FINAL REPORT

Economic Benefit Analysis of NOAA's Space Weather Products and Services to the Electric Power Industry

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Lexington, Massachusetts

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1 Executive Summary

The purpose of this study is to conduct an economic benefit analysis of NOAA's space weather products and services to the United States electric power industry; NOAA contracted Eastern Research Group, Inc. (ERG) to perform this work.

Space weather events present significant risks to the United States economy as these events have the potential to disrupt electric power systems; satellite, aircraft, and spacecraft operation; telecommunication and automation systems; positioning, navigation and timing services; as well as other technologies and infrastructures critical to the Nation's security and economic vitality. National resiliency against space weather events was most recently addressed in the 2019 National Space Weather Strategy and Action Plan (NSW-SAP). The NSW-SAP underscores the need to improve our Nation's understanding of the social and economic effects that space weather events can have on industry, the U.S. economy, citizens, and National security.

This work builds from NOAA's 2017 research into the social and economic effects of space weather on various technological sectors but focuses only on the economic benefits that NOAA's products and services generate for the electric power industry. Thus, the economic benefit estimates provided in this document are not a reflection of the complete economic value of NOAA's space weather products and services, but only the value to the electric power sector. The space weather products and services in this report are comprised of:

- Observations from the NOAA National Environmental Satellite, Data, and Information Services (NOAA/NESDIS); and
- Products and services for the user community from the NOAA National Weather Service (NOAA/NWS), in particular the NWS Space Weather Prediction Center (SWPC).

We conclude that NOAA's space weather observations, products, and services can generate economic benefits to the electric power industry by reducing or eliminating operational and service interruption/blackout costs during a space weather event. We estimate that NOAA's space weather observations, products, and services can generate approximately $27 billion of economic benefits to the electric power industry during an extreme (e.g., K9) geomagnetic disturbance (GMD) event that causes a service interruption/blackout lasting 16 hours in a highly populated area (50 million people). As has been observed from historical space weather events, extreme events can cause catastrophic service interruptions resulting in blackouts lasting much longer than 16 hours. In cases where space weather events affect less populated areas for shorter durations and smaller scale events, the benefits can still be significant, as we estimate an upper bound benefit of over $100 million. Our results are summarized in Table ES-1 (Valuation of Economic Benefits, pgs.8-9) below. These results only estimate the event-based benefits generated by reducing or eliminating operational and service interruption costs, and do not include other avoided costs such as equipment replacement costs or monitoring costs. These economic benefit estimates will fluctuate depending on the geography of the GMD event, which we incorporate qualitatively into our analysis. Finally, these event-based benefits do not include the economic benefit NOAA's space weather observations, products, and services generated when an event is not occurring; we refer to these benefits as constant monitoring or "peace-of-mind" benefits, which are not quantified in this study. Instead, we present these "peace-of-mind" benefits qualitatively.

1.1 Space Weather and the Electric Power Industry

NOAA's SWPC defines space weather as "the variations in the space environment between the Sun and Earth, and, in particular, describes phenomena that impact systems and technologies in orbit and on Earth" (NOAA SWPC, 2020a). When a space weather storm reaches Earth, it energizes Earth's magnetosphere, resulting in a disturbance in the geomagnetic field referred to as a geomagnetic disturbance (GMD) or a geomagnetic storm, (NOAA SWPC, 2020a).

The electric power industry is particularly vulnerable to GMDs since fluctuations in the Earth's electromagnetic field can disrupt the generation, transmission, and delivery of electric power. These electromagnetic variations can cause geomagnetically induced currents (GICs) in the ground, which can destroy essential components of the electric grid's infrastructure. Specifically, GICs can create harmonics that can trip protective relays or cause transformer saturation or overheating, and cause service interruptions or blackouts (Gish et al., 1994; NRC, 2008; Kappenman, 2010a). Extended exposure to GICs may degrade equipment performance of grid components, shorten equipment life, and in severe cases, induce transformer mis-operation or failure. The infrastructure of the expansive electric grid in North America is valued at over $1 trillion in assets and consists of more than 360,000 miles of transmission lines, including over 180,000 miles of high voltage-lines (DOE, 2012). Furthermore, the electric power grid is considered especially vulnerable to space weather phenomena due to its interconnected nature. That is, although some grid redundancy and re-routing capabilities exist, a relatively minor system change or mis-operation in one system can result in momentous cascading effects through the interconnected system which can ripple through the economy, infrastructure, and defense systems.

1.2 Approach

ERG developed a methodology, detailed below, to assess the economic benefits of NOAA's space weather products and services to the electric power industry. ERG's approach included the following elements.

1.2.1 Initial Literature Review

ERG conducted a thorough analysis of NOAA's 2017 report, *Social and Economic Impacts of Space Weather in the United States* (NOAA, 2017). This helped to bolster our baseline understanding of NOAA's work in this area to date and was the starting point for a more in-depth literature review. ERG proceeded to identify more than 50 additional pieces of literature on space weather and electric power grid economics and operations to inform our initial expert engagement.

1.2.2 Initial Expert Engagement

ERG reached out to six stakeholders in the electric power industry to 1) further ground-truth information from the 2017 report, like the impact mechanism (Figure 2, NOAA, 2017) and the physical effects and impact categories (Table 3, NOAA, 2017); and 2) help ERG start to better understand the pathway by which NOAA's space weather products and services generate economic benefits to the electric power industry. ERG used this information to construct value chains to illustratively show how NOAA creates value for the electric power industry.

1.2.3 Value Chain Development

ERG developed value chains to defensibly and illustratively show how value is generated and translated into monetizable economic and societal benefits. The value chain approach aligns with the NOAA's Chief Economist Office approach on other valuation efforts. During this effort, ERG identified two primary pathways by which NOAA's space weather products and services generated economic value for the electric power industry. These pathways are: 1) event-based benefits; and 2) constant monitoring ("peace-of-mind")

benefits. ERG iteratively ground-truthed these value chains with experts and the NOAA project team. See value chains in Appendix B.

1.2.4 Expert Elicitation

ERG used these value chains, and pathways of economic value generation, to inform the design of our expert elicitation interview guide (Appendix C). The expert elicitation interviews were staged to garner a deeper understanding of how the electric power industry uses NOAA's space weather products and services, where industry sources their situational awareness data (i.e., from NOAA's SWPC), how NOAA's data and products affect day-to-day electrical grid operations and typical operational responses to geomagnetic disturbances based on the severity (Kp-index rating) of the storm.

1.2.5 Benefits Tables

ERG used the information obtained from the expert elicitation to create event- and constant monitoring- ("peace-of-mind") based benefit tables which outlined, in greater detail how value was generated (expanding initial value chains) and the economic benefits of NOAA's space weather observations, products, and services to electric utilities. These benefit tables served as the basis of our valuation model. See Appendix D and Appendix E for the benefit tables.

1.2.6 Valuation Literature Review

ERG conducted a second, targeted literature review to identify studies that could aid in the valuation of the economic benefits identified in the benefit tables. This round of literature review had a much narrower scope than the initial literature review, and garnered information that informed our valuation.

1.3 Valuation of Economic Benefits

ERG determined that many of the event-based benefits identified in the benefits table could be combined and quantified as benefits associated with avoiding electric power service interruptions/blackouts. ERG used a 2009 study and its 2015 update from the Lawrence Berkeley National Laboratory (LBNL), authored by Sullivan et al. (Sullivan et al., 2009, 2015) on the cost of service interruption to estimate the benefits of NOAA's space weather products and services to the electric power industry for service interruptions/blackouts of varying durations across four key storm sizes: K3, K7, K8/9-, and K9.

1.4 Quantified Event-Based Benefit Valuation

ERG developed a Google Sheets-based valuation model to estimate the event-based economic benefits of NOAA's space weather products and services to the electric power industry. To conduct this valuation, ERG leveraged the LBNL study (Sullivan et al., 2015) to estimate service interruption costs for various customer types and sizes, and expert elicitation data to approximate operational costs. The economic benefits associated with NOAA's space weather products and services are generated when utilities are able to use the information to prepare for, and thus, reduce or eliminate operational costs (data from expert elicitation) and/or service interruption/blackout costs (data from LBNL study) associated with a space weather event. We present our economic benefit estimates in Table ES-1 below. These low and high benefit estimates depend on:

- The geomagnetic storm severity,
- The duration of the resulting electric power service interruption/blackout, and
- The population affected.

Table ES-1. Economic Benefit Estimates of NOAA's Space Weather Products and Services to the Electric Power Industry

Event size	Benefit of NOAA's Space Weather Products and Services per Event ($1,000's)								
	20,000 Geographic Area Population			1,000,000 Geographic Area Population			50,000,000 Geographic Area Population		
	Low	High	Duration of interruption (hrs.)	Low	High	Duration of interruption (hrs.)	Low	High	Duration of interruption (hrs.)
K1-K6	$1	$245	0.083	$1	$56,963	0.083	$1	$110,765	0.083
K7	$73	$452	1	$9,821	$97,930	1	$76,542	$765,138	1
K8/K9-	$4,040	$14,061	8	$924,809	$3,236,753	8	$7,343,295	$25,701,453	8
K9	$7,915	$15,010	16	$1,819,970	$3,457,915	16	$14,435,062	$27,426,590	16

These benefits are expected each time a geomagnetic disturbance event occurs. For example, for a given K1-K6 event, we assume the event would cause a 5-minute service interruption if a utility did not receive NOAA's space weather products and services. The benefits for utilities are generated by using NOAA's space weather products and services to avoid or mitigate costs from the 5-minute service interruption and associated operational costs. In this example, the benefit estimates range from $1,000 to $245,000 in hypothetical geographic areas with 20,000 people, $1,000 to $57 million in hypothetical geographic areas with one million people, and $1,000 to $111 million in hypothetical geographic areas with 50 million people. As can be seen, the lower bound is always $1,000 which reflects avoided operational costs associated with receiving NOAA's space weather products and services.

As noted, the estimates in Table ES-1 reflect per-event values. More severe geomagnetic storms are low frequency, high risk events and the most severe events elicit the greatest benefits per event. For context on the frequency of these events, Table ES-2 below gives the number of days in a solar cycle where a certain Kp level was measured at least once and provides context for the relative frequency of each event.

Table ES-2. Frequency of Events by Magnitude

Kp-Index	Number of days in Solar Cycle 23 with an event (a)	Average number of days in a solar cycle with an event (b)
1	3,067	
2	3,849	
3	3,357	
4	1,786	
5	739	900
6	250	360
7	90	130
8/9-	31	60
9	14	4

a. Extracted from NOAA's daily archives of geomagnetic data for years 1996 to 2008, approximately one solar cycle. Note that while the average solar cycle is approximately 11 years, it is possible for solar cycles to be less than or greater than 11 years.

b. NOAA's SWPC provides the total number of "storm days" or days with at least one event for a K5, K6, K7, K8/K9- and K9 that occur in an approximately 11-year solar cycle (NOAA SWPC, 2020c).

1.4.1 Geographic Variation

How a GMD affects a portion of the grid is both dependent on its magnetic latitude and the geology below the grid infrastructure, or Earth impedance. Lack of data for the relationship between magnetic latitude, Earth impedance, and the electric power grid did not allow us to quantitatively incorporate geography in our benefit model. However, Lucas et al. (2020) conducted work to combine magnetotelluric survey data, along with GMD data from geomagnetic observatories and data on thousands of transmission lines, to

model transmission line voltages during a 100-year geomagnetic storm (Lucas et al., 2020). This study, conducted for two thirds of the continental United States, identified the East Coast (Maine to Georgia), the Pacific Northwest, the Upper Midwest, and the Denver metropolitan areas as particularly vulnerable to geoelectric hazards. That is to say, the benefit estimates presented in Table ES-1 are likely larger for these regions, across similar population distributions.

1.5 Qualitative Constant Monitoring ("Peace-of-Mind) Benefits

ERG and the NOAA project team determined that it would be best to present constant monitoring ("peace-of-mind") benefits qualitatively. Though these benefits are an important part of the story of how NOAA's space weather products and services generate economic value for the electric power industry, there were little data to defensibly quantify these benefits. Furthermore, when compared to the event-based benefits, the quantified constant monitoring benefits might not resonate with target audiences as they are likely to be several orders of magnitude smaller than the event-based benefits. These benefits include:

- Decreased monitoring efforts
- Decreased defensive investments
- Less chance of lost revenue from sub-optimal operation
- Decreased costs from improper diagnostic efforts
- Less uncertainty
- Reduced cost associated with space weather monitoring information

For more details regarding these qualitative benefits, see Appendix E.

1.6 Recommendations for Future Research

Recommendations for future research include:

- Quantitative analysis of geographic variation in effects of geomagnetic disturbances based on magnetic latitude, Earth conductivity, and grid engineering.
- Economic benefits of NOAA's space weather products and services for extended service interruptions (past 16 hours).
- Assessment of the economic benefits of NOAA's space weather products and services to other vulnerable industries/sectors (e.g., telecommunications, aviation, satellites, and Department of Defense and/or Homeland Security).
- Quantitative economic analysis of constant monitoring benefits of NOAA's space weather products and services.
- Assessment of the economic benefits of improvements to NOAA's space weather products and services.

2 Introduction

Space weather events present significant risks to the United States economy as these events have the potential to disrupt electric power systems; satellite, aircraft, and spacecraft operation; telecommunication and automation systems; positioning, navigation and timing services; as well as other technologies and infrastructures critical to the Nation's security and economic vitality. These complex technological and critical infrastructure systems are especially vulnerable due to the extent to which they are interconnected. That is, although some grid redundancy and re-routing capabilities exist, a relatively minor system change or mis-operation in one system can result in momentous cascading effects through the interconnected system which can ripple through the economy, infrastructure, and defense systems.

Resiliency against space weather events was most recently addressed in the 2019 National Space Weather Strategy and Action Plan (NSW-SAP). The NSW-SAP underscores the need to improve our Nation's understanding of the social and economic effects that space weather events can have on citizens, industry, the U.S. economy, and national security.

2.1 Defining Space Weather

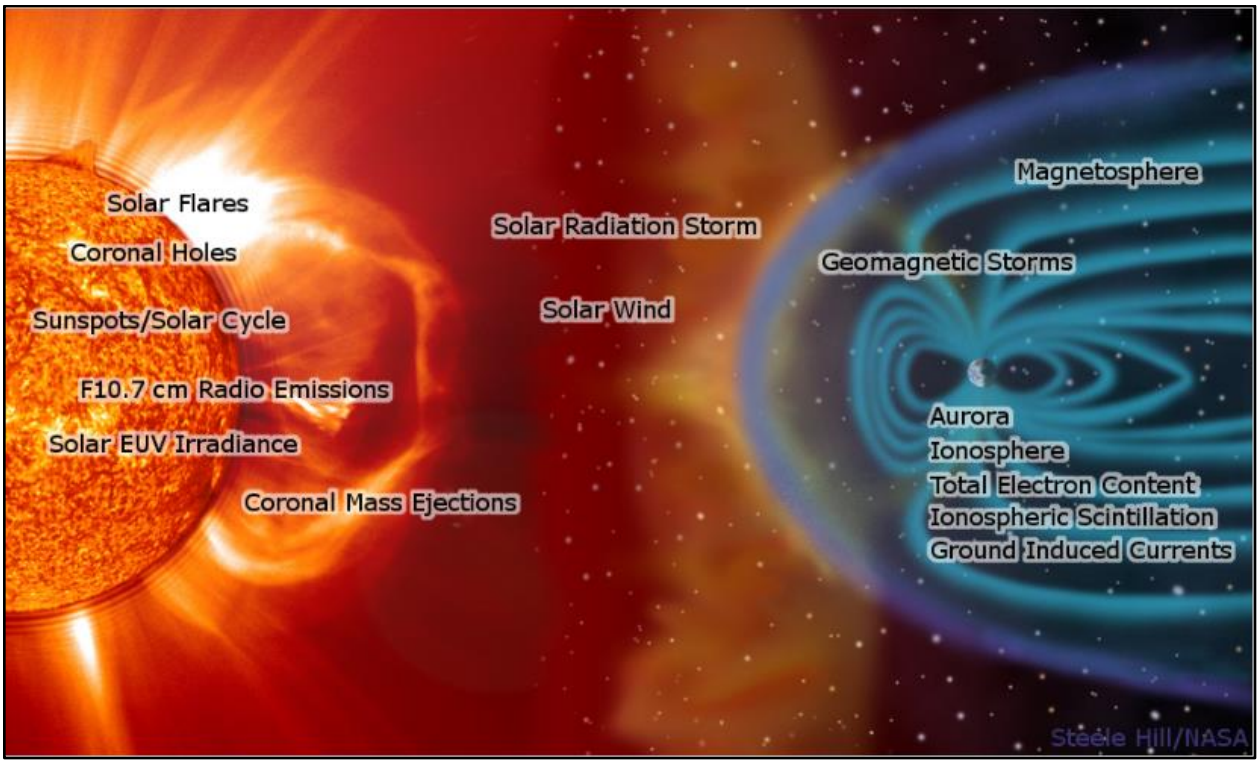
NOAA defines space weather as:

> *Space weather describes the variations in the space environment between the sun and Earth. In particular the term space weather describes phenomena that impact systems and technologies in orbit and on Earth. Space weather can occur anywhere from the surface of the sun to the surface of the Earth. As a space weather storm leaves the sun, it passes through the corona and into the solar wind where it travels toward Earth. Once the space weather storm reaches Earth, it energizes Earth's magnetosphere and accelerates electrons and protons down to Earth's magnetic field lines where they collide with the atmosphere and ionosphere, particularly at higher latitudes (NOAA SWPC, 2020a).*

The fluctuations in the Earth's magnetic field when a space weather storm reaches Earth are referred to as geomagnetic disturbances (GMDs) or geomagnetic storms. These magnetic field fluctuations can then disrupt or damage Earth-based systems such as the electric power grid.

Figure 1 below illustrates types of solar storms, how they travel toward Earth, and the resulting activity on Earth. This study deals with how coronal mass ejections (CMEs) result in GMDs and ground induced currents (GICs) on Earth.

Figure 1. Solar Storms Interacting with Earth



Source: NOAA SWPC, Steele Hill/NASA (NOAA SWPC, 2020a)

2.2 NOAA's Space Weather Prediction Center (SWPC)

NOAA's Space Weather Prediction Center monitors the sun's activity via NOAA's National Environmental Satellite, Data and Information Service (NESDIS) satellites (including satellites shared with NASA and other entities), and phenomena such as coronal mass ejections (CMEs), the solar wind, and the Earth's magnetic field at geostationary orbit. By making these data publicly available, NOAA's SWPC acts as a unified source of space weather information. When GMDs occur, ground based magnetic observatories can measure the severity of an ongoing geomagnetic event by the magnitude of the change in Earth's magnetic field over time, or dB/dt. Various countries and industries have derived indices that best convey dB/dt information as it relates to specific purposes.

SWPC uses a scale called the K-index, which is derived from ground-based magnetometers, instruments that measure Earth's magnetic field, and reports magnetic field fluctuations on a quasi-logarithmic scale from 0 to 9, K=5 and above representing a geomagnetic storm, and K= 9 being unbounded and representing the full spectrum of possible severe magnetic fluctuations (NOAA SWPC, 2020b). Each magnetometer observatory has a unique conversion from magnetic fluctuations in nanoteslas (nT) to the K-index. These conversions are configured such that the K-index describes the magnitude of local disturbances, but the frequency of each size event (K=1 to K=9) is approximately normalized across all observatories globally (NOAA SWPC, 2012). The variation in the K-index between observatories is discussed further in the section Geographic Variability of the K-index below.

2.2.1 SWPC Watches, Warnings, and Alerts

To provide geomagnetic information effectively, SWPC compiles and averages K-indices from around the world to estimate a planetary Kp-index, or a measure of global geomagnetic activity (NOAA SWPC, 2012). NOAA has also created a G-scale, rated 1 through 5, rating the severity of geomagnetic storms that is directly related to the Kp-index, with a G1 storm being equivalent to a Kp=5 or K5 event, and a G5 storm being equivalent to a K9 event (NOAA SWPC, 2020b). Table 1 provides a crosswalk of Kp-index (all GMDs) to the G-scale (geomagnetic storms) (NOAA SWPC, 2020c).

Table 1. Kp-Index - G-Scale Crosswalk

G-Scale	Kp-Index
-	0
-	1
-	2
-	3
-	4
1	5
2	6
3	7
4	8/9-
5	9

Since the severity of a K9 is unbounded, a K9- refers to an event on the lower end of a K9. The magnetic measurements that define these levels vary by geomagnetic observatory station. Therefore, a G4 can refer to an 8 or a relatively mild 9 on the K-index.

Based on these indices, SWPC disseminates space weather watches, warnings, and alerts, to subscribed stakeholders, including electric utilities. For a Kp-index of 4 or above, SWPC will issue a:

- **Watch:** when there is a risk of harmful space weather event; lead-time of hours to days,
- **Warning:** when a significant event is imminent, or likely to occur; lead-time of minutes to a few hours,
- **Alert:** when an event has started (NOAA NWS, 2020).

Receiving these watches, warnings, and alerts informs stakeholders of impending space weather conditions, and for the electric power industry, enables utility operators to take preparatory or mitigating actions to best protect their system from the equipment damages and/or service interruptions and blackouts.

In addition to the use of indices and Kp derived products, NOAA's Space Weather Prediction Center has recognized the importance of providing the electric power industry with regional specification and

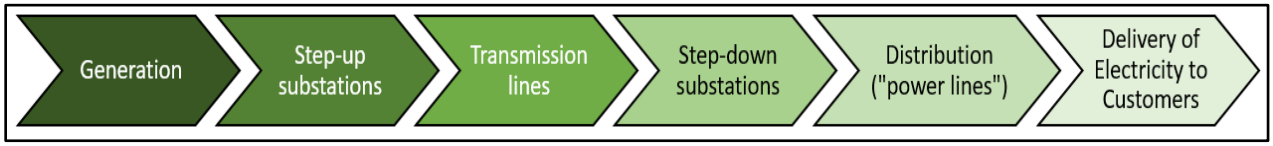
forecasts for GMDs that have the potential to disrupt the electric power grid (e.g., damage equipment) and/or cause service interruptions. In 2016, SWPC introduced a new regional gridded display that provides a short-term warning for magnetic variations that could cause geomagnetically induced currents. Furthermore, based on discussions with the electric power grid industry, SWPC introduced an initial version of experimental 1D Geoelectric Field Maps (graphics), followed by full deployment to SWPC operational systems in late 2019. The Geoelectric Field Maps are based on combining observed, real-time magnetic variations with a ground-conductivity model to provide a regional view of the geoelectric activity. SWPC continues to work on new products that will continue to provide enhanced services to the electric power industry.

2.3 Electric Power Industry

2.3.1 Industry Overview

The electric power industry is a critical infrastructure that ensures the Nation's security and economic vitality. Furthermore, the electric power industry is the foundation on which much of the United States' economic activity, telecommunications, transportation, and emergency services are built. The expansive and interconnected electric grid in North America represents more than $1 trillion of total assets, and includes over 360,000 miles of transmission lines, including more than 180,000 miles of high-voltage lines, and close to 10,000 power plants across the United States (DOE, 2012, EIA, 2019). At a high-level, the figure below illustratively presents the electric power supply chain in the United States (figure adapted from DOE, 2015).

Figure 2. Electricity Supply Chain



The North American power system is composed of four connected grids known as interconnections (DOE, 2015). Three of these four interconnections are located within the continental United States. These are the Eastern Interconnection, the Western Interconnection, and the Electricity Reliability Council of Texas (ERCOT) Interconnection. Though these interconnections primarily work independently of one another, they are technically tied to one another through a handful of connections (DOE, 2015).

In most parts of the country, within these interconnections, either a regional transmission organization (RTO) or an independent system operator (ISO) will monitor, coordinate, and operate the transmission system. There are five ISOs and four RTOs operating within the three interconnections in the continental United States (DOE, 2015).[1] Sub-regional utilities, such as investor-owned utilities, municipal or public utilities, and not-for-profit co-ops operate over smaller geographic scales to deliver electricity directly to customers, often under a governing RTO or ISO (DOE, 2015).

2.3.2 Space Weather Phenomena Interactions with The Grid

As electricity is sent longer distances on highly charged electrical transmission lines, fluctuations in the Earth's electromagnetic field have the potential to disrupt the generation, transmission, and delivery of electric power. One destructive effect of GMDs includes geomagnetically induced currents (GICs), which are

[1] There are two additional ISOs located in Canada that operate in North America's fourth interconnection.

currents created by changes in the Earth's magnetic field that may flow through the ground and into the electrical grid (Forbes and St. Cyr, 2004). These currents often interrupt the transmission of electricity but may also destroy essential components of grid infrastructure by creating harmonics that trip protective relays or by causing transformer saturation and overheating (Gish et al., 1994; NRC, 2008; Kappenman, 2010a). The harmonics created by GMDs may also trip generators offline, cutting out essential power supply (NOAA, 2017). GIC exposure over time may degrade the performance of grid components and equipment lifespan, and in severe cases, may induce transformer mis-operation or failure, which can result in damaged equipment or service interruptions/blackouts.

2.3.3 Vulnerability to Space Weather Phenomena

Usually, the interconnected nature of the electric power grid is a significant strength of the United States' system. The interconnectedness allows for redundancies should one portion of the grid suffer operational obstacles. These connections in the grid can allow regional operators to devise a coordinated response to minimize or avoid service interruptions for customers and damages to generation, transmission, and distribution equipment. However, the grid's interconnectedness can also be a vulnerability. When a severe GMD interacts with the grid, cascading effects can result in damages to grid equipment, service interruptions, and even blackouts over large geographic areas that cause catastrophic damages and losses to both utilities and entities relying on the grid.

For example, in March 1989, a K9 geomagnetic storm caused transformer saturation and a reactive power shortage in Quebec, Canada that led to a blackout in the Hydro-Quebec power system (located in one of North America's four interconnections). The entire Quebec provincial grid collapsed in 90 seconds, leaving 6 million people without power for approximately 9 hours; the blackout even extended into the Northeastern United States. However, the service interruptions were less severe in the United States because the collapse did not occur during a time of high power transfer (such as the winter or summer) between Quebec and the United States the service interruptions were less severe in the United States because the collapse did not occur during a time of high power transfer (such as the winter or summer) between Quebec and the United States (Forbes and St. Cyr, 2004; Molinski et al., 2000). The total cost for this blackout was approximately $6 billion, including $1.2 billion in damaged grid equipment (CENTRA Technology, Inc., 2011).

Another example of cascading effects occurred during a non-GMD blackout in August 2003. During this event, a blackout that started in Ohio had significant cascading effects to the grid, resulting in blackouts across eight states and one Canadian province, affecting nearly 50 million people (NERC, 2004).[2] Power was not restored for between four and 10 days in parts of Canada, and the costs of the event are estimated to be between $4 and $10 billion (NERC, 2004). Thus, it is conceivable that a low frequency, high risk event, like a severe K9 could cause catastrophic and cascading losses to the electric power industry and entities who rely on the electric power grid.

2.4 NOAA 2017 Report: *Social and Economic Impacts of Space Weather in the United States*

In 2017, NOAA invested in a preliminary effort to capture and quantify the potential effects of space weather events on four technological sectors, including the electric power industry. The 2017 effort culminated in a report, *Social and Economic Impacts of Space Weather in the United States,* in which NOAA estimates that electric power service interruptions caused by a moderate space weather event could

[2] The August 14, 2003 blackout was not caused by a GMD or other space weather event, but it highlights the interconnected nature and vulnerability of the electric power grid across the United States and Canada.

conceivably cost consumers between ~$400 million to ~$10 billion, and interruptions caused by a more extreme event could cost consumers between ~$1 billion and ~$20 billion (NOAA, 2017). The 2017 report also provided a preliminary analysis of the potential costs of a space weather event in three other sectors: satellites, global navigation satellite system (GNSS) users, and aviation.

NOAA determined that the magnitude of the potential costs to end users identified in the 2017 report, combined with the electric power industry's reliance on NOAA's space weather observations, products, and services, justified investment in a more robust economic benefits assessment of their space weather products and services to the electric power industry. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) contracted Eastern Research Group, Inc. (ERG) in 2018 to perform this assessment and build from the 2017 analysis.[3]

2.5 Purpose of This Study

ERG has been contracted to identify, describe, and quantify the economic benefits associated with the NOAA's space weather observations, data, and products to United States interests. In this study, we conducted an economic benefit analysis of NOAA's space weather products and services to the electric power industry focusing on avoided service interruptions.

This work builds from NOAA's 2017 research into the social and economic effects of space weather but focuses only on the economic benefits that NOAA's products and services generate associated with the operation of the electric power grid. Thus, the benefit estimates provided in this document are not a reflection of the complete economic value of NOAA's space weather observations, products, and services, as benefits to satellite, aircraft, and spacecraft operations, telecommunication systems, positioning, navigation, and timing services, as well as other technologies and infrastructures critical the Nation's security and economy are not included in this study.

[3] The 2017 study was not performed by ERG.

3 Approach

ERG's approach to assessing the economic benefits of NOAA's space weather products and services to the electric power industry is detailed below. Our approach included two rounds of literature reviews, two rounds of iterative expert engagement (initial interview and expert elicitation), and qualitative and quantitative economic benefit modeling.

3.1 Initial Literature Review

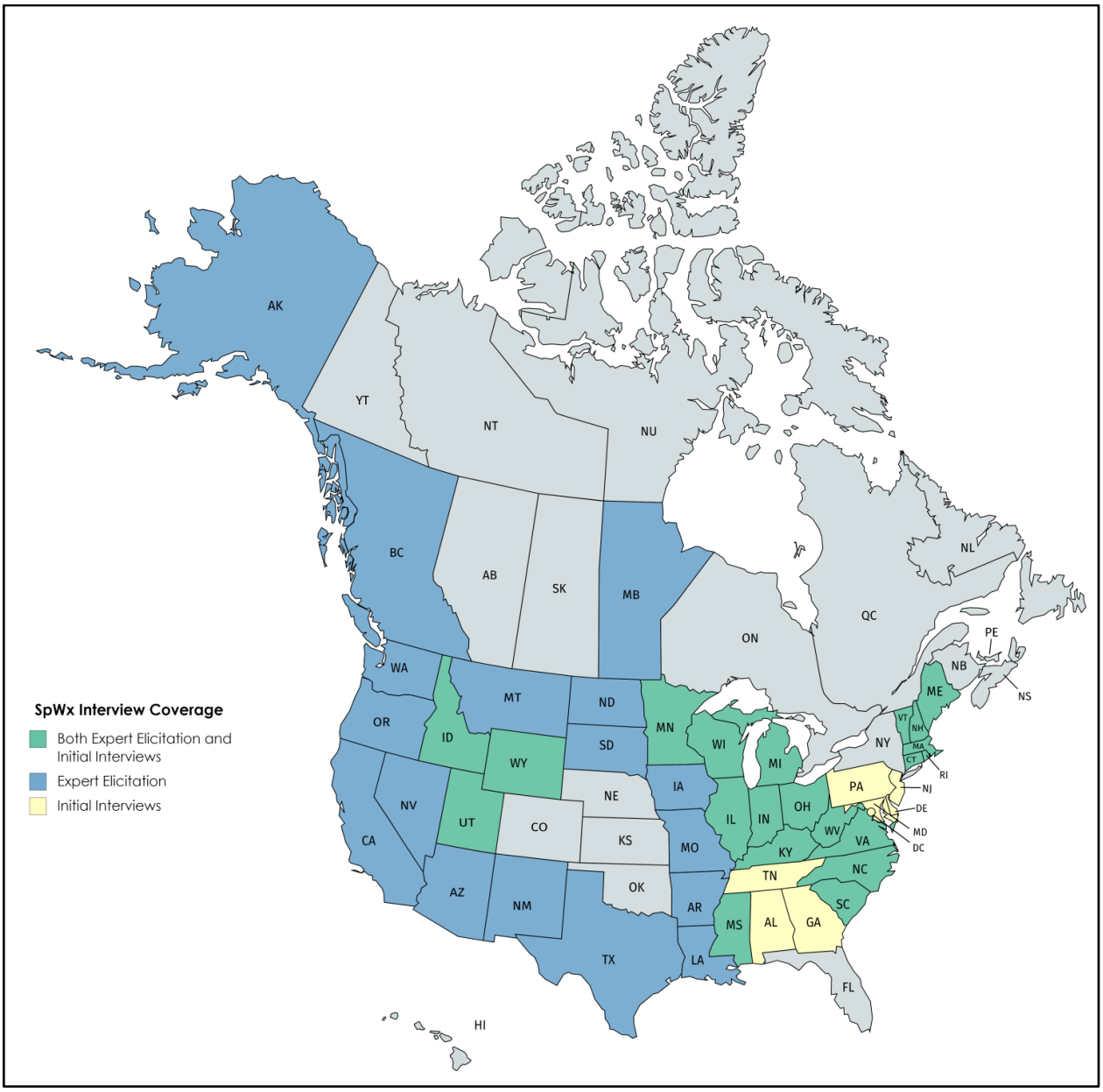
ERG started with a thorough review of NOAA's 2017 report, *Social and Economic Impacts of Space Weather in the United States* (NOAA, 2017). This helped to bolster our baseline understanding of NOAA's work in this area to date and was the starting point for a more in-depth literature review. ERG proceeded to identify more than 50 additional pieces of literature that were sourced from independent research, the citations in NOAA's 2017 report, consultation with ERG's subcontractor, and conversations with industry and regulatory personnel. The literature search informed our initial expert engagement as well as primed our thinking about the potential economic benefits of NOAA's space weather products and services.

3.2 Initial Expert Engagement

The initial expert engagement served a dual purpose. ERG used the initial engagement to further ground-truth information from the NOAA 2017 study, like the impact mechanism (Figure 2, NOAA, 2017) and the physical effects and impact categories (Table 3, NOAA, 2017). This ground-truthing process confirmed ERG's baseline understanding of how space weather can affect the electric grid. The second purpose of the initial expert engagement was to help ERG better understand the pathway by which NOAA's space weather products and services generate economic benefits to the electric power industry.

To achieve this dual purpose, ERG developed a brief document (Appendix A) with five interview questions, using information obtained from our initial literature review, that reflected our understanding of how space weather, specifically, geomagnetic disturbances, might affect the electric power industry. ERG worked with NOAA to recruit six individuals from industry entities and regulatory authorities for the initial engagement process. Interviewees included one RTO, one ISO, one regulatory authority, one co-op, and two mixed (i.e., generation and transmission) electric power entities. For these initial interviews, all six individuals who were contacted agreed to participate. These interviews helped ERG better understand how these individuals and organizations used and valued various NOAA products and services. Figure 3 below shows the geographic representation of the six entities interviewed during this effort. ERG used the information from these initial interviews to draft value chains, or socio-economic valuation mechanisms, which started to map our perception of how NOAA's space weather products and services generate economic value to the electric power industry.

Figure 3. Geographic Representation (by operational jurisdiction) of the Expert Elicitation

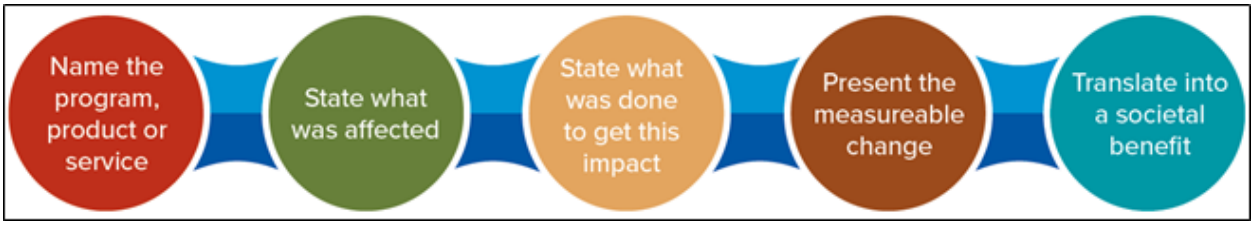


Note: One entity interviewed during the expert elicitation operated in some capacity in Northern Mexico. **Green:** Both Expert Elicitation and Initial Expert interview; **Blue:** Expert Elicitation; and **Yellow:** Initial Interviews.

3.3 Value Chains

ERG used value chains to illustrate how value is generated and translated into a monetizable benefit. The value chain approach aligns with the NOAA's Chief Economist Office recent approach on other valuation efforts. Figure 4 below presents an example value chain to show our general approach to connect NOAA's space weather products and services to societal benefits that can be translated into monetizable benefits.

Figure 4. Example Value Chain



ERG developed two draft branching value chains, using the model above, following our initial expert interviews. ERG and NOAA determined that branching value chains, rather than many single-line value chains, would best illustrate the many benefits generated by NOAA SWPC products and services. ERG determined that two separate branching value chains would best illustrate the two categories of benefits that accrue to the electric power industry: event-based (e.g., when a GMD event occurs) and constant monitoring ("peace-of-mind") economic benefits.

Appendix B presents the value chains ERG developed. The benefits presented in these value chains are not exhaustive as they represent initial benefits identified and ground-truthed by a relatively small sample of the electric power industry during our initial expert interview process. These initial value chains were considered the starting point of ERG's socio-economic analysis. ERG was able to flesh out the value chains in much greater detail as part of our expert elicitation, our second and more detailed expert engagement exercise (the expert elicitation). We used five elements to develop the value chains:

- "NOAA's observations, products, and services" (i.e., SWPC forecasts, watches, warnings, alerts, and continuous monitoring).
- "What could be affected" (i.e., utilities could incur equipment damages or service interruptions from a space weather event).
- "Electric power industry action" (i.e., actions that can be taken in response to NOAA notifications or alerts).
- "Measurable change" (i.e., results of the actions that can be taken in response to NOAA notifications or alerts).
- "Benefit" (i.e., the quantifiable benefits that accrue to industry from actions taken in response to NOAA notifications).

Although the five stages do not always occur sequentially, we illustrate them in a linear, before—during—after an event, manner to show how NOAA space weather products and services can lead directly to economic benefits.

The value chains in Figure B-1 and Figure B-2 in Appendix B provide detail on how NOAA space weather monitoring efforts produce tangible benefits for the electric power industry and those who rely on it.

- The first value chain (Figure B-1) is based on the benefits that accrue to the electric power industry during an event (event-based benefits).
- The second value chain (Figure B-2) is based on the benefits that accrue to the electric power industry from NOAA's constant monitoring as constant monitoring ("peace-of-mind") benefits.

3.3.1 Ground-truthing

ERG iteratively worked with industry and regulatory experts and the NOAA project team, following the initial expert engagement, to refine and ground-truth the initial value chains. These value chains illustratively demonstrate how NOAA's products and services generate economic value to the electric power industry. This ground-truthing exercise helped ERG to better understand and characterize the pathways through which NOAA generates economic value to the electric power industry. ERG was able to use the ground-truthed value chains to develop an interview guide for the expert elicitation by tailoring our questions to better understand specific aspects of how the electric power industry uses and relies on NOAA's products and services.

3.4 Expert Elicitation

To gather more detailed information on the effects space weather has on electrical power grid operations, ERG conducted a second round of expert engagement via an expert elicitation. These interviews were staged to garner a more detailed understanding of how industry uses and relies on NOAA's space weather products and services, where industry sources their data (e.g., from NOAA's SWPC), how space weather products and services affect day-to-day electrical grid operations and typical operational responses to geomagnetic disturbances. The full interview guide ERG used to conduct the expert elicitation can be found in Appendix C.

ERG searched for experts that either controlled operations at their respective utilities or worked closely with the electric power industry and the industry's response to space weather events. ERG identified stakeholders that fulfilled the following pre-screened criteria:

1. Monitors space weather
2. Experienced space weather event
3. Represents unique or diverse geographies within the United States

With these prerequisites, ERG identified and interviewed eleven[4] experts that represented utility operators, RTOs, ISOs, non-profit electric power research entities, and regulatory entities. Figure 3 above shows the geographic representation of the eleven entities we spoke with during the expert elicitation, as well as the six entities we interviewed during the initial interview process.

Several of the interviewees provided ERG with operational guidance documents detailing their utility's planned course of action for GMD events. ERG conducted follow-up interviews on these guidance documents as necessary. Key takeaways from these interviews and documents are presented in the Valuation Data section.

3.5 Valuation Literature Review

After the expert elicitation process, ERG carried out the second phase literature review which had a narrower scope than the initial, information gathering literature review. The second phase literature review focused on literature for key model inputs to inform the valuation and quantification of economic benefits.

[4] One of these 11 experts was ERG's paid subconsultant. Another expert was a Federal regulatory employee. Neither of these experts counted toward ERG's Office of Management and Budget (OMB) requirement to submit and obtain Information Collection Request (ICR) approval, as ERG only interviewed 9 non-Federal members of the public (the limit). Furthermore, the initial interview process did not request the same information as the expert elicitation.

Along with the pieces compiled in the first phase of the literature review, ERG added literature documents provided by interviewees and our subcontractor. ERG then organized the literature into:

1. Research on equipment damage costs from space weather;
2. Research on costs of grid outages, service interruptions, and blackouts;
3. Background information that informs our value chains; and
4. Research on the probability of GMD events occurring given event severity and geographic location.

ERG was then able to draw on valuation methodologies found in the literature as well as information obtained during the expert elicitation to begin the valuation process by connecting specific actions taken by grid personnel to physical effects on the grid and service to end customers to overall benefits of NOAA's space weather products and services for the bulk power system.

3.6 Valuation

ERG consolidated information from the expert elicitation and both phases of literature review to value the benefits identified by the draft value chains. ERG was able to distill these benefits through creating an event-based and a constant monitoring space weather benefits table (Appendix D and Appendix E). Using interruption cost data from service reliability studies from Lawrence Berkeley National Laboratory (Sullivan et al., 2009, 2015), ERG was able to quantify the event-based benefits of NOAA's space weather products and services that are associated with the costs of blackouts and service interruptions of selected durations and for three different affected population sizes. ERG also captured the operational costs that utilities would avoid by having the context of knowing whether a space weather event was occurring by relying on NOAA's watches, warnings, and alerts.

Developing a National benefit estimate would require incorporating some aspect of geographic variation throughout the United States. The effect of a GMD on a portion of the grid is dependent upon magnetic latitude, as well as the geology of the area (Earth impedance). Incorporating the magnetic latitude, geology, population, and grid density/interconnectedness of an area, as well as the frequency of different size GMDs, would allow a valuation at the National level. However, the detailed geomagnetic and geoelectric field mapping and data that would allow for a quantitative, geographically dependent analysis is not available at this time. Therefore, ERG based the quantitative event-based benefits on population and incorporated geographic variation qualitatively.

ERG qualitatively described the benefits of constantly monitoring space weather using contextual information offered by stakeholders in the expert elicitation. ERG organized and extracted benefits through creating a benefits table that highlights economic benefits generated by utilities knowing that a space weather event is not occurring (i.e., they do not receive an event watch, warning, or alert). With the context of knowing that a space weather event is not occurring, utilities can operate more efficiently and confidently. ERG's methods, assumptions, and limitations are explained in the following sections.

4 Valuation of Economic Benefits

ERG compiled data from expert interviews, literature, and information obtained from our draft value chains to determine how to best quantify the economic benefits of NOAA's space weather products and services to the electric power industry. When quantification was infeasible (primarily due to lack of data), ERG presented the economic benefits qualitatively. The data used in the valuation process, the valuation methodology, and the benefit results are explained in the following sections.

4.1 Valuation Data

The following section outlines key data ERG collected to inform and use as inputs to our valuation model.

4.1.1 Expert Elicitation

Nine of the eleven experts interviewed stated either they or their utility subscribes to SWPC's alert system or monitors space weather using NOAA resources. The two experts who did not actively subscribe to nor monitor SWPC's alert system were in the research and government fields, and they did not report regularly obtaining space weather information from other sources. Four of the RTOs interviewed provided ERG with operations plans detailing specific actions that generation and transmission operators may take during a geomagnetic disturbance. Most of these protocols call for implementing operational changes at an event size K8 or above and employing those changes to a greater degree for a K9. However, some RTOs also have internal communication procedures that begin at a K7 alert. ERG compiled common mitigating actions that either experts expressed during their interviews or were taken from GMD operational plans in Table 2. Experts noted that some level of communication occurs (even if just two people exchanging a single email), for all K-events.

Many of the experts consulted detailed a few common actions and operational changes for space weather events. Some of the key actions that are detailed in Table 2 include coordinating transmission line and generator loads with ample lead time, following space weather forecasts closely and monitoring the system's currents, voltages, and power consumption on the day of the event, and finally monitoring transformer overheating and taking vulnerable transmission lines offline or bringing reserve transmission lines online during the a severe GMD.

Table 2. Common Mitigating Actions for GMDs

Long Lead-Time (a)	Day of Event (b)	Real Time (c)
(i) Assess the readiness of black start generators[5] (ii) Coordinate with field personnel about potential on-site monitoring for substations	(i) Monitor GMD data, transformer neutral currents, unusual voltages and reactive power, and abnormal temperatures (ii) Monitor reactive power losses of Extreme High Voltage transformers.	(i) Report occurrences of abnormal conditions to the Regional Coordinator (ii) Monitor transformer heating

[5] Black start generators are small generators (e.g., diesel generators) used to restore an electric power station or a part of an electric grid to operate without relying on the external electric power transmission network to recover from a total or partial shutdown. See, for example, Knight, U.G., 2001. *Power systems in emergencies: From contingency planning to crisis management*. Wiley.

Long Lead-Time (a)	Day of Event (b)	Real Time (c)
(iii) Review transmission outages and determine if any can be returned to service (iv) Possibly delay or postpone planned transmission outages during Warning or Alert period (v) Remove shunt reactors[6] (vi) Modify protective relay settings	(iii) Prepare for unplanned system tripping. (iv) Prepare for telecommunications systems disruptions. (v) Coordinate to run generators near unity power factor. (vi) Start off-line generation and synchronous condensers. (vii) Enter conservative operations with possible reduced transfer limits.	(iii) Remove transformer(s) vulnerable to overheating from service (iv) Remove vulnerable transmission line(s) from service

Note: This table shows common actions recommended in several RTO GMD operations plans for a K8 or above (a) when operators receive a GMD event watch or warning up to several days before the event; (b) when operators receive a GMD event watch or warning up to several hours before the event the day of the event; and (c) when operators receive a GMD warning or alert soon before and during the event.

4.1.2 Space Weather Benefits Tables

Using the information from the expert elicitation, ERG was able to create detailed benefits tables that expanded our initial draft value chains. These benefits tables first identify actions that utilities would take if they did not have access to NOAA's space weather products and services and the resulting effects on the system and utilities. The tables then identify actions that utilities would take if they did receive NOAA's space weather products and services and the resulting measurable changes to grid operations and service. The difference between the expected effects of not having NOAA's space weather products and services and measurable changes when utilities do have this information represent the benefits to utilities from NOAA's space weather products and services. The benefits tables for event-based and constant monitoring benefits can be found in Appendix D and Appendix E.

4.1.2.1 Event-Based

ERG used the typical mitigating actions recommended during a GMD event based on the several guidance documents provided, along with the potential grid damages documented in space weather literature to compile the effects of a K-event to the electric power industry. ERG broke the effects on equipment and service into four scenarios based on the size of the GMD: K3, K7, K8/9-, and K9. ERG originally asked experts about typical operations for a K3 event during the elicitation but received feedback from experts and industry members that the same operational procedures were usually taken for events ranging from K1 through K6, but to slightly varying degrees. Experts also stated that the effect on equipment and service remained very small, near zero, for these less severe geomagnetic events. Therefore, the system effects of an event that ERG has documented for a K3 remain the same, though to slightly varying extents, for a K1 to a K6 event. Thus, the four scenarios K3, K7, K8/9-, and K9 represent the spectrum of geomagnetic disturbance severity as explained to ERG by the experts. ERG will treat K7 as the first inflection point for operational changes and more serious potential for equipment damages and service interruptions.

[6] Shunt reactors, used to maintain constant voltage, can transmit GICs.

For each of the four event sizes, ERG detailed the effects on the system in scenarios where (a) a utility/operator monitors space weather conditions and (b) when a utility/operator does not monitor space weather and has no access to NOAA's space weather products and services. In scenario (a), ERG assumed that the utility/operator receives K-index watches, warnings and alerts and has an operational guidance document with detailed communication procedures for a K7 and specific mitigating procedural actions for K8 and above.

In scenario (b), ERG assumed that the utility/operator has no access to information on space weather conditions, but does have internal, real-time monitoring capabilities, such as in-ground GIC monitors, reactive power consumption, and voltage load and current gauges. ERG framed the effects in the no space weather monitoring scenario by assuming that if an event occurred, operators would be able to see changes in their real-time monitoring system gauges (i.e., increased GICs, voltage drops, decreased reactive power supply), and would go through steps to increase situational monitoring, diagnose the cause of the system fluctuations, and troubleshoot the potentially destructive and/or disruptive effects. ERG similarly allowed for the possibility that operators will take improper actions without the context of knowing that a GMD is occurring (e.g., improper diagnostics of system fluctuations) such as taking transmission lines offline for maintenance or troubleshooting the system fluctuations incorrectly.

Many of the effects and measurable changes detailed in the benefits tables flow as a direct consequence from the actions that operators take during a particular event. For example, during a K8/K9- event with no NOAA space weather products and services, operators may take actions that reflect *significant diagnostic efforts*, and the labor associated with those actions results in a cost *related to diagnostics*. Conversely, during a K8/K9- event with NOAA space weather products and services, following GMD operational guidelines results in a measurable *change related to operational/communication procedures*. ERG also documented overarching effects and measurable changes such as *effects related to service interruptions/blackouts* and *changes related to damaged equipment* that do not result from specific actions.

ERG identified the benefits of monitoring space weather during an event by taking the difference between the measurable changes to the grid operation and electricity service when utilities/operators do receive NOAA's space weather conditions, and those incurred when utilities/operators do not, which are otherwise known as the "baseline" effects. The baseline effects were often mitigated by actions taken with knowledge provided by NOAA's space weather products and services, resulting in positive benefits to utilities. ERG was then able to focus on valuing these specific benefits during the valuation process.

4.1.2.2 Constant Monitoring ("Peace-of-Mind")

ERG similarly documented the economic effects and measurable changes brought about by actions taken with and without space weather monitoring when an event is not occurring to find the benefits of constantly monitoring space weather conditions. Without the context of knowing if and when a GMD event is occurring, even during times where there is no geomagnetic storm, utilities/operators would not be able to plan for operations such as scheduled maintenance as efficiently or with as much certainty.

In the scenario that a utility/operator does not monitor space weather, ERG assumed that the utility/operator would be aware of the potential effects GMDs may have on the grid. In this case, it is likely that the utility/operator would make increased defensive investments to "harden the system" to ensure their system is protected, as opposed to taking mitigating actions when events do occur. In the scenario that a utility does monitor space weather, a utility/operator could check the geomagnetic forecast for the day and be confident that there is very little risk of a severe GMD. Experts explained that the utilities/operators would then have "peace-of-mind" to take certain transmission lines offline for routine

(i.e., not in response to an event) maintenance. This knowledge creates a *measurable change related to optimal operation* as opposed to an *effect related to sub-optimal operation* with no space weather information from NOAA.

ERG identified the benefits of constantly monitoring space weather by taking the delta of the measurable system changes when grid utilities/operators do monitor space weather conditions, and the effects when utilities/operators do not, which are otherwise known as the "baseline" effects. ERG was able to capture these constant monitoring benefits qualitatively.

4.1.3 Service Reliability

During the second phase of the literature search, ERG identified the study *Estimated Value of Service Reliability for Electric Utility Customers in the United States* by Sullivan et. al (2009, 2015) from Lawrence Berkeley National Laboratory (LBNL). This 2009 study and its 2015 update estimated the costs of service interruptions for three different customer groups: residential, small commercial and industrial (C&I), and medium and large commercial and industrial customers. Small C&I customers are defined as all non-residential customers with annual usage less than or equal to 50,000 kWh, while medium and large C&I are all non-residential customers that use more than 50,000 kWh per year.[7] The study also provided the costs to these three groups of customers by the duration of the service interruption in the increments: momentary (less than 5 minutes), 30 minutes, 1 hour, 4 hours, 8 hours, and 16 hours. Since electricity demand and thus cost of a service interruption varies based on the season and the time of day, Sullivan et al. also provided an average cost per customer per duration by weighting summer versus non-summer and morning, afternoon, and evening/night costs (Sullivan et al., 2015).

Sullivan et al. calculated the total interruption costs for commercial and industrial customers using survey responses estimating costs to companies for various season and duration scenarios. The total interruption cost values include lost production/sales, equipment damage, extra overhead, labor, and other costs. The study calculated the total costs to residential customers using willingness-to-pay household survey responses for the aforementioned season and time scenarios.

These data were summarized in Table ES-1 of the 2015 updated Sullivan et al. study. ERG adjusted these cost data to 2019 dollars and used them to estimate the avoided cost of GMD-induced service interruptions, due to receiving NOAA's space weather products and services during a geomagnetic storm.

4.2 Valuation Methodology

The detailed methodology ERG used to determine the benefits of NOAA's space weather products and services is explained below.

4.2.1 Event-Based

ERG developed a methodology to value and quantify the event-based benefits identified in the event-based benefits table that could be applied to the four K-index events (K3, K7, K8/K9-, K9). ERG valued the benefits presented in the event-based benefits table based on whether they could be rolled up into the umbrella benefit of avoiding the cost of a GMD-induced service interruption or blackout (no or minimal interruption costs, less equipment damage) or if they could be wrapped into the avoided additional operational costs companies incur by not monitoring space weather information (increased monitoring and

[7] For the entities included in the Sullivan et al. study, the average annual consumption was 7,140,501 kWh for medium and large C&I customers, 19,214 kWh for small C&I customers, and 13,351 kWh for residential customers (Sullivan et al. 2015).

diagnostic efforts). ERG quantified these two categories in the valuation and treated the remaining benefits identified within the benefits table qualitatively.

ERG used Sullivan et al. (2009, 2015) data on the cost of service interruption per customer per interruption to estimate the benefit of NOAA's products and services during various sized GMD events. ERG built a valuation framework to assess the benefits of monitoring space weather for three different population sizes: small, medium, and large; for the four different event severities: K3, K7, K8/K9-, and K9.

A complete estimate of the value of NOAA's space weather products and services for a specific geographic area would require four main components:

1. The cost of service interruptions when events occur
2. The probability that an event that occurs has an effect on the power grid
3. The probability that an event that occurs affects the specific geographic area
4. The probability of an event occurring

In this section, we develop estimates for the first, second, and fourth components above. We then discuss the complications of developing geographic probabilities. We then are able to develop estimates of economic value based on the first and second and use the fourth component to provide qualitative context. Based on this, the estimates we present reflect *the value of space weather information when events occur within the context of the likelihood of those events occurring.* ERG also used available data from experts to value event-based benefits associated with the operational costs that utilities avoid when they receive NOAA's space weather products and services.

4.2.1.1 Choosing Hypothetical Affected Populations

A key aspect of the cost of service interruptions is the affected population, defined as the total number of people that will experience a service interruption related to a GMD event. We defined three hypothetical population sizes to use in the analysis reflecting different sized areas that may be affected by GMDs. ERG chose the largest population to represent a total of 50 million people affected by service interruptions, which was approximately the number of people affected during a non-GMD-induced blackout in August 2003 that had similar characteristics to a GMD-induced blackout. From there, we selected a medium population of 1 million people (2% of 50 million) and a small population of 20,000 people (2% of 1 million). ERG used three specific geographies within the continental U.S. to approximate the small, medium and large costs per customer in our model. These geographies were selected because their populations approximately aligned with the scaled population estimates. The areas for which we modeled costs are:

- **Small affected population:** 20,000 people represented by Stutsman County, North Dakota.
- **Medium affected population:** 1,000,000 people represented by the State of Montana.
- **Large affected population:** 50,000,000 people represented by the 9 Northeast States plus Washington, D.C. (Connecticut, Maine, Massachusetts, New Hampshire, Vermont, New Jersey, New York, Pennsylvania, Rhode Island, District of Columbia).

The effect a GMD has on an area will in part be determined by the geographic location of the affected population and the density of the affected population. ERG expands on the geographic variation in GMD effects in the section Assessing Geographic Variability below. However, due to data restrictions, the populations in this analysis currently do not represent defined geographic areas. The representative areas

are only used to estimate the number of residential and C&I customers typical for a population of that size using U.S. Census Statistics of U.S. Business (SUSB) data.

4.2.1.2 Estimating the Number of Customers Based on Population

ERG estimated the total number C&I customers consuming less than 50,000 annual kWh, and C&I customers consuming more than 50,000 kWh for the small, medium, and large populations using U.S. Census Statistics of U.S. Business (SUSB) data. ERG estimated the number of residential customers in an area to be the total number of individuals in the population divided by 2.6, or the average number of individuals per household (U.S. Census, 2012).

ERG estimated the number of C&I customers using the following steps:

1. Assume one employee on average uses 10,000 to 14,000 kWh annually.[8]
2. Use business size as a proxy for small versus medium and large C&I customers assuming that businesses with 0-4 employees use less than 50,000 annual kWh, and business with 5+ employees use greater than 50,000 annual kWh
3. For a small population, use county-level U.S. Census Statistics of U.S. Businesses (SUSB) data to sum the total number of businesses with 0-4 and with 5+ employees in the representative geography Stutsman County, North Dakota. This provided representative numbers of C&I customers that use less than and more than 50,000 kWh per year for a population of 20,000.
4. For a medium population, use state-level U.S. Census Statistics of U.S. Businesses (SUSB) data to sum the total number of businesses with 0-4 and with 5+ employees in the representative geography of the state of Montana. This provided representative numbers of C&I customers that use less than and more than 50,000 kWh per year for a population of 1,000,000.
5. For a large population, use state-level U.S. Census Statistics of U.S. Businesses (SUSB) data to sum the total number of businesses with 0-4 and with 5+ employees in the representative geography of the nine Northeastern states plus District of Columbia. This provided representative numbers of C&I customers that use less than and more than 50,000 kWh per year for a population of 50,000,000.

4.2.1.3 Calculating the Cost of Service Interruptions

ERG was able to use the cost of a service interruption per customer per duration, the estimated number of customers in the hypothetical geographic area (based on population), and the selected duration of the service interruption to determine the cost of service interruption for residential, small C&I, and medium and large C&I customers.[9]

ERG's valuation model allows for a user-selected interruption duration based on the six durations presented in the Sullivan et al. study: 5 minutes, 30 minutes, 1 hour, 4 hours, 8 hours, and 16 hours. For the

[8] Best Professional Judgement in conjunction with data from EIA 2012

[9] For the entities included in the Sullivan et al. study, the average annual consumption was 7,140,501 kWh for medium and large C&I customers, 19,214 kWh for small C&I customers, and 13,351 kWh for residential customers (Sullivan et al. 2015).Therefore, the 50,000 kWh threshold is low relative to average C&I consumption and we expect to see more medium and large C&I customers (consume > 50,000 kWh annually) than would be intuitive using more common "small," "medium," and "large" definitions, see

Table 4.

analysis, ERG selected interruption durations appropriate for the severity of an event based on previous research and information provided by industry members during the expert elicitation. With context from previous events such as the Hydro-Quebec blackout, which lasted 9 hours, ERG discerned that a more mild event such as a K3 would, at a maximum, only cause a momentary interruption, whereas a unbounded K9 event could cause more severe system damages that result in a blackout lasting 16 hours. Many experts indicated that a severe K9 event could result in service interruptions/blackouts lasting much longer than 16 hours. However, due to restrictions associated with defensibly extrapolating the Sullivan et al. regression equation, ERG did not estimate the costs and thus, the benefits of NOAA's products and services for service interruptions/blackouts lasting more than 16 hours, which likely would have increased the benefit estimates significantly.

Based on this information, and further context obtained in the expert elicitation and literature, ERG also determined reasonable service interruption durations for an interruption caused by a K7 and a K8/K9-. The interruption durations, derived from Sullivan et al., can be found in Table 3 for each event severity in our analysis.

Table 3. Duration of Interruption

	K3	K7	K8/K9-	K9
Estimated Duration of Interruption (hrs.)	0.083	1	8	16[10]

For each event severity (K3, K7, K8/K9-, K9) and each affected population size (small, medium, large), ERG performed the following calculations to determine the cost of a blackout/service interruption to customers.

ERG calculated cost of service interruption for each customer type by multiplying the weighted average cost per customer per duration from the updated Sullivan et al. (2015) study, by the user selected interruption duration and the number of customers for the population size. The number of customers for each population and customer type (C&I and residential) estimated using the representative geographies in parentheses in Table 4.

Table 4. Number of Customers by Customer Type and Population

	Population of 20,000	Population of 1,000,000	Population of 50,000,000
Number of C&I > 50,000 kWh Customers	420	100,000	750,000
Number of C&I < 50,000 kWh Customers	230	2,500	750,000

[10] Due to the regression used in the Sullivan et. al. paper, we were unable to extrapolate their service interruption cost estimates past the 16-hour interval they identified. However, extreme GMD events have historically caused service interruption/blackouts lasting much longer than 16 hours. Historically, cascading blackouts have left some customers without electricity for up to 10 days (NERC 2004). Though these particular blackouts were not caused by a GMD, their effect on the grid was comparable to grid effects caused by GMDs.

	Population of 20,000	Population of 1,000,000	Population of 50,000,000
Number of Residential Customers	7,692	384,615	19,230,769

The cost of interruption can be estimated as:

$$Cost\ of\ interruption = \ estimated\ interruption\ cost\ per\ customer\ per\ duration \times interruption\ duration \times \#\ customers \quad (1)$$

ERG applied Equation (1) to find the cost of service interruption/blackout to all three customer types in all three sample population sizes with the following elements:

- **Cost of interruption:** the costs of a service interruption based on the duration of the interruption and the customer type affected.
- **Estimated interruption cost per customer per duration:** these data are from Sullivan et al. (2015), which they obtained by surveying customers on losses from and willingness to pay to avoid service interruptions. ERG adjusted these values to 2019 dollars.
- **Interruption duration**: ERG estimated typical durations in hours for the four event severity situations based on research and expert input. Input values are shown in Table 3 (above).
- **Number of customers:** ERG estimated the number of residential and medium and large C&I customers using U.S. Census data for the three selected representative geographies. Input values found in Table 4 (above). The full estimation process is outlined in the section Estimating the Number of Customers Based on Population.

The total blackout/interruption cost is the sum of the interruption costs for residential, small C&I, and medium and large C&I customers.

4.2.1.4 Estimating the Probability an Event Affects the Power Grid

As ERG documented in the benefits tables (Appendices D and E), access to information regarding current space weather conditions, including watches and warnings about incoming space weather storms, enables utilities to avoid certain costs, such as those associated with power interruptions. ERG differentiated the expected cost of a blackout per event with and without NOAA's space weather products and services by applying probabilities that represent the percent chance a K3, K7, K8/K9- or K9 causes damage to or service interruption for the utility. ERG learned from the expert elicitation that if a utility knows a GMD event is coming and has operational guidelines to follow in such an event, utilities/operators are able to take action to mitigate or eliminate potential equipment damages or service interruptions from the event. Thus, receiving NOAA's space weather products and services and having operational guidelines would lower the probability that a GMD will affect the grid.

ERG estimated the probability ranges of a space weather event affecting utilities and/or service with and without NOAA's space weather products and services based on information obtained from the expert elicitation and then ground-truthed these probabilities with two experts who have combined over 60 years of experience with the effects of GMDs on the electric grid. These probabilities are summarized in Table 5 below. The upper bounds of each range represent the probability that an event will cause *any* effect to the

grid (i.e., a system element tripping offline), while the lower bound represents the probability that an event will cause a service interruption or blackout.

Table 5. Probability of Effects with and without NOAA's space weather products and services

Probability that a GMD Event Affects the Grid with and without NOAA's space weather products and services	K3		K7		K8/K9-		K9	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Probability event causes effect with **no** space weather info.[11]	0.01%	5%	1%	10%	25%	75%	40%	99%
Probability event causes effect with space weather info.[12]	0.01%	1%	0.50%	5%	15%	40%	30%	80%

4.2.1.5 Estimating Blackout Costs with and without NOAA's space weather products and services

ERG applied these probabilities to the total blackout/interruption costs to determine the expected blackout/interruption cost per event with and without NOAA's space weather products and services.

$$Expected\ blackout\ cost\ per\ event\ =\ blackout/interruption\ costs\ \times\ probability\ event\ causes\ damage \quad (2)$$

ERG applied Equation (2) to find the expected blackout cost per event with NOAA's space weather products and services and the expected blackout cost per event with no space weather information with the following elements:

- **Expected blackout cost per event:** calculated to *determine expected blackout cost per event without NOAA's space weather products and services and expected blackout cost per event with NOAA's space weather products and services.*
- **Blackout/interruption costs:** the sum of the interruption costs for residential, small C&I, and medium and large C&I customers explained in section Calculating the Cost of Service Interruptions.
- **Probability event causes effect**: ERG estimated the probability that each event would cause any effect to the grid and the probability the event would cause a service interruption for the four event severity situations based on research and expert input. Input values found in Table 5.

ERG then calculated the costs that would be avoided during an event through proper mitigating actions by taking the difference between the *expected blackout cost per event with no space weather (SpWx) products*

[11] ERG used best professional judgment and iteratively ground-truthed these estimates with industry and regulatory experts.

[12] ERG used best professional judgment and iteratively ground-truthed these estimates with industry and regulatory experts.

and services and the *expected cost per event with space weather (SpWx) products and services* estimated above.

$$Avoided\ blackout\ cost\ per\ event\ =\ expected\ blackout\ cost\ no\ SpWx\ -\ expected\ blackout\ cost\ with\ SpWx \quad (3)$$

4.2.1.6 Calculating Avoided Operational Costs

In the event-based space weather benefits table, ERG identified operational action-based benefits such as less monitoring, diagnosing, and troubleshooting efforts taken by grid operators. ERG captured these costs by eliciting, from the expert elicitation, estimates of the labor hours associated with performing operations without NOAA's space weather products and services. The sum of the costs estimated with information from the experts are the costs utilities would avoid by receiving notices and information from SWPC. ERG also factored in the costs of certain quantifiable actions that would be taken with NOAA space weather products and services but did not quantify the costs of many mitigating actions due to lack of data and expert consensus.

For each mitigating action for which data were available, ERG followed Equation (4) to determine the additional operational labor costs utilities would likely incur if a GMD event occurred and they did not receive any space weather information from NOAA, including SWPC alerts.

$$Operational\ cost\ per\ activity\ =\ duration\ of\ activity\ \times\ \#people\ participating\ \times\ loaded\ avg.utility\ wage \quad (4)$$

Equation (4) includes the following elements:

- **Duration of activity:** how long an operator/utility would be performing a certain activity during an event (ex., monitoring for the duration of the event). These data were supplied by an industry expert and are summarized in Table 6.
- **Number people participating:** how many operators at or across utilities will be participating in the activity. These data were supplied by an industry expert and are summarized in Table 6.
- **Loaded average utility wage**: the wage for an average utility worker carrying out this activity. ERG developed an average loaded wage for an electrical utility operator by using the midpoint between the national average wage for a meter reader and an electrical engineer. The national wages used were from the Bureau of Labor Statistics (BLS) 2019 National Occupational Employment Statistics (OES) (Bureau of Labor Statistics, 2019b). Prior to calculating the midpoint, ERG loaded each wage using total benefit values for private industry workers from the BLS 2019 economic news release (Bureau of Labor Statistics, 2019a). These data are summarized in Table 6.

ERG quantified the labor costs of the following activities that would occur during an event if a utility did not receive space weather information from NOAA:

1. Monitoring efforts when a GMD causes abnormal system readings,
2. Diagnostic efforts to identify the cause of abnormal readings,
3. Troubleshooting efforts to correct issue,
4. Coordinating/emailing efforts during an event;

And the following activity that would occur prior to an event if a utility did receive NOAA's space weather products and services:

5. Receiving and processing SWPC watch or warning.

ERG followed up after the expert elicitation with a stakeholder from an ISO to ascertain how many people would likely be performing these activities and for what duration of time. ERG elicited responses for the number of people and labor-hours for activities 1 - 4 above for both a situation where a K3 occurred and a K9 occurred and a utility did not have NOAA's space weather products and services. The inputs used to calculate the operational cost for each activity are in Table 6.

Table 6. Operational Activity Cost Model Inputs

Event	Activity	Duration (hours)		Number of Participating Operators		Loaded Hourly Wage
		Lower	Upper	Lower	Upper	
K3	Monitoring	1	30 (a)	0	1 (b)	$45.54 (f)
	Diagnosing	0	0.085 (d)	0	1	
	Troubleshooting	0	0.085	0	1	
	Communicating	0	0.085	0	1	
	Receiving SWPC notice	-0.085	-0.25 (e)	0	10 (c)	
K7	Monitoring	1	30	5	8	$45.54
	Diagnosing	0.25	1	5	8	
	Troubleshooting	2	72	10	15	
	Communicating	1	2	2	10	
	Receiving SWPC notice	-0.085	-0.25	1	10	
K8/ K9-	Monitoring	1	30	5	8	$45.54
	Diagnosing	0.25	1	5	8	
	Troubleshooting	2	72	10	15	
	Communicating	1	2	2	10	
	Receiving SWPC notice	-0.085	-0.25	1	10	

Event	Activity	Duration (hours)		Number of Participating Operators		Loaded Hourly Wage
		Lower	Upper	Lower	Upper	
K9	Monitoring	1	30	5	8	$45.54
	Diagnosing	0.25	1	5	8	
	Troubleshooting	2	72	10	15	
	Communicating	1	2	2	10	
	Receiving SWPC notice	-0.085	-0.25	1	10	

a. ERG assumed operators would be monitoring the time that system readings are abnormal which is likely the duration of an event. ERG set the upper bound based on the explosion of solar activity in 2003 lasting from October 29 to 31 (NERC, 2014). This is referred to as the "Halloween storm" of 2003.

b. An expert from an ISO provided ERG with the number of people participating in monitoring, diagnosing, troubleshooting and communicating activities after a set of follow up questions tailored to the operational cost analysis.

c. ERG asked experts about the number of people per utility who typically receive SWPC notifications in the expert elicitation. 10 people represents the full operations room. SWPC alerts begin at a K4.

d. The expert provided activity duration information for a K3 and a K9 without NOAA's space weather products and services. ERG assumed that the monitoring, diagnosing, troubleshooting and communicating efforts would take the same amount of time for a K7 and K8/K9- as a K9 because of feedback that K7 is an inflection point for when abnormal readings and potential system effects may become more pronounced.

e. ERG denoted receiving SWPC notifications as a negative benefit because it reflects labor costs associated with receiving and processing NOAA's space weather products and services. This negative benefit is thus quite small and is subtracted from the benefit of the total avoided operational cost.

f. ERG developed an average loaded wage for an electrical utility operator by using the midpoint between the national average wage for a meter reader and an electrical engineer. The national wages used were from the Bureau of Labor Statistics (BLS) 2019 National Occupational Employment Statistics (OES) (Bureau of Labor Statistics, 2019b). Prior to calculating the midpoint, ERG loaded each wage using total benefit values for private industry workers from the BLS' 2019 economic news release (Bureau of Labor Statistics, 2019a).

ERG used Equation (4) with the lower and then the upper bound estimates for labor hours and number of people to calculate a lower bound and upper bound estimated operational cost per activity. ERG then summed the lower bound costs for each activity to arrive at a lower estimate for *total operational cost per event,* and the same for an upper estimate *total operational cost per event*. In the model, ERG took the mean of the lower and upper bound operational costs to find the total *avoided operational costs per event*. These avoided costs are presented in Table 7 below. These costs reflect the inflection point of K7 for many operational guidelines.

Table 7. Avoided Operational Costs

	K3	K7	K8/K9-	K9
Avoided Operational Costs per Event	$630	$31,275	$31,275	$31,275

4.2.1.7 Estimating the Total Benefit of NOAA's Space Weather Products and Services per Event

The benefit of NOAA's space weather products and services per event is the sum of:

- The *avoided cost of a blackout* (computed in section Estimating Blackout Cost with and without NOAA's space weather products and services), assuming that with space weather products and services, a utility is more likely to mitigate GMD damages and avoid a service interruption for customers, and
- The *avoided operational costs* (computed in section Calculating Avoided Operational Costs), assuming utility operators would not need to spend time monitoring, diagnosing, or troubleshooting the system problems during a GMD event.

$$Benefit\ of\ SpWx\ per\ event = \ avoided\ cost\ of\ blackout\ +\ avoided\ operational\ costs \quad (5)$$

ERG estimated the benefit of having NOAA's space weather products and services for each event scenario (K3, K7, K8/K9-, K9), each population size (small, medium, and large), as well as for the upper and lower bounds of the effect probabilities (probability of *any* effects and probability of service interruption/blackout).

4.2.1.8 Estimating Relative Frequency of Events

Very large coronal mass ejections (CMEs) are rare, therefore extreme GMDs are considered low frequency, high risk events. To garner an understanding of the relative frequency of each event, ERG found the average number of "storm days" in a solar cycle, or average number of days that have at least one Kp reading of each of the magnitudes presented in Table 8 below, using NOAA's space weather scales for geomagnetic storms. A solar cycle lasts approximately 11 years but varies slightly (10 to 13 years) based on the Sun's conditions. Table 8 below summarizes the data ERG captured from SWPC's scales (NOAA SWPC, 2020c).

Table 8. Number of Days with Events per Solar Cycle

	K5 (G1)	K6 (G2)	K7 (G3)	K8/K9- (G4)	K9 (G5)
Number of storm days per solar cycle (a)	900	360	130	60	4

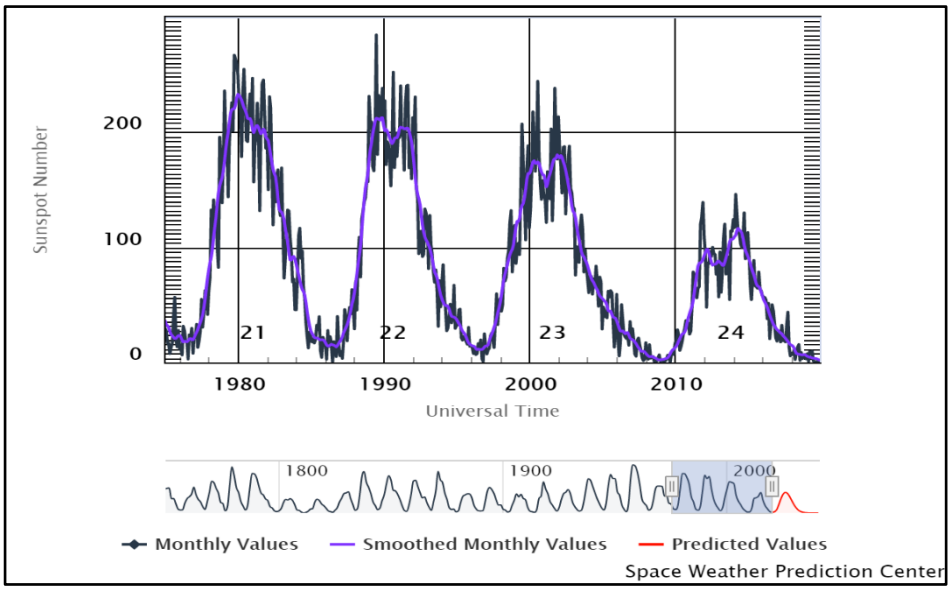
Estimates are the number of events globally per solar cycle.

These data show that the most severe events occur much less frequently than less severe events. To estimate the number of events that would occur in a given year during a solar cycle, or similarly the number of days with an event, we would have to account for which stage of the solar cycle the Sun is in for each recorded event during a defined period of time. Over the course of the average 11-year solar cycle, the Sun goes through a period of high activity and of low activity. The solar activity can be represented by

the number of sunspots, as shown for the past few solar cycles below, with high activity correlating to more frequent and severe solar storms and geomagnetic disturbances.

Figure 5 below shows the sunspot number recorded each year since 1975 and reveals the rise and fall associated with each solar cycle.

Figure 5. Solar Activity for Solar Cycles 21 through 24



Source: NOAA SWPC (NOAA SWPC, 2020d)

In addition to these data, NOAA publishes archives of daily planetary K-index readings that are taken every 3 hours year-round. ERG compiled data from solar cycle 23, years 1996-2008, or approximately 4,300 days, and counted the number of days that had at least one 3 hour reading that registered a Kp of 1, 2, 3, 4, 5, 6, 7, 8, and 9. These data are presented in Table 9 below.

Table 9. Number of Days that Registered Each Kp Magnitude

Kp-Index	Number of days in Solar Cycle 23 with an event (a)
1	3,067
2	3,849
3	3,357
4	1,786
5	739
6	250
7	90

Kp-Index	Number of days in Solar Cycle 23 with an event (a)
8/9-	31
9	14

a. Extracted from NOAA's daily archives of geomagnetic data for years 1996 to 2008, approximately one solar cycle. Note that while the average solar cycle is approximately 11 years, it is possible for solar cycles to be less than or greater than 11 years.

ERG considered the relative frequency of each magnitude of event qualitatively for our final event-based benefits estimation.

4.2.1.9 Assessing Geographic Variability

The severity of damages or service interruptions/blackouts that a GMD causes to a particular area of the grid is both dependent on its magnetic latitude and the geology below the grid infrastructure (Earth impedance). At higher geomagnetic latitudes, there are strong electrical currents in the atmosphere, which are driven by energy in the solar wind and magnetosphere. GMDs occur where these currents exist, meaning that geomagnetic activity is often strongest at higher geomagnetic latitudes (> 65°), but severe events may cause geomagnetic activity at lower geomagnetic latitudes (< 50°) as well. Therefore, utilities located at higher geomagnetic latitudes, where the strong atmospheric currents flow, are more likely to experience magnetic field fluctuations strong enough to damage infrastructure and/or cause service interruptions/blackouts.

On the other hand, the type of rock that comprises the top of the Earth's crust determines what the Earth impedance in that area will be. Earth impedance also has an effect on the size of the magnetic fluctuations and how ground-based magnetometers will read those changes in magnetic field. As much of the electrical power system infrastructure is either in the ground or connected to the Earth, the solid Earth geophysics of an area, as well as geomagnetic latitude, will determine the severity of the GICs that run through the system and ultimately damage critical grid components in the event of a GMD (Lucas et al., 2020).

Geographic Variability in the K-index

As previously mentioned, the planetary K-index is a measure of global geomagnetic activity, combining data from ground-based magnetometers across the world. Each magnetometer observatory has a site-specific quasi-logarithmic scale that converts raw magnetic fluctuation readings in nanoteslas (nT) to the K-index. Since the overall frequency of K1 through K9 events should be normalized across all stations, each site-specific conversion takes into account the geographic variability of magnetic fluctuations during a GMD. Table 10 presents some of the observatories that are used by the German Research Centre for Geosciences (GFZ) to create the official Kp-index. The table displays the geomagnetic latitude of the station and the magnetometer reading in nanoteslas that defines a K9 at each station. These variations in nanotesla fluctuations should still be treated as local indicators and cannot be extrapolated to larger regions or geographies.

Table 10. Kp-Observatories

Name	Country	Geomagnetic Latitude (2015) (a)	K9 in nT
Lerwick	Scotland	61.82°N	1,000 nT
Meanook	Canada	61.17°N	1,500 nT
Sitka	United States	60.20°N	1,000 nT
Ottawa	Canada	54.88°N	750 nT
Wingst	Germany	53.85°N	500 nT
Hartland	England	53.64°N	500 nT
Brorfelde	Denmark	51.79°N	600 nT
Fredericksburg	United States	47.67°N	500 nT

a. As the geomagnetic field, and thus geomagnetic latitudes, change over time, we must specify which year the geomagnetic latitude of a location was modeled. These data are from the International Geomagnetic Reference Field taken in 2015 (IGRF-12).

Table 10 orders the stations in decreasing geomagnetic latitude and generally reflects that magnetometers at higher latitudes typically experience larger magnetic fluctuations. However, while the Lerwick observatory is at a higher latitude than the Meanook observatory, it only registers a 1,000 nT fluctuation as a K9, while the Canadian observatory defines a K9 at 1,500 nT. This shows that both geomagnetic latitude and geology must be considered to determine whether a GMD will cause severe magnetic fluctuations and ultimately damage the electrical grid and/or cause service interruption.

Qualitative Geographic Variability Analysis

A full valuation that incorporates how GMDs affect different geographies would thus require a comprehensive model of both the geomagnetic field and geologic composition of the United States. These models would rely on widespread magnetotelluric measurements, or measurements of Earth's conductivity based on geoelectromagnetic field variations at the Earth's surface. Lucas et al. gathered this magnetotelluric survey data, along with GMD data from geomagnetic observatories and data on thousands of transmission lines, to model transmission line voltages during a 100-year geomagnetic storm (2020). Available data only allowed for mapping on two thirds of the continental United States, but the mapping revealed that four areas in particular are most vulnerable to geoelectric hazards. ERG will use this geographical variation as context when discussing the quantified benefit estimates. These particularly vulnerable areas include [Lucas et al., 2020]:

- The East Coast,
- The Pacific Northwest,
- The Upper Midwest, and
- The Denver metropolitan area.

4.2.2 Constant Monitoring ("Peace-of-Mind")

NOAA's space weather products and services generate benefits to the electric power industry, even in the absence of a space weather event. That is to say, there are economic benefits to knowing that a storm or space weather event is *not* occurring. We refer to these benefits generated by NOAA's constant monitoring efforts accrue to utilities as constant monitoring ("peace-of-mind") benefits. For example, electric utilities benefit from constant monitoring information as it allows them to plan maintenance schedules or plan when to bring transmission lines on- or off-line with more confidence.

Without NOAA's space weather products and services, utilities would likely have to invest more in defensive investments to harden their systems in the event of a severe GMD, or even potentially pay for private space weather information from independent vendors.

The seemingly most important, yet not easily quantifiable, benefit of constantly monitoring space weather is the alleviated uncertainty for utilities whose mission is to provide reliable electricity service to customers. This reduced uncertainty is a benefit in and of itself, but also generates benefits associated with optimal operation and efficient power distribution that ultimately will result in cost savings for utilities. The ERG and NOAA project team determined that while constant monitoring benefits were part of the story of the economic benefits of NOAA's space weather products and services to the electric power industry, it would be best to qualitatively present these benefits. ERG could not quantify these benefits due to lack of data.

4.3 Valuation Results

4.3.1 Event-Based

The economic benefits associated with NOAA's space weather products and services are generated when utilities are able to use the information to prepare for, and thus, reduce or eliminate operational costs and/or service interruption/blackout costs associated with a space weather event. ERG used Equations (1) through (5) in conjunction with the input data outlined in the Valuation Data and Valuation Methodology sections to estimate the economic benefits accrued to the electric power industry from NOAA's space weather products and services. The benefit estimates presented below are estimated for each event size and associated service interruption/black duration. We present these summarized benefits by the size of the population affected and for the specific interruption durations selected in Table 11 below. These low and high benefit estimates depend on the: geomagnetic storm severity, duration of the resulting electric power service interruption, and population affected.

Table 11. Summarized Benefits of NOAA's Space Weather Products and Services

	Benefit of NOAA's Space Weather Products and Services per Event ($1,000's)								
	20,000 Geographic Area Population			1,000,000 Geographic Area Population			50,000,00 Geographic Area Population		
Event size	Low	High	Duration of interruption (hrs.)	Low	High	Duration of interruption (hrs.)	Low	High	Duration of interruption (hrs.)
K1-K6	$1	$245	0.083	$1	$56,963	0.083	$1	$110,765	0.083
K7	$73	$452	1	$9,821	$97,930	1	$76,542	$765,138	1
K8/K9-	$4,040	$14,061	8	$924,809	$3,236,753	8	$7,343,295	$25,701,453	8
K9	$7,915	$15,010	16	$1,819,970	$3,457,915	16	$14,435,062	$27,426,590	16

We expand on the contents of each row of event-based benefits below:

- **K1-K6:** For a given K1-K6 event, we assume the event would cause a 5-minute service interruption if a utility did not receive NOAA's space weather products and services. The benefits for utilities are generated by using NOAA's space weather products and services to avoid or mitigate costs from the 5-minute service interruption and associated operational costs. In this example, the benefit estimates range from $1,000 to $245,000 in hypothetical geographic areas with 20,000 people, $1,000 to $57 million in hypothetical geographic areas with one million people, and $1,000 to $111 million in hypothetical geographic areas with 50 million people. As can be seen, the lower bound is always $1,000 which reflects avoided operational costs associated with receiving NOAA's space weather products and services.
- **K7:** For a given K7 event, we assume the event would cause a 1-hour service interruption if a utility did not receive NOAA's space weather products and services. The benefits for utilities are generated by using NOAA's space weather products and services to avoid or mitigate costs from the 1-hour service interruption and associated operational costs. In this example, the benefit estimates range from $73,000 to $452,000 in hypothetical geographic areas with 20,000 people, $10 million to $98 million in hypothetical geographic areas with one million people, and $76 million to $765 million in hypothetical geographic areas with 50 million people.
- **K8/K9-:** For a given K8/K9- event, we assume the event would cause an 8-hour service interruption if a utility did not receive NOAA's space weather products and services. The benefits for utilities are generated by using NOAA's space weather products and services to avoid or mitigate costs from the 8-hour service interruption and associated operational costs. In this example, the benefit estimates range from $4 million to $14 million in hypothetical geographic areas with 20,000 people, $925 million to $3.2 billion in hypothetical geographic areas with 1 million people, and $7.3 billion to $26 billion in hypothetical geographic areas with 50 million people.
- **K9:** For a given K9 event, we assume the event would cause a 16-hour service interruption if a utility did not receive NOAA's space weather products and services. The benefits for utilities are generated by using NOAA's space weather products and services to avoid or mitigate costs from the 16-hour service interruption and associated operational costs. In this example, the benefit estimates range from $7.9 million to $15 million in hypothetical geographic areas with 20,000 people, $1.8 billion to $3.5 billion in hypothetical geographic areas with 1 million people, and $14 billion to $27 billion in areas with 50 million people.

Severe geomagnetic storms are low frequency, high risk events and the most severe events elicit the greatest benefit in avoiding damages and service interruption/blackout per event. Out of the approximately 4,000 to 4,300 days in a solar cycle, there are on average only 60 days where a K8 is measured and 4 days where a K9 is measured. When ERG looked at the raw planetary K-index data for the 23rd solar cycle using years 1996 to 2008, we found that the least frequent index reading was a K9, measured on 14 days, whereas the most frequent index reading was a K2, measured on 3,849 days in the cycle. Therefore, although the benefits to the power industry are larger for severe geomagnetic events, the benefits from K1 through K6 events will accrue to the electric power sector much more frequently and are an important part of the story of economic value that NOAA's space weather products and services accrue to the electric power industry.

The three population areas represent hypothetical geographies, but research has highlighted that the East Coast, Pacific Northwest, Upper Midwest, and the Denver metropolitan areas are particularly vulnerable to

GMDs due to the geology and the grid engineering at these particular regions of the grid in conjunction with the magnetic field.

We see in the wide range of values that the benefits depend heavily on the duration of the GMD-induced interruption and population affected. The low and high estimates also reflect the extent of grid damages, with the high estimate using the expected probability of an event causing *any* damage to the electric grid, and the low estimate using the expected probability of an event causing damages so severe that it results in service interruptions/blackouts.

Avoided operational costs were often small compared to the costs of a service interruption for events K7 through K9. On the other hand, the majority of the avoided costs emerged from the costs of a service interruption/blackout for 'medium and large' commercial and industrial customers, or those that use more than 50,000 annual kWh of electricity. This shows that service reliability is essential to the Nation's businesses and economic vitality.

4.3.1.1 Geographic Variability Context

The benefit estimates presented in Table 11 (above) are likely larger for geographic areas, with similar population distributions, that are particularly vulnerable to geoelectric hazards. The magnitude of effects of a GMD on the electric grid is both dependent on its magnetic latitude and the geology below the grid infrastructure, or Earth impedance. Lack of data for the relationship between magnetic latitude and Earth impedance at a National scale did not allow ERG to quantitatively incorporate geographic distribution in our model. However, Lucas et al. (2020) conducted work to combine magnetotelluric survey data, along with GMD data from geomagnetic observatories and data on thousands of transmission lines, to model transmission line voltages during a 100-year geomagnetic storm (Lucas et al., 2020). This study, conducted for two thirds of the continental United States, identifies the East Coast, the Pacific Northwest, the Upper Midwest, and the Denver metropolitan areas as particularly vulnerable to geoelectric hazards.

4.3.2 Constant Monitoring ("Peace-of-Mind")

We present the constant monitoring ("peace-of-mind"), benefits qualitatively in Table 12 below and in detail in Appendix E.

Table 12. Summarized Constant Monitoring Benefits of NOAA's Space Weather Products and Services

Constant Monitoring Benefits of NOAA's Space Weather Products and Services
Decreased monitoring efforts
Decreased defensive investments
Less chance of lost revenue from sub-optimal operation
Decreased costs from improper diagnostic efforts
Less uncertainty
Reduced cost associated with space weather monitoring information

Since these economic benefits are realized during day-to-day operations when no space weather events are occurring, they are an important part of the story of how NOAA's space weather products and services generate economic benefits to the electric power industry. However, ERG did not quantify these benefits due to lack of existing data and resources during this effort. ERG predicts the constant monitoring benefits

will likely be smaller than the event-based valuation outputs but will likely accrue to the electric power industry on a more consistent basis.

5 Recommendations for Future Research

5.1 Geographic Variability: Magnetic Latitudes and Earth Impedance

ERG captured the geographic variation in the grid's vulnerability to geomagnetic disturbances qualitatively, identifying particularly vulnerable areas of the grid using a Lucas et al. (2020) study that modeled transmission line voltages during a 100-year geomagnetic storm. This study only modeled two-thirds of the continental United States since data at the cross-section of geomagnetic disturbances, magnetic latitude, and geology, are often unavailable or under development.

During the expert elicitation, multiple stakeholders mentioned the National Energy Reliability Council (NERC) mandated planning standards TPL-007 or *Transmission System Planned Performance for Geomagnetic Disturbance Events*. This plan requires utilities to implement and carry out planning studies that assess how a benchmark GMD event affects their system, including measuring GICs and transformer heating (NERC, 2019). Part of this standard includes calculating geoelectric and geomagnetic fields during a benchmark GMD event and designing engineering solutions to mitigate the specific damages caused to the system. These standards are being implemented in a staggered manner through 2022 but will then provide key information how GMDs affect individual utilities across the country.

The results of NERC's mandated standards might provide intelligible insight into the cross-section of geoelectromagnetic field, geological, and engineering research. These data will account for the geographic variability, since they will be collected at the individual utility level, as well as the interconnectedness and system engineering of the grid.

Future research efforts could draw from these data as well as the expertise of space weather scientists, geologists, engineers, and economists to develop a national benefit estimate of the space weather observations, products, and services to the electric power industry that quantitatively accounts for the nuances within geographic variability and grid engineering.

5.2 Economic Benefits of NOAA's Space Weather Products and Services for Extended Service Interruptions

ERG relied on a study (published in 2009 and updated in 2015) by Sullivan et al. from the Ernest Orlando Lawrence Berkeley National Laboratory (LBNL) to estimate the cost of service interruptions based on customer type and size. Sullivan et al. collected willingness to pay (WTP) primary data from residential customers as well as estimated losses to commercial and industrial businesses to determine the value of service reliability for electric utilities customers across the United States.

Sullivan et al. designed a two-stage regression model estimated using generalized linear model (GLM) methods. In doing so, they estimate a "first stage" that models the presence of non-zero costs for interruption and then a "second stage" for the non-zero values; the two stages are linked with a probability model. However, neither the 2009 original paper nor the 2015 update provided ERG with enough information to defensibly recreate the regression to extrapolate service interruption duration and costs, by customer size and type, past a 16-hour service interruption.

Future research might consider working with LBNL to extrapolate their regression or conducting a primary study to develop a new regression to estimate costs, and thus, benefits of NOAA's space weather products

and services, for service interruptions lasting longer than 16-hours. These costs and benefits would likely increase exponentially from the estimates in this paper and are feasible given service interruptions across large areas have lasted between four to 10 days in the past (NERC, 2004).

5.3 Assessment of the Economic Benefits of NOAA's Space Weather Products and Services to Other Vulnerable Industries/Sectors

During the initial expert interviews and expert elicitation process, multiple electric industry experts emphasized that NOAA's space weather observations, products, and services generate significant economic value to other sectors and industries, in addition to the electric power industry. Electric power experts specifically highlighted the following industries and sectors for whom NOAA's space weather products and services generate economic benefits:

- Telecommunications (especially considering the rise of 5G technology);
- Satellites;
- Aviation; and
- The Department of Defense and Homeland Security.

Future research could conceivably apply the valuation framework developed under this effort to estimate the economic benefits of NOAA's space weather products and services to one of the above, or other, industries or sectors.

5.4 Quantification of the Constant Monitoring (Peace-of-Mind) Economic Benefits of NOAA's Space Weather Products and Services to the Electric Power Sector

ERG identified two categories of economic benefits that NOAA's space weather products and services provide to the electric power sector. The event-based benefits represent the economic benefits of NOAA's products and services, to the electric power sector, when a GMD occurs. Conversely, ERG also identified constant monitoring or "peace-of-mind" economic benefits of NOAA's space weather products and services that accrue to the electric power sector when there is no GMD or space weather event occurring. In other words, the constant monitoring benefits represent the economic benefits of definitively knowing that a space weather event is not occurring, which can enhance operational efficiency and planning capabilities. ERG only quantified event-based economic benefits, as we were unable to quantify constant monitoring benefits due to the lack of available data. Future research might consider further ground-truthing the constant monitoring benefits identified in Appendix E. and collecting further data to quantify those benefits.

5.5 Assessment of the Economic Benefits of Improvements to NOAA's Space Weather Products and Services

In late 2019, NOAA SWPC introduced an experimental product, the 1D Geoelectric Field Maps (pictured below) that combines observed, real time magnetic variations with a ground-conductivity model to provide regional gridded geoelectric field data. This electric field drives GICs, so these data may be used by the electric power sector to analyze regional GMD vulnerability. In other words, this experimental product takes into account spatial variability and ground conductivity during GMDs. The absence of this quantified relationship prior to this experimental release is a limitation of this effort. NOAA SWPC developed this experimental product in response to requests from the electric power sector. Future research might assess the economic benefits of these enhanced experimental products and regional specificity compared to the global Kp-index, the unit of measure utilities currently receive information in.

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Appendix A – Initial Expert Engagement 2-Pager

Background

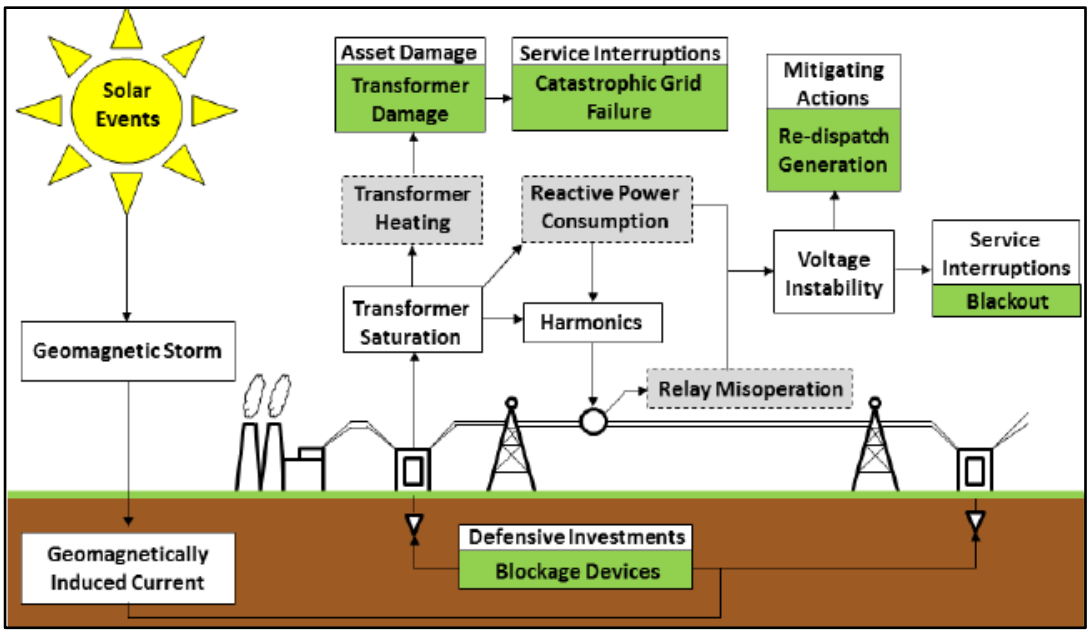
NOAA previously developed estimates of the economic and social impacts of space weather events (coronal mass ejections [CMEs]) on various sectors, including the electric power industry.[13] For each sector, NOAA generated economic impact estimates by analyzing the **physical effects** of theoretical space weather events (one moderate, one severe[14]) on various socioeconomic **impact categories**. For example, NOAA estimated that a space weather event may cost U.S. consumers of electricity ~$400 million (moderate) to ~$20 billion (severe) depending on the severity of the event and where within the U.S. it occurs. The physical effects and impact categories used in that study are summarized in the table below.

Physical effects	Impact categories
Reactive power consumption Transformer heating Improper operation of protective relaying equipment Real power imbalances Generator tripping Loss of precision timing	Defensive investments (e.g., infrastructure hardening) Mitigating actions (e.g., reduced transmission flows) Asset damage (e.g., damaged equipment) Service interruptions (e.g., degradation in power quality) Health effects (e.g., cancer, lower cognitive ability)

NOAA developed the impact mechanism diagram below for the electric power sector to outline the primary causal pathways from a solar event to physical effects (grey boxes) that can in turn cause a variety of social and economic impacts (green boxes).

[13] https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf

[14] There is no standard definition nor scientific agreement on what constitutes an "extreme" or "moderate" event. NOAA has previously defined a "moderate" event as a hypothetical event that causes protective relays to mis-operate and in turn leads to a power outage that is commensurate in duration and scale with the Quebec 1989 storm. NOAA has previously defined an "extreme" event as a hypothetical event that causes a ~9-hour blackout to an entire U.S. energy market during peak demand.



Objectives of this work

NOAA wants to develop a better qualitative and quantitative understanding of how the electric grid sector uses space weather monitoring and warnings systems, as well as their associated benefits. Better demonstrating these benefits could help ensure the future investment in and availability of NOAA space weather monitoring. NOAA also wants to identify related cost-effective mitigating actions and investments that will offset the impacts of space weather events.

How you can help

We'll hold a brief interview with you and ask to discuss a few starting questions:

1. Does the impact mechanism diagram (page 1) align with your understanding? Are we missing anything?
2. How does the electric power industry use space weather monitoring data?
   a. What decisions are affected?
   b. Do you have an understanding of the economic impacts of space weather on each segment of the electric power industry, including which infrastructure systems within those segments are most affected? (Power industry infrastructure systems, transformers, delivery mechanisms, etc.)
3. What are the industries, sectors, or entities connected to the grid that would be most impacted from grid failure caused by space weather events?
4. What criteria should we use for defining "moderate" and "extreme" space weather events?

Appendix B – Value Chains

Figure B-1. Value Chain of Event-Based Benefits

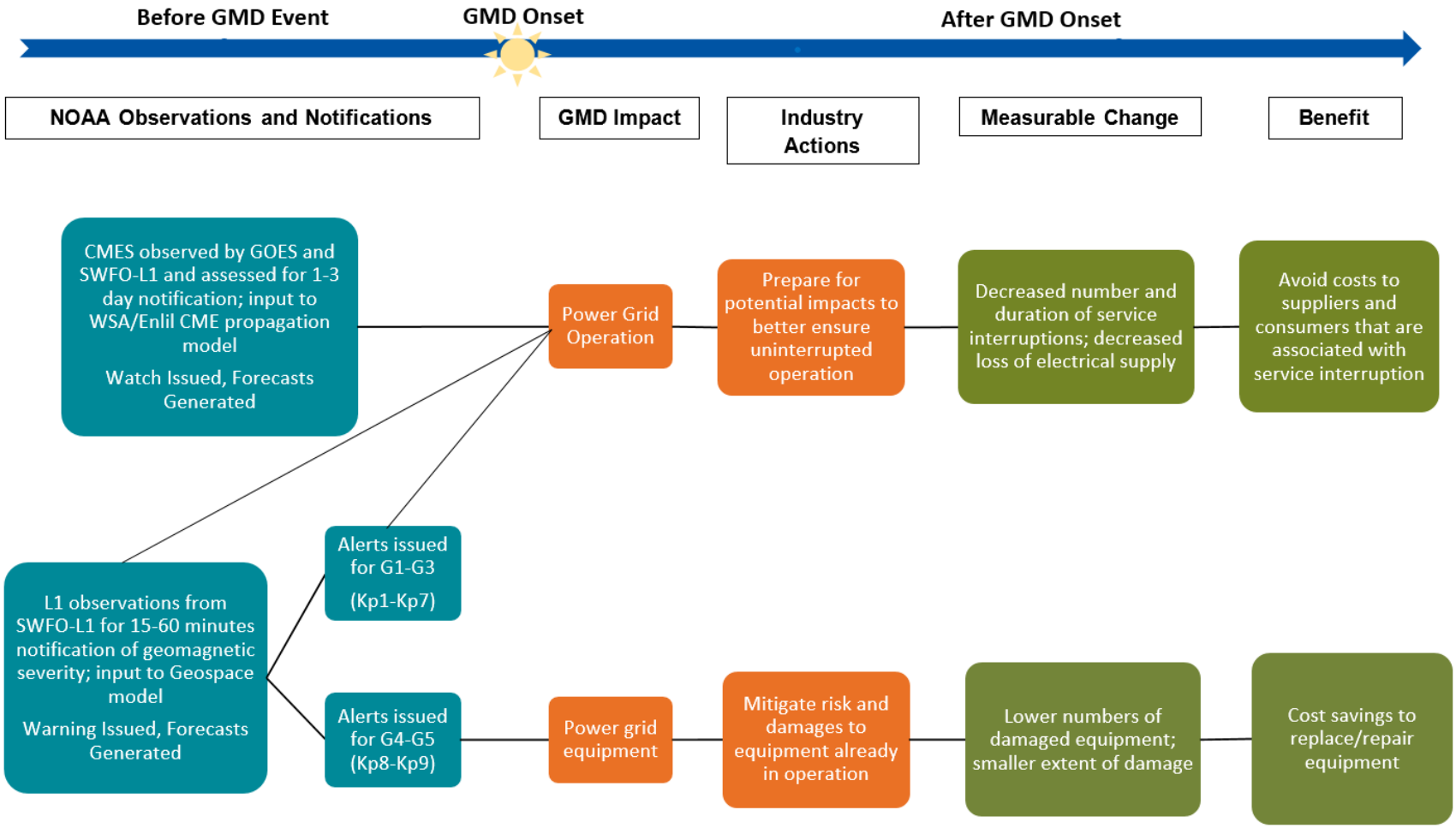
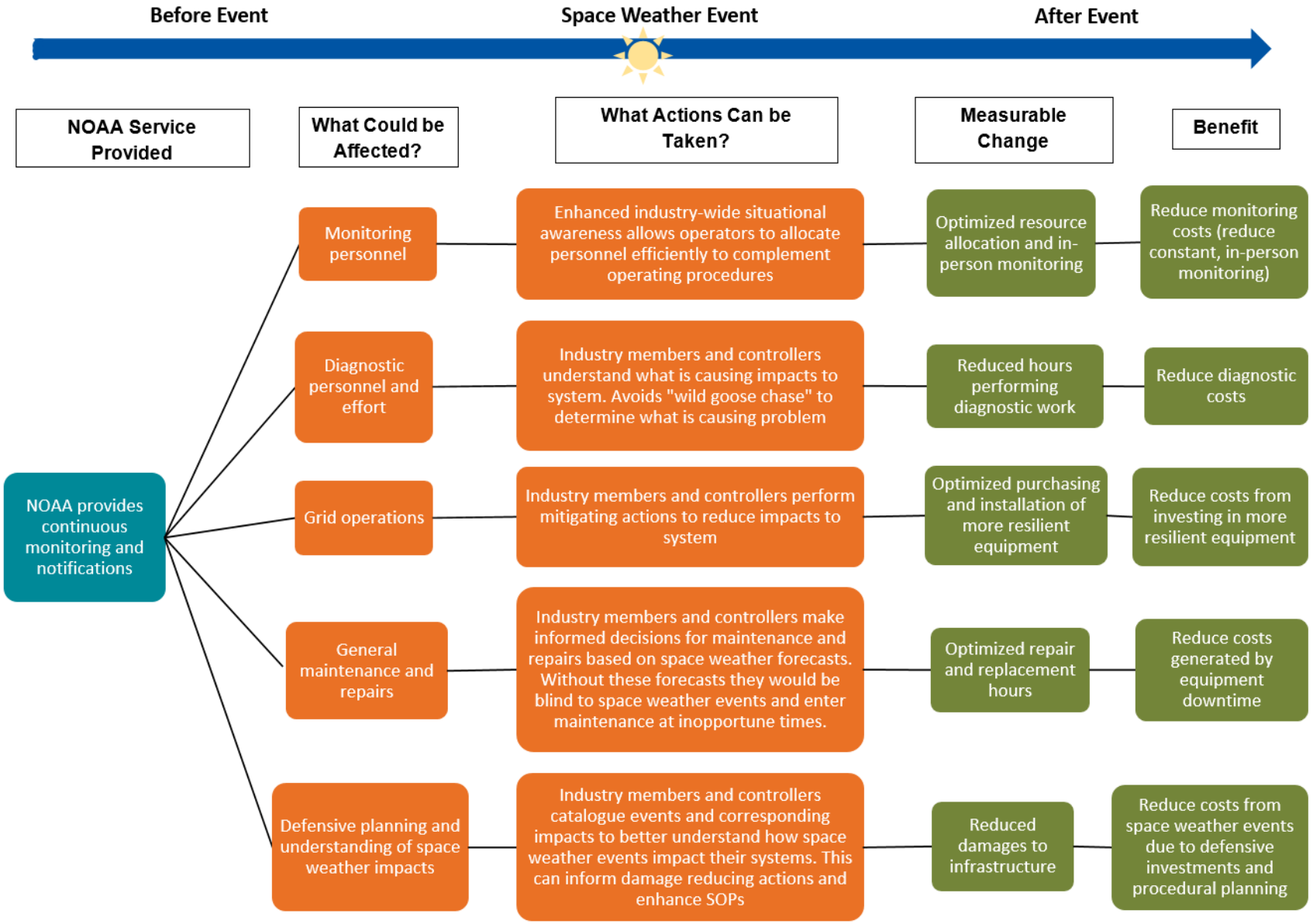


Figure B-2. Value Chain of Constant Monitoring Benefits



Appendix C – Expert Elicitation Interview Guide

Expert Elicitation Interview Guide

INTERVIEWEE NAME, ORGANIZATION
DATE AND TIME

Classification/Context Questions

1. What is your job title, roles, and responsibilities especially related to space weather?
2. How many years have you worked in this industry?
3. What type of utility do you represent (e.g., electric transmission, electric generation, bulk power management)?
4. Which state(s) do you operate in?
5. What is the largest geomagnetic disturbance (GMD) or "space weather" event that you have experienced? (K8, G4, etc.). Please feel free to include related information such as:
    a. Date, start time, duration
    b. Response of your utility
    c. Response of other utilities

Whether and How Industry Uses Space Weather Data

1. How do you currently monitor (real time or forecasted) or receive watches, warnings, and alerts relating to space weather activity? Please feel free to include details such as:
    a. Number of people monitoring (if other than yourself)
    b. Source (NOAA/SWPC or other government)
    c. Frequency of monitoring
    d. Response time
    e. typical response plan for an actionable alert
2. Do you subscribe to a third-party service that provide information on space weather? If so, which one? What type of information do they provide (e.g., re-packaging NOAA SWPC alerts into a format more applicable to you and your business)?
3. Does your company conduct its own forecasting efforts using NOAA data? Do you have one "go-to" forecasting or space weather monitoring person?

Data Source Questions

1. If you subscribe to or purchase from a third-party vendor, could you describe the product and how you use it?
    a. E.g., we have heard of third-party vendors providing "stoplight reports" based on NOAA SWPC data – Red = take action; Yellow = increased monitoring/be on lookout; Green = all clear.
2. Are you generally aware of where this vendor sources its data and if they add to or alter the data in any way?
3. Does your company have policies that limit your use of information from private sector vendors?
4. Does your utility monitor the following?
    a. dB/dt: variations in the geomagnetic field
    b. Geomagnetically induced currents anywhere in the transmission grid
5. Has your utility developed (or plans to develop) software or hardware tools for equipment vulnerability assessment?

Day-to-Day Operations and Space Weather

1. What kind of impacts have you experienced (if any) related to space weather?
    a. Equipment damage? [Ask for general description]

   b. Service interruptions? [Ask for general description]
2. What actions do you take on a regular basis to protect against space weather related events? [What do they do even without warnings from NOAA or other providers of space weather information?]
   a. Actions that protect equipment.
   b. Actions that protect against service interruptions.
   c. Monitoring, other precautionary actions whose cost could be reduced with better forecasting?

Event Based Decision Making with Space Weather Alerts and Data [Event questions]
We would like to ask you to describe what would happen when you receive specific types of alerts from NOAA (or your third-party vendors). We want to run through three different event types:

- **K3 (<G1) - Minor - More than 1700 per solar cycle, more than 900 days per cycle**
- **K7 (G3) - Strong - 200 per solar cycle, 130 days per cycle**
- **K8/9 (G5) - Extreme - 4 per solar cycle, 4 days per cycle (Quebec 1989, Halloween 2003)**

[*For each event type, run through the following questions*]

1. What monitoring and/or defensive/ preparatory operations, if any, do you implement when you receive an alert for one of these events?
   a. Do any operations change compared to a period with no alerts? [*Compared to above*]
   b. [*First time through, get at the following*:] At what threshold do your typical operations change? For example, do operations differ following a K4 and K5 alert? What about K5 and K8?
2. Given the actions you take on a regular basis (from above), what would happen if a {event} occurred without warning?
   a. What would happen to your equipment?
   b. About how many customers would be affected by the service interruptions/losses in this case?
   c. What is the likely duration of this interruption?
3. How effective would those actions be at reducing the impact? In other words, how do the actions you would take reduce the impact on equipment and service interruptions? [*Probe for quantitative values or percentages.*]

Space weather versus terrestrial weather: Impacts and ripple effects

1. How comparable are interruptions caused by terrestrial events compared to space weather events?
   a. Can you describe the difference in impacts of space weather events and more commonly occurring terrestrial events (e.g., tornado, snowstorm)?
2. Are interventions or preparatory actions for space weather events different from interventions or preparatory actions for terrestrial weather events?
3. How would a GMD event impact major utility users and which industries might be most affected?
   a. Do you have some sort of market analysis that includes sensitivity to outages that you are able to share?

Concluding Questions

1. Based on your experience, what are the greatest opportunities for space weather forecasting to reduce cost?
   a. Even if you have never experienced a space weather event, your company has likely incurred significant preventative costs associated with space weather; Do good space weather forecasts reduce the need for preventative/ protective baseline investments?

Appendix D – Event-Based Benefits Table

Situation	K3 (K1-K6 or G1-G2)	K7 (G3)	K8/9- (G4)	K9 (G5)
No SpWx Monitoring **(Actions and Effects)**	**Actions** Some abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Some increased monitoring ● There could be some increased diagnostic efforts ● Some increased troubleshooting to adapt to current conditions ● Possible improper or inefficient operational procedures **Effects** ● Near $0 cost ● Possible effect related to improper operation ● Possible effect related to heightened state of awareness ● No blackout, service interruptions or equipment failure ● Uncertainty related to no knowledge of current conditions	**Actions** Considerably abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Considerable increased monitoring efforts ● Considerable diagnostic efforts ● Considerable troubleshooting efforts ● Possible improper or inefficient operational procedures ● Significant regional coordination necessary to discuss event and actions **Effects** ● No blackout ● Very little to no effect related to equipment damage ● Possible effect related to service interruption ● Possible effect related to coordination ● Possible effect related to monitoring ● Possible effect related to diagnostics ● Possible effect related to troubleshooting ● Possible effect related to improper operation	**Actions** Significantly abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Significant increased monitoring efforts ● Significant diagnostic efforts ● Significant troubleshooting efforts ● Improper or inefficient operational procedures ● Extreme regional coordination necessary to discuss event and actions **Effects** ● Possible effect related to blackout ● Possible effect related to service interruption ● Possible effect related to damaged equipment ● Effect t related to coordination ● Effect t related to monitoring ● Effect related to diagnostics ● Effect related to troubleshooting ● Likely effect related to improper operation	**Actions** Extremely abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Extreme increased monitoring efforts ● Extreme diagnostic efforts ● Extreme troubleshooting efforts ● Likely improper or inefficient operational procedures ● Extreme regional coordination necessary to discuss event and actions **Effects** ● Extreme panic and uncertainty ● Probable effect related to blackout ● Effect related to service interruption and cascading damage ● Effect related to equipment damage ● Effect related to coordination ● Effect related to monitoring ● Effect t related to diagnostics ● Effect related to troubleshooting ● Likely effect related to improper operation ● Possible effects related to failure of automated telecommunication systems within the grid

Situation	K3 (K1-K6 or G1-G2)	K7 (G3)	K8/9- (G4)	K9 (G5)
SpWx Monitoring **(Actions and Measurable Changes)**	**Actions** Some abnormal real-time readings on own system/ monitoring equipment (e.g., voltage, current, vibrations ● Receive SWPC alert, watch, or warning ● This would lead to no operational changes but increased communication and coordination **Measurable Change** ● Near $0 change ● No blackout, service interruptions or equipment failure ● Change related to receiving and processing SWPC alert, watch, or warning ● Change related to communication and coordination	**Actions** Considerable abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Receive SWPC alert, watch, or warning ● Start communication procedures per GMD operational protocols ● Very low chance of some preparatory operational changes ● Some regional coordination **Measurable Change** ● Change related to communication procedures ● Possible change related to preparatory operational changes ● Possible change related to coordination ● Change related to receiving and processing SWPC alert, watch, or warning ● Little to no chance of equipment damage ● No blackout and much less to no chance of service interruptions	**Actions** Significant abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Receive SWPC alert, watch, or warning ● Operate and communicate according to GMD operational procedures guidelines ● Regional coordination **Measurable Change** ● Change related to operational/communication procedures ● Change related to regional coordination ● Change related to receiving and processing SWPC alert, watch, or warning ● Low possibility of change related to blackout ● Low possibility of change related to service interruption ● Low possibility of change related to equipment damage	**Actions** Extremely abnormal real-time readings on own system/monitoring equipment (e.g., voltage, current, vibrations) ● Receive SWPC alert, watch, or warning ● Operate and communicate according to GMD operational procedures guidelines ● Regional coordination **Measurable Change** ● Change related to operational/communication procedures ● Change related to regional coordination ● Change related to receiving and processing SWPC alert, watch, or warning ● Possible change related to blackout ● Possible change related to service interruption ● Possible change related to equipment damage
Benefit of SpWx Monitoring (SpWx - Baseline Effects)	Less anxiety and more confidence about the protocols to operate reliably Less diagnostic efforts Less troubleshooting efforts Less monitoring Decreased operational costs Cost of receiving and processing SWPC alert, watch, or warning	Less coordination needed Less monitoring Less diagnostics Less troubleshooting (alerts only, none for watches/warnings) Less chance of service interruption Less chance of equipment damage Less uncertainty Decreased operational costs Cost of receiving and processing SWPC alert, watch, or warning	Less coordination needed Less monitoring Less diagnostics Less troubleshooting (alerts only, none for watches/warnings) Less chance of service interruption Less chance of equipment damage Less uncertainty Less chance of blackout Decreased operational costs Cost of receiving and processing SWPC alert, watch, or warning	Less coordination needed Less monitoring Less diagnostics Less troubleshooting (alerts only, none for watches/warnings) Less chance of service interruption Less chance of equipment damage Less uncertainty and panic Less chance of blackout Decreased operational costs Less chance of cascading effects Cost of receiving and processing SWPC alert, watch, or warning

Appendix E – Constant Monitoring ("Peace-of-Mind") Benefits Table

Situation	Constant Monitoring ("Peace-of-Mind")
No SpWx Monitoring **(Actions and Effects)**	**Actions** ● Increase monitoring efforts ● Increase defensive investments ● Perform sub-optimal operation ● Perform sub-optimal maintenance planning ● Try to pay other entities for data **Effects** ● Likely effect related to increased monitoring efforts ● Likely effect related to increased defensive investments ● Possible effect related to sub-optimal operation (lost revenue) ● Potential cost for available private data
SpWx Monitoring **(Actions and Measurable Changes)**	**Actions** ● Receive space weather monitoring information ● Optimal operation ● Optimal maintenance planning ● Make optimal defensive investments **Measurable Change** ● Change related to receiving and acting on space weather monitoring information ● Change related optimal operation ● Change related to optimal maintenance ● Change related to defensive investments
Benefit of SpWx Monitoring (SpWx - Baseline Effects)	Decreased monitoring efforts Decreased defensive investments Less chance of lost revenue from sub-optimal operation Decreased costs from improper diagnostic efforts Less uncertainty Reduced cost associated with space weather monitoring information