans' to mitigate GMD vulnerabilities, and [authorizing] time extensions to implement "corrective action plans". Meanwhile, the North American Electric Reliability Corporation (NERC) works to "examine potential vulnerabilities associated with EMPs and to develop possible areas for improvement" (Lipiec & Humphreys, 2020). This fits well with the stages of the risk management framework that involve making decisions about which options to implement and taking actions to implement them.
"facilitate the protection and restoration of the reliability of the electrical power grid during a presidentially declared grid security emergency"

The Department of the Interior is responsible for providing funds to support research and development related to EMPs (Lipiec and Humphreys, 2020, p. 14), so it primarily aligns with the "analyzing the risks" stage of the risk management framework. The Department of State plays an influential role in the decision-making stage by "negotiating and promoting international norms and practices with respect to outer space" (Lipiec & Humphreys, 2020, p. 15). This is relevant to the process of deciding which options to implement on an international scale.

When addressing the risk in the context of the ConEd, the primary electricity grid servicer and utility provider for the New York City metropolitan area, it is important to note that New York does not have legislation or individualized policy about dealing with major geomagnetic storms that impact day-to-day life. This lack of regulation and direct governance at the state level is overshadowed by the aforementioned national response plans to a possible extreme space weather event. This is for good reason, as an event on the scale mentioned in this report would require addressing the problem on a national level. There are several reasons why there may be less of an emphasis on creating a policy to address this risk, even though major geomagnetic events have occurred throughout history. According to historical documents, a large geomagnetic storm affected Earth in May of 1921. Fortunately, due to the lack of electrical infrastructure in New York City at the time, hardly any damage or disruption was noted (Cliver, Hiyaka, Love, 2019). Regulation and governance is a constantly evolving process that takes in information to output thoughtful policy measures. This report team recommends New York City and ConEd to study the effects of past geomagnetic events and develop contingency plans for extreme space weather in conjunction with the national government. The chain of command for policy implementation could have a greater emphasis on research and collaboration throughout various levels of government in order to achieve more effective risk regulation and governance.

II. Characterizing the Uncertainty

Objective Probabilities

When evaluating the risks posed by extreme space weather for the reliability of electric power, it is important to consider the likelihood of an extreme weather event impacting Earth. Of course, there are many methods one might use to quantify this likelihood, such as performing a Bayesian analysis using a prior based on previous research studies (e.g. counting process with Weibull inter-occurrence times; Moriña, Serra, Puig, & Corral, 2019). For this project, our team has decided to assess this likelihood using objective probabilities.[3] Our approach involves synthesizing multiple previously-proposed probability estimates. Although this approach is by no means guaranteed to yield the most accurate approximation, we believe it will provide a rough, well-informed guess that should be sufficient to set the stage for policy recommendations. More specifically, the methodology can be decomposed into two components: (1) examining how the frequency of geomagnetic storms fluctuates as a function of the 11-year solar cycle and (2) determining the relative proportion of solar flares which ultimately affect electric grid systems in the form of geomagnetic storms, i.e. the proportion of flares which reach the final stage, in which CMEs violently interact with the Earth's magnetosphere, with kinetic energies large enough to warrant concern (*Solar Storms, Flares, CMEs, Geomagnetic Storms, Vulnerable Grid*).

The 11-year solar cycle describes the behavior of our Sun as a function of time. Scientists have observed that, over a period of 11 years, the Sun transitions between varying levels of activity and magnetic field strengths in accordance with the number of sunspots visible on the Sun's surface (*What is the solar cycle?*, 2020; Guido & Kalaw, 2019, p. 1). During times of peak solar activity, the number of sunspots—regions that appear relatively cool as a result of an increase in magnetic field activity—exceeds the typical amount. Sunspots contribute to magnetic arcs, which, once destabilized, eject large amounts of solar material into outer space (commonly in the form of CMEs or solar flares; *What is the solar cycle?*, 2020). So, by identifying which portion of the solar cycle our Sun occupies in any given year, scientists may be able to better predict when extreme space weather events will be more probable. For instance, in an analysis of solar cycle 23 (which occurred during the period of May 1996 to December 2008), it was determined that geomagnetic storm events were most numerous in the years 2000 and 2001—the peak of the solar cycle—and relatively infrequent afterwards. Explicitly, there were eight geomagnetic storms (all at least moderately strong) between 2000 and 2001 and only six storms between 2002 and 2008 (Guido & Kalaw, 2019, p. 4). Additionally, these six storms were not uniformly distributed throughout the period; rather, two storms occurred in quick succession (i.e. a matter of days or months) in 2003, 2004, and 2005 (Guido & Kalaw, 2019, p. 4).

However, it is important to remember that, even if geomagnetic storms are more prevalent at a particular point in the cycle (the peak), these events may not necessarily pose the greatest threat to Earth's inhabitants. The aforementioned study concluded that the most severe geomagnetic storm event occurred during the descending phase (i.e. after the peak) of solar cycle 23, e.g. the storm which produced the greatest change in the Disturbance Storm Time (Dst) index[4] occurred in late 2003 (Guido & Kalaw, 2019, p. 4). The data suggests that, if we want to safeguard our electric grids, not only must we be vigilant during times of peak solar activity (when geomagnetic storms seem to be most probable), but we must remain equally (or even more) cautious during later points in the solar cycle "when energy accumulates and may be released in single but very powerful events" (*A method to study extreme space weather events*, 2020).

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[3] In the proposal, we articulated an objective-subjective approach; however, upon further investigation, there is no major subjective component since we do not have personal experience with or strong beliefs about severe space weather events (independent of research).

[4] The severity of a geomagnetic storm is defined by changes in the Dst index.

According to a recent report, the probability[5] of a similar storm (to the Carrington event of 1859) occurring in the following decade ranges, with 95% confidence, between 0.46% and 1.88% (Moriña et al., 2019). Furthermore, of the $> 30,000$ CMEs observed by SOHO/LASCO (Solar Heliospheric Observatory/ Large Angle Spectrometric Coronagraph) in the period 1996 to 2015, only 314 were considered large kinetic energy CMEs (kinetic energies greater than or equal to 10^{31}ergs). So, in almost two decades, roughly $\frac{314}{30000} \times 100\%$ =1.047% of CMEs[6] possessed sufficiently large kinetic energies to warrant concern (Guido & Kalaw, 2019, p. 3). This result is in accordance with the 95% confidence interval given above; there seems to be considerable evidence to suggest that this interval is indeed quite accurate (at least based on the current state of the field). It is important to note that these recent findings seemingly contradict earlier estimates; a comprehensive literature review found that previous estimates—which hovered around 6 to 12%—overestimated the likelihood of extreme geomagnetic storms (Moriña et al., 2019; Krausmann, Andersson, Gibbs, & Murtagh, 2016). Nevertheless, these estimates have limitations. An inherent weakness in all of these estimates is a consequence of the rarity of extreme weather events (e.g. there have not been many geomagnetic storms in history); even though we may be able to roughly approximate the likelihood of such an event occurring, it is still virtually impossible to construct a forecasting model with high predictive accuracy. Finally, the probability of occurrence of a Carrington-like (or worse) event is sensitive to the definition of *event* since one can assess severity in a plethora of ways. For instance, if the threshold is a change in (magnitude of) Dst of at least 850 nT as opposed to a change in (magnitude of) Dst of at least 1700 nT, then the likelihood of an extreme geomagnetic storm is relatively high (Riley, 2014).

The Language of Risk and Risk Narratives

When attempting to characterize a risk and its possible outcomes, it is crucial to dissect the narratives that inform our perceptions and decisions. With other risks drawing more immediate attention, it can be easy for individuals to underestimate the threat of extraterrestrial or space-related events and assume they would not affect life on Earth in the near future. An investigation into how an anthropocentric narrative might skew humanities perception of extreme space weather risks is crucial for understanding how to highlight this risk in day-to-day activities. For instance, some residents may deem the chance of a severe geomagnetic storm as being too far-fetched to motivate tighter regulations or planning. This assumption has the potential to impact decision-making at various levels, from an individual homeowner to the federal government. In 2007, Inderscience Publishers highlighted that disasters are worsening and the US must become better equipped to handle large-scale catastrophic events. Federal regulations and risk awareness emphasis are placed on risks that our current culture has perceived as pertinent or the most dangerous in our world, whether that be a global pandemic or the threat of a terrorist attack; however, our perception of danger is dependent on the narrative that we believe. Anthropocentrism is a framework that is founded in the belief that humanity is far too advanced and "special" to be influenced by natural or extraterrestrial catastrophes. This concept is amplified as humanity continues to be sheltered by the confines of cities and urban areas from the "outside" natural world. For example, some of the most susceptible areas to

[5] To be precise, these are percentage estimates.
[6] We assume that SOHO/LASCO captured data regarding *all* CMEs, so this percentage is an upper bound.

large-scale damages from extreme solar weather in the US are large metropolitan areas like New York City. It makes sense that these areas also are prime examples of the lived-experiences and assumptions made through anthropocentric viewpoints in native city-dwellers. The rarity of such extreme space weather could make this narrative more difficult to combat.

Given that humanity only has information from about five well-documented extreme space weather events, scientists must resort to extrapolation techniques in an attempt to construct predictive models (Hilgers, 2016). Particularly in first-world, western countries, many citizens are largely unaware of the serious danger posed by severe geomagnetic storms and instead rely upon distorted mental models (which may be influenced by popular culture, including science fiction films, television, and novels). Others who encounter messaging about space less frequently may incorrectly assume that space weather is highly unlikely to impact life on Earth. In clarifying the relationship between a particular (anthropocentric) risk narrative and public perception, scenarios can be useful in ensuring that the framework surrounding this risk is managed appropriately and is clear to the general public. Through this clarification, we are working to ensure that measured outcomes are understood through the lenses of the narratives that impact their perception and preparation. One recommendation is to educate the general public to eliminate misconceptions and misattributions about this risk. This must be done accurately and thoroughly to ensure that residents of New York can understand the impacts of a risk like extreme solar weather. Through public policy analysis and creating thoughtful campaigns, future generations can adequately be prepared to use the language of this risk and alter personal and societal narratives surrounding the danger. As we have seen from prominent public awareness campaigns for smoking and sexually transmitted diseases, education can work for the people in the world and save lives in the long run (Christopher et al., 2012). Characterizing the uncertainty of this risk is highlighting the educational awareness, personal narratives we subscribe to and the ways in which we prepare the general public for a catastrophe, like a major geomagnetic storm.

III. Identifying and Describing the Perceptions and Preferences

Risk Tolerance

A comparative analysis of risk tolerance levels offers an adaptive methodology to evaluate the often conflicting preferences of stakeholders. This is because risk tolerance offers a way to characterize the point at which a given stakeholder (citizen, regulatory agency, utility company) would be sufficiently incentivized to act in support of risk mitigation efforts (and hence is useful for our policy-focused analysis). In the modern age, electricity powers everything from cell phones to nuclear plant coolant water systems. Therefore, one might hypothesize that the risk tolerance for a blackout caused by a geomagnetic storm is extremely low, irrespective of the type of stakeholder. In reality, this assumption must be explored in depth since—based on our class discussions—individuals and groups often act in ways that may be counterproductive to accomplishing their respective objectives. For instance, it could be true that regulatory authorities at all levels agree on a low risk tolerance threshold, whereas residents grossly underestimate this risk (principally due to misinformation or the lack of information; issues related to risk communication addressed in Section V) and hence maintain a relatively high risk tolerance level for a complete or partial blackout. Our research indicates that utility companies, particularly power grid operators, are the most risk-aware stakeholder (Krausmann et al., 2016). By contrast, ordinary (not an expert in space weather) residents appear to be the least risk-aware stakeholder. This phenomenon is evident based on the popularity of anthropocentric narratives (addressed in Section II). It is a well-known fact that risk awareness is correlated with risk tolerance (Krausmann et al., 2016). However, the precise nature of the correlation (positive/negative) is context-dependent, i.e. having less information (low awareness) about a phenomenon sometimes permits us to underestimate threats (high tolerance).[7] Even though the literature does not adequately address the differences in risk tolerance levels among various stakeholders, we can still describe how tolerance thresholds might vary between utility companies and residents.[8] In general, large utility companies, like ConEd, are intrinsically motivated by profit maximization. During a blackout, not only do customers face hardships but utilities undergo long periods of net loss. Combining this realization with the aforementioned result that utilities are particularly risk-aware (i.e. well-informed about the expected cost of damages), we believe ConEd would have a very low tolerance threshold for extreme geomagnetic storms. While gauging the tolerance thresholds for New York City residents is very difficult (diversity of preferences), the lack of effective communication regarding space weather events would suggest that most residents have a relatively high tolerance for this risk. We acknowledge, however, that there are exceptions to this classification since, for example, many laypersons are avid science fiction readers and viewers.[9]

Social Welfare

Another important criterion by which one can assess the preferences of stakeholders is the choice of a social welfare function (SWF). For instance, assuming that the stakeholder in question is a federal regulatory agency like FERC, perhaps a Rawlsian SWF would be selected to protect the well-being of those American citizens who are the least well-off. Accordingly, it might be true that this federal authority approves regulations depending on the corresponding impacts on the least well-off members of society. In this scenario, the relevant criterion for social welfare maximization would be the utility of the least well-off individuals. On the other hand, assuming that the stakeholder in question is ConEd (investor-owned utility), a Bentham SWF might be chosen. In this case, we hypothesize that a large utility company—like any other business—is indifferent to the varying degrees of well-being of its customers and instead takes a utilitarian perspective where it is purely interested in maximizing collective well-being, which means the least well-off individual is no longer the benchmark.

Initially, our team had planned on considering social welfare maximization with both the Rawlsian and Bentham SWFs (testing our hypotheses); however, a thorough examination of the literature reveals that this aspect of the analysis is inadequately addressed. Therefore, some of the major considerations we outlined in the proposal, including how the choice of social welfare function depends on the type of stakeholder, will not be fully addressed in this report. Instead, we will primarily consider how social welfare can be assessed by various stakeholders in the context

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[7] Consider how individuals violated lockdown protocols at the beginning of the COVID pandemic (when scientific knowledge was relatively limited). The reader should also be familiar with the opposite relationship, i.e. given more information about the potential consequences of a particular risk, an individual develops a lower risk tolerance threshold.

[8] We have omitted a discussion of the tolerance levels associated with regulatory agencies for the sake of conciseness (and the lack of credible information). We acknowledge this to be a limitation of our assessment of risk tolerance levels but hope that a two-way comparison (residents vs. utility companies) is still illuminating.

[9] From these sources, an individual would not obtain the most accurate information; in fact, most science fiction pieces exaggerate the danger posed by a particular phenomenon/object.

of a blackout situation (in New York City, as before). Suppose you wake up one day and see an alert on your phone that says a Carrington-sized geomagnetic storm may occur within the next 24 hours (i.e. a fast CME blasted off the Sun's surface in the direction of Earth). Assuming that you are an ordinary citizen, the alert might only be concerning[10] for a fleeting moment (i.e. "life" happens). The next day, you learn, due to the effects of the forecasted storm, the power grid operated by ConEd (which services residents and businesses of New York City) is offline in ~60% of the service area (roughly three of the five boroughs of the city). As discussed previously, the loss of electric power has a cascading effect on almost every aspect of our modern society, i.e. in the affected service area, basic societal functions, including water and fuel supply, heating, mobile communication, and ATM services, will be disrupted (Krausmann et al., 2016). In the days to come, blackouts will continue to hamper basic societal functions and arouse unrest among residents[11]. With communication and navigation technologies (e.g. GPS) rendered useless, first responders will quickly become overwhelmed. From this hypothetical scenario, it should be clear that all relevant stakeholders must take this risk seriously (regardless of its rarity, elaborated in Section II). Thus, when it comes to assessing social welfare, one might believe stakeholders share a common perspective. Such an assumption is not valid. Simply consider the diversity in perspectives/preferences regarding the mask policy during the COVID pandemic (in which the possibility of societal collapse was entertained). Nevertheless, based on our interpretation[12] of the literature, it seems that both public and private stakeholders—utility companies, like ConEd, and federal regulatory agencies, like FERC—would reject both the Rawlsian and Bentham frameworks in favor of a framework which accounts for the ranking of welfare levels, without concentrating exclusively on the welfare levels of the least well-off individuals (Sen, 1974). This is mainly because the affected population would be so large and diverse (in terms of socioeconomic status); only considering the effects on members of the lowest welfare level would conflict with governmental obligations to protect the interests of all citizens and the profit-maximizing goals of utility companies (i.e. the utilitarian perspective is effectively modified to accommodate a burdensome situation). In sum, the impact of a Carrington-like storm on societal well-being would likely be devastating in the short-term. The question is: what would be the long-term impact of such a geomagnetic storm? The literature suggests that, if appropriate proactive measures (discussed in Section VI) are universally adopted by all relevant stakeholders, the effects of an extreme weather event can eventually be reversed (Thompson, 2014; Geller, 2020; Krausmann et al., 2016). In other words, the societal collapse (into a chaotic, lawless environment) which seems inevitable based on the description of short-term impacts is, as a matter of fact, preventable.

IV. Making a Decision

Expected Utility Maximization

To find expected utility, we must calculate the probability of our event (a blackout of duration x) and multiply it by the utility lost due to the blackout. We will use our previous estimations of the probability of a large scale geomagnetic storm and the expected duration of the

[10] This kind of response is typical since public awareness of the risks associated with extreme space weather is very limited.

[11] Considering the fact that New York City is the tenth-most densely populated city in the world, civil unrest can quickly escalate into violence.

[12] Again, this assertion is not completely justified due to gaps in the field.

event, as well as the value of damaged equipment combined with the value of lost load, a measure of the value placed on lost kilowatt-hours (kWh), as utility. Value of Lost Load (VoLL) is a well-studied macroeconomic concept that spans a few decades of literature in several different countries using several different methods. In this report, we chose to focus on one study done in 2013 that uses willingness-to-pay (WTP) to calculate the value placed on lost kWh. The report examines VoLL over 3 different groups (Medium and Large Scale Commercial and Industrial Enterprises, Small Scale Commercial and Industrial Enterprises, and Residential Homes). For simplicity, we will use the metrics associated with Medium and Large Scale Commercial Enterprises. We assume that there will be more of these institutions in the event of a catastrophe in New York City, so the utility provider should adjust according to the expected utility of those institutions. We thus get the following equation:

(VoLL * Expected Number of Hours the system is offline * kWh of electricity consumed per hour) * Probability of the event

The VoLL is $12.70 per unserved kWh, we will use 5 days (or 120 hours) as the expected number of hours[13], 29.2 * (1050911 + 8336817) to approximate the amount of electricity to be used, and we will use average demand for kWh in the US according to the US Energy Information Administration. The numbers are the total number of establishments and the total number of residents, and the probability of the event is between .46% and 1.88% (US EIA, 2019, US Census Bureau, 2019). Therefore, (12.70 * 120 * 29.2 * (1050911 + 8336817) * .0046) = $1.9 billion and (12.70 * 120 * 29.2 * (1050911 + 8336817) * .0188) = $7.9 billion. In other words, ConEd should be willing to spend at least $1.9 billion and no more than $7.9 billion on severe solar activity prevention. An important limitation is that these values and calculations can shed light on the concepts as a theory, but they are only rough estimates and should not be applied as certain values.

Prospect Theory

Daniel Kahneman and Amos Tversky developed prospect theory to describe the decisions made by human beings instead of rational agents, and the framework begins with the initial premise of loss aversion (Kahneman, 2013). Geomagnetic storms present a particular challenge in navigating loss-averse human behaviors; since there does not seem to be a way to benefit from these storms, all of the utility from protective measures comes from prevention rather than gains. According to prospect theory, we would suspect that individuals, corporations, utilities, and governments would be willing to spend large sums of money on mitigation strategies for this risk, perhaps more than is truly appropriate. Enunciating clear tradeoffs and helping institutions be clear and consistent about their goals will be a large focus in this project. In addition to this, we hope to make various stakeholders aware of their own biases (as well as ours), thereby allowing them to counteract those biases as they wish rather than how we think they should. Thus, we suggest that ConEd be willing to spend nearer the maximum estimate ($7.9 trillion) as opposed to the minimum estimate ($1.9 trillion), and perhaps over that estimate. Sticking to a pre-established budget and clearly enunciating boundaries with spending money are perhaps the most important things our client can do to prevent asking for/spending too much money. Given that ConEd makes $12.033 billion in revenue and just $1.5 billion in operating income, it is in

[13] The kind of event that we are considering could lead to small blackouts that last a few hours or Carrington-like events that last for months.

the best interest of the organization to also keep its costs down and spread the costs out over a period of time (Sec, 2017).

V. Outreach and Communication

Risk Communication

Most people are not very familiar with geomagnetic storms and their potential impacts on Earth, and thus, the risks are not discussed very frequently. Bradley and colleagues (2020) suggest that "risk communication influences people's capability and motivation to perform protective behaviors. However, public alarm about a novel hazard and low trust in authorities may result in 'outrage'" (p. 1).

When understanding public perception of the risk of geomagnetic storms, it could be useful to consider its attributes in the context of Sandman's outrage factors. For example, since geomagnetic storms would be considered a natural rather than industrial risk, and Sandman suggests that "government and industry are far more attractive villains" (Sandman, 1993, p. 17), one might expect lower levels of alarm among the general public. On the other hand, geomagnetic storms are likely to be perceived as more of an 'exotic' risk than a 'familiar' risk, and Sandman suggests that "to reduce the outrage that comes with unfamiliarity, it helps to acknowledge that the risk is, in fact, unfamiliar" (Sandman, 1993, p. 21). News articles about geomagnetic storms (or solar storms in general) often include a decent amount of scientific terminology from experts, which could play a role in contributing to a sense of exoticism and unfamiliarity.

A Carrington-level geomagnetic storm could be considered a rare catastrophic risk. Thus, it may also be important to consider how to avoid a "tragedy of the uncommons," where unavailability, numbing, and under-deterrence could lead people to mischaracterize a rare but catastrophic risk (Wiener, 2016). Without proper risk communication, the general public could fall victim to this "tragedy of the uncommons" and be underprepared due to an underestimation of the impacts of geomagnetic storms. Perhaps more dangerous is the possibility of electric utilities like ConEd falling into this trap, as a more vulnerable transmission system collapsing could have the potential to affect millions of people. Fortunately, existing regulation and insurance has made an environment where electric utilities will not completely ignore the risks; however, it is still important to have an effective risk communication strategy to motivate stronger protective measures. Therefore, we will propose a risk communication strategy that could be used to better inform and prepare ConEd's stakeholders and the general public for a severe geomagnetic storm.

In order to devise a strategy that could be implemented to increase awareness without creating an unproductive level of outrage, we apply experts' principles and recommendations for disaster risk communication to the topic of geomagnetic storms (Robinson, 2017).

1. Invest in audience research throughout the process
2. Select the right media and communication platforms
3. Incorporate multiple channels and enable two-way flows of information
4. Make the messages clear, relevant, engaging and practical
5. Collaborate with multiple stakeholders

For ConEd and the residents of New York City, we propose a risk communication campaign that emphasizes preparedness and gives accurate, accessible information about the likelihood and impact of an extreme geomagnetic storm. For communicating with New york residents, we would also recommend highlighting protective measures that ConEd has taken to mitigate the risks. This would help reduce outrage and establish greater trust in ConEd's infrastructure and services. After all, the general public in New York City would likely have no prior experience or recollection of what a geomagnetic storm warning is or how it would affect them. More concretely, this might include giving the public email and phone alerts with follow-up phone calls. It would be important to include neutral rather than alarming messaging, as the information could quickly spread on existing routes of information-sharing, such as social media platforms. We would also recommend outlining emergency plans for securing water and food supplies in case of a long-lasting, widespread blackout. These plans should be accessible, easy to follow, and considerate of members of the public in different circumstances (e.g. parents of infants and toddlers, elderly residents, individuals with disabilities). Outside of these specific disaster contingency plans, it would be essential for the risk communication campaign to have cities provide examples of what a "good" plan is and what a "bad" plan qualifies as. It is crucial that families have adequate plans that work the first time.

Stakeholder Engagement

In crafting policy-focused responses to the possibility of extreme space weather, it can be complicated to decide how to work with powerful stakeholders on a national (or even international) level. Because countries and institutions with a heavy reliance on electrical and computer systems stand to lose the most in the event of a severe geomagnetic storm, they can pioneer the necessary changes in electric grids. Some of the major stakeholders who must consider the risks of geomagnetic storms are electric utilities, regulatory agencies, and government actors—along with the citizens who are most directly impacted by insecurities in electric power. We know that stakeholders play an absolutely crucial role in understanding how to prepare those who use their services or are invested in their continued existence as a company. For the scope of this final risk report, the largest individual stakeholder that will be addressed is the private electric company, ConEd. This utility service provides electrical systems and power to most of the New York City metropolitan area, a region we have noted as particularly vulnerable to the damage from a severe solar flare and geomagnetic storm (*Solar Storms, Flares, CMEs, Geomagnetic Storms, Vulnerable Grid*). It is important to note that regulatory agencies and private companies naturally have the most input when it comes to preparing grid systems for solar storms of varying sizes. As noted earlier when elaborating about the "Social Welfare" aspect of our risk, stakeholders are often charged with being much more knowledgeable about a risk than an ordinary citizen. ConEd actually created a detailed podcast and outlined the dangers that are posed by the possibility of extreme space weather. This media engagement mentioned many of the protocols and best practices used to try and protect the grid from GIC problems, these strategies include "early awareness protocols, mobilizing local power reserves to support voltage and de-loading vulnerable transformers to protect them from overheating." (Con Edison Media Relations, 2018).

A key aspect of stakeholder engagement involves reaching out to the populations that would be most seriously impacted by the destruction of electrical and communication systems. Specifically, among government agencies, the National Weather Service provides engagement opportunities for citizens to prepare for the impacts of space weather here on Earth (*NOAA Space Weather Scales*). These outreach programs provide the opportunity to brainstorm different scenarios and evaluate their actualized effectiveness across all entities. In this project, an analysis of multiple stakeholders will hopefully highlight solution models from different institutions. Based on this comparison, we can discover salient policy-oriented solutions that address the outcomes and risk management alternatives associated with extreme space weather. For example, an electric utility would have to consider the ways in which its electric grids could be susceptible to long-term damage. This evaluation will depend on many factors, including the location, age, and design of the grid system. These considerations are crucial when developing policy recommendations because they highlight the ways in which stakeholders can assess the potential consequences of this risk. Based on these real world scenarios and examples, there are clear and valuable recommendations that can be made to make stakeholder engagement work for everyone. First and foremost, stakeholders must take their positions of power and do the work necessary to protect grids, citizens, and be prepared for even the most obscure risks. ConEd has already done a great deal of planning and communication about their contingency plans for extreme solar weather and these are also in-line with many governmental regulations as well. A multi-risk governance approach is needed to address issues related to the risks of cascading effects and the many different stakeholders that manage the risk often in isolation from each other (Krausmann et al., 2016). Communication between key stakeholders will make the difference between a clear-cut and successful response or a dangerous and potentially deadly response failure.

VI. Recommendations

The key scenario that we have considered is the partial blackout of New York City as a result of damages to the electric grid operated by ConEd. According to the literature, potential risk mitigation strategies (alternatives) include: (1) installing current-blocking capacitors and GIC monitors to protect transformers and regulate power flow, (2) using effective risk communication strategies to increase public awareness of the dangers of geomagnetic storms, (3) allocating funding to NASA's Solar Shield program or a similar initiative which seeks to determine which voltage transformers are most susceptible, (4) mandating more frequent tests of voltage transformers for vulnerabilities to big disturbances in the Earth's magnetic field, (5) shifting to renewable energy sources so that power can be produced by more localized sources, thus limiting the interconnectivity of the electric grid and increasing resiliency overall, (6) "increasing the reserves of both active and reactive power to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers," and (7) pursuing "further geophysics, transmission network, and transformer modeling research to understand the effects of GIC on individual transformers, including the thermal effects, reactive power effects, and the production of harmonics," as well as to enhance understanding of the magnetic field orientation of CMEs before they hit the Earth―which is critical to geomagnetic storm forecasting (Thompson, 2014; Geller, 2020; Royal Academy of Engineering, 2013). In our view, alternatives (1), (2), (6), and (7) are most important and should (ideally) be executed in a timely fashion. As highlighted earlier in the discussion of the "tragedy of the uncommons," societies can have unique challenges incorporating learned experiences into thoughtful policy implementation. A risk management alternative such as (6) would require a policy overhaul and foresight in private companies to plan for a fail-safe in this manner. A primary recommendation in relation to this contingency plan would be to start early and be effective in the communication of the risk to all parties involved: utility companies, regulatory agencies, and citizens. In sum, the most important issue associated with extreme space weather is the lack of knowledge and planning surrounding a risk that society has had limited exposure to; with a thoughtful education campaign and detailed policy initiatives, we believe that New York City can prepare for this potential catastrophe.

Works Cited

Anthropocentrism. (n.d.). Retrieved April 13, 2021, from https://www.britannica.com/topic/anthropocentrism

Bradley, D. T., Mansouri, M. A., Kee, F., & Garcia, L. M. (2020). A systems approach to preventing and responding to COVID-19. *EClinicalMedicine, 21*.

Bolduc, L. (2002). GIC observations and studies in the Hydro-Québec power system. *Journal of Atmospheric and Solar-Terrestrial Physics*. doi: 10.1016/s1364-6826(02)00128-1

Consolidated Edison Incorporated. (2017). SEC.https://www.sec.gov/Archives/edgar/data/23632/000104786218000037/ed-20171231x10k.htm

Eastwood, J. P., Biffis, E., Hapgood, M. A., Green, L., Bisi, M. M., Bentley, R. D., … Burnett, C. (2017). The Economic Impact of Space Weather: Where Do We Stand? *Risk Analysis*, *37*(2), 206–218. doi: 10.1111/risa.12765

Executive Office of the President of the United States, & Droegemeier, K., National Space Weather Strategy and Action Plan (2019).

Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA). (2019). US Energy Information Administration. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

Geller, D. (2020, July 13). Actually, It Can Happen to Us: Solar Storms. Retrieved April 13, 2021, from https://www.verisk.com/insurance/covid-19/iso-insights/actually-it-can-happen-to-us-solar-storms/.

Guido, R., Kalaw, J. (2019). Characterizing Coronal Mass Ejections in Solar Cycle Analysis. *International Journal of Astronomy*, *8*(1). doi: 10.5923/j.astronomy.20190801.01

Hilgers, A. (2016). (rep.). *Extreme space weather events*. Paris, France: European Space Agency.

Inderscience Publishers. (2007, November 12). Disasters Getting Worse -- US Government Must Be Better Prepared, Report Urges. ScienceDaily. Retrieved April 19, 2021 from www.sciencedaily.com/releases/2007/11/071112073337.html

Kahneman, D. (2013). *Thinking, Fast and Slow* (1st ed.). Farrar, Straus and Giroux.

Kirkham, H., Makarov, Y. V., Dagle, J. E., DeSteese, J. G., Elizondo, M. A., & Diao, R. (2011). Geomagnetic Storms and Long-Term Impacts on Power Systems. doi: 10.2172/1059627

Kopnina, H., Washington, H., Taylor, B., & Piccolo, J. (2018). Anthropocentrism: More than Just a Misunderstood Problem. *J Agric Environ Ethics*, *31*, 109–127. doi: 10.1007/s10806-018-9711-1

Krausmann, E., Andersson, E., Gibbs, M., & Murtagh, W., Space Weather & Critical Infrastructures: Findings and Outlook, EUR 28237 EN, 2016, doi:10.2788/152877

Love, J. J., Hayakawa, H., & Cliver, E. W. (2019). Intensity and impact of the New York Railroad superstorm of May 1921. Space Weather, 17, 1281– 1292. doi: 10.1029/2019SW002250

Lipiec, E., & Humphreys, B. E. (2020, January 6). *Space Weather: An Overview of Policy and Select U.S. Government Roles and Responsibilities* (CRS Report No. R46049). https://fas.org/sgp/crs/natsec/R46049.pdf

Moriña, D., Serra, I., Puig, P., & Corral, Á. (2019). Probability estimation of a Carrington-like geomagnetic storm. *Scientific Reports*, *9*(1). doi: 10.1038/s41598-019-38918-8

NOAA Space Weather Scales. (n.d.). Retrieved April 12, 2021, from https://www.swpc.noaa.gov/noaa-scales-explanation

Omenn, G. S., Kessler, A. C., Anderson, N. T., Chiu, P. Y., Doull, J., Goldstein, B., … Rall, D., Framework For Environmental Health Risk Management Final Report (1997). Washington, DC.

Oughton, E., Copic, J., Skelton, A., Kesaite, V., Yeo, Z. Y., Ruffle, S. J., ... Ralph, D. (2016). Helios Solar Storm Scenario. *Cambridge Risk Framework*. Centre for Risk Studies, University of Cambridge.

Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, *15*(1), 65–83. doi: 10.1002/2016sw001491

Rabin, M., & Thaler, R. (2001). Anomalies. *Journal of Economic Perspectives*, *15*(1), 219–232.

Riley, P. (2014, October 07). On the Probability of Occurrence of Extreme Space Weather Events. In *SSB Committee on Solar and Space Physics*. Retrieved April 23, 2021, from https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_153147.pdf

Robinson, L. (2017). *A. Public Communication for Disaster Risk Reduction*. Words into Action Guidelines: National Disaster Risk Assessment Special Topics. https://www.preventionweb.net/files/52828_apubliccommunication[1].pdf.

Royal Academy of Engineering. (2013) *Extreme space weather: impacts on engineered systems and infrastructure* (1-903496-96-9). Royal Academy of Engineering. https://www.raeng.org.uk/publications/reports/space-weather-summary-report

Sandman, P. M. (1993). *Responding to community outrage: Strategies for effective risk communication*. Fairfax, VA: American Industrial Hygiene Association.

Schrijver, C. J., Dobbins, R., Murtagh, W., & Petrinec, S. M. (2014). Assessing the impact of space weather on the electric power grid based on insurance claims for industrial electrical equipment. *Space Weather*, *12*(7), 487–498. doi: 10.1002/2014sw001066

Sen, A. (1974). Rawls versus bentham: An axiomatic examination of the pure distribution problem. *Theory and Decision, 4*(3-4), 301-309. doi:10.1007/bf00136651

Skolkovo Institute of Science and Technology. A method to study extreme space weather events. (2020, August 17). Retrieved April 23, 2021, from https://phys.org/news/2020-08-method-extreme-space-weather-events.html

Solar storms could cost USA tens of billions of dollars. (2017, January 19). Retrieved April 24, 2021, from https://www.cam.ac.uk/research/news/solar-storms-could-cost-usa-tens-of-billions-of-dollars

Solar Storms, Flares, CMEs, Geomagnetic Storms, Vulnerable Grid. (n.d.). Retrieved April 13, 2021, from http://solarsystemcentral.com/solar_storm_page.html

Sullivan, M. J., Schellenberg, J., & Blundell, M. (2015). Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States. *ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY*, 1. https://www.osti.gov/servlets/purl/1172643

The Consolidated Edison Company (ConEd). (2018, September 18). Solar Flares & Weather. Retrieved April 23, 2021, from https://www.coned.com/es/about-us/media-center/news/20180928/solar-flares-and-weather

Thompson, J. R. (2014, March 27). The dangers of solar storms: That which gives power can also take it away. Retrieved April 12, 2021, from https://www.earthmagazine.org/article/dangers-solar-storms-which-gives-power-can-also-take-it-away

U.S. Census Bureau QuickFacts: New York city, New York; New York. (2019). Census Bureau QuickFacts. https://www.census.gov/quickfacts/fact/table/newyorkcitynewyork,NY/PST045219

What is the solar cycle? (2020, September 10). Retrieved April 12, 2021, from https://spaceplace.nasa.gov/solar-cycles/en/

Wiener, J. B. (2016). The Tragedy of the Uncommons: On the Politics of Apocalypse. *Global Policy*, *7*, 67–80. https://doi.org/10.1111/1758-5899.12319

VII. Appendix

Note that the Cover Page, Table of Contents, and Appendix were essentially copied directly from the proposal. Recommendations and Works Cited were written as a team. Generally editing and consulting was completed by each team member in another section so that we could best work to convey a message. Many of our roles remained the same for the Final Report

Team Member's Name	Contributions
Devan Wainright	The Language of Risk and Risk Narratives, Stakeholder Engagement, Regulation and Governance
Jachin Friday	Expected Utility Maximization, Prospect Theory
Lucy Ren	Measuring Outcomes, Risk Communication, Regulation and Governance
Nagaprasad Rudrapatna	Objective Probabilities, Risk Tolerance, Social Welfare