United States Government Accountability Office

Report to Congressional Requesters

February 2018

CRITICAL INFRASTRUCTURE PROTECTION

Electricity Suppliers Have Taken Actions to Address Electromagnetic Risks, and Additional Research Is Ongoing

GAO-18-67

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GAO Highlights

Highlights of GAO-18-67, a report to congressional requesters

Why GAO Did This Study

A severe GMD or HEMP event could potentially have significant impacts—including power outages—on the nation's electric grid, which could affect other sectors that depend on electricity, such as communications. In response, NERC created two regulatory standards requiring certain U.S. and Canadian suppliers to assess their vulnerability to GMD and take appropriate steps in response.

GAO was asked to review electricity industry actions to prepare for and mitigate electromagnetic risks. This report examines, among other things, (1) to what extent U.S. and Canadian electricity suppliers have identified information about GMD and HEMP effects on the grid, (2) what steps selected U.S. and Canadian suppliers have taken to protect against GMD and HEMP, and (3) what opportunities exist for U.S. suppliers to recover costs for protecting against GMD and HEMP.

GAO examined government and industry studies and interviewed federal and industry officials about potential GMD and HEMP effects on grid infrastructure; reviewed regulatory standards, monitoring processes, and NERC compliance audit data from April 2015 through August 2017; reviewed federal regulations and interviewed state regulators on cost recovery issues; and interviewed officials from a nongeneralizable sample of 13 U.S. and Canada electricity suppliers, selected based on factors such as GMD experience and preparation for GMD and HEMP events.

GAO provided a draft of this report to five federal agencies and NERC. Technical comments provided were incorporated as appropriate.

View GAO-18-67. For more information, contact Chris Currie at (404) 679-1875 or curriec@gao.gov or Frank Rusco at (202) 512-3841 or ruscof@gao.gov.

What GAO Found

U.S. and Canadian electricity suppliers—electricity generation and transmission owners and operators—have identified information on the potential effects of a severe geomagnetic disturbance (GMD), resulting from a solar storm, but have identified less information about the potential effects of a high-altitude electromagnetic pulse (HEMP), resulting from the detonation of a nuclear device, on the electric grid. There is general agreement that more research is needed on both GMD and HEMP. Government and industry have publicly reported on the potential impacts of GMD on the grid. For example, one study identified two main risks: (1) potential voltage instability, causing power system collapse and blackouts; and (2) possible damage to key system components. However, these studies do not address the unique aspects of individual suppliers' networks. Recognizing this, 11 of the 13 selected suppliers GAO contacted said they had assessed their network vulnerability; of these 11, 6 expected GMD effects to be relatively small. In contrast, Department of Energy (DOE) and industry officials told GAO that information on HEMP effects is limited in that suppliers lack key information to fully understand HEMP effects on their networks. Historically, study of HEMP effects focused on impacts to military equipment rather than the commercial electric grid. Recently, DOE and industry began research to better understand HEMP effects. Of the 11 suppliers who responded to GAO about their HEMP efforts, 3 reported having studied the impact of HEMP on their networks and 2 of the 11 had integrated, or planned to integrate, HEMP-resistant features into new control centers.

Of the 13 selected suppliers GAO contacted, 10 reported making technological and operational improvements to enhance overall network reliability that also provided some protection against GMD and HEMP risks. For example, suppliers reported making technological improvements such as replacement of some older transformers and unprotected control centers. As of May 2017, all 13 suppliers stated they had complied with a GMD regulatory standard issued by the North American Electric Reliability Corporation (NERC)—the federally designated regulatory authority responsible for developing and enforcing reliability standards—to develop operating procedures to mitigate GMD effects. A second regulatory standard—which is to be implemented in phases through 2022—will generally require suppliers to further assess their vulnerability to GMD.

Selected U.S. suppliers told GAO that costs they have incurred to protect against GMD and HEMP have been relatively small so far and they expect to recover those costs through customer rates. Suppliers could face future increased costs depending on corrective actions needed to comply with the second GMD regulatory standard. Federal and state regulators indicated that regulated U.S. suppliers' costs for protecting against GMD are generally recoverable through customer rates, but recovery is less certain for protection against HEMP because less is known about HEMP risks. Further, some suppliers could face challenges to cost recovery. Specifically, independent owners of power plants—those that sell power in wholesale electricity markets and are not part of an integrated utility—must recover reliability improvement costs through their sales of electricity and are not assured of cost recovery; federal regulators told GAO they are aware this could be a challenge for these independent owners.

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Abbreviations

BPA	Bonneville Power Administration
CME	coronal mass ejection
DHS	Department of Homeland Security
DOE	Department of Energy
DOE Action Plan	U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan
DSCOVR	Deep Space Climate Observatory
EEI	Edison Electric Institute
EGCC	Energy Government Coordination Council
ERCOT	Electric Reliability Council of Texas
EMP	electromagnetic pulse
EMP Commission	Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack
EPRI	Edison Power Research Institute
ERO	electric reliability organization
FERC	Federal Energy Regulatory Commission
GIC	geomagnetically induced current
GMD	geomagnetic disturbance
HEMP	high-altitude electromagnetic pulse
ISO	independent system operator
Joint Strategy	Joint Electromagnetic Pulse Resilience Strategy
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
NRC	United States Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PPD	Presidential Policy Directive
RTO	regional transmission organization
SARA	Scientific Applications & Research Associates
STEP	Spare Transformer Equipment Program
SWPC	Space Weather Prediction Center
QER	Quadrennial Energy Review
WAPA	Western Area Power Administration

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U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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Congressional Requesters

The electric grid is crucial to our country's economy and wellbeing, providing electricity to over 300 million people and representing more than $1 trillion in assets, as well as supporting other critical infrastructure.[1] Consequently, the reliability of the grid—its ability to meet consumers' electricity demand at all times—is essential to national safety and security. As early as 1941, electric power industry researchers have expressed concerns about the potential risks posed to grid reliability by electromagnetic events.[2] An electromagnetic event can result from a naturally occurring, large-scale geomagnetic disturbance (GMD), caused by severe solar weather, or from human-made sources, such as the high-altitude detonation of a nuclear device to create a high-altitude electromagnetic pulse (HEMP).[3] A major GMD or HEMP event could have long-term, significant impacts on the nation's electric grid—the commercial electric power transmission and distribution system. Given the interdependency among infrastructure sectors, a disruption to the electric grid could also result in potential cascading impacts on fuel distribution, transportation systems, food and water supplies, and communications and equipment for emergency services, as well as other

[1]Presidential Policy Directive-21, *Critical Infrastructure Security and Resilience* (Feb. 12, 2013) (PPD-21) identifies 16 critical infrastructures sectors, of which energy is one.

[2]Davidson, W.F., "Sun-Spot Disturbances of Terrestrial Magnetism." *Electrical Engineering*, vol. 60, issue 2 (1941); the substance of this paper was presented in 1940. In the 1950s and 1960s, the United States conducted several tests on high-altitude nuclear devices, during which effects on long-distance communications, among other things, were observed.

[3]A high-altitude electromagnetic pulse (HEMP) event is caused by the detonation of a nuclear device above the atmosphere, resulting in a burst of electromagnetic radiation that can disrupt or destroy electronic equipment. Non-nuclear electromagnetic pulse (EMP) weapons—those that produce electromagnetic radiation such as devices that generate localized EMP using microwave-type technologies—can also be designed to intentionally disrupt electronics, but these weapons generally have a short range and are not a threat to multiple assets. For example, a non-nuclear EMP weapon might damage a power substation but would not widely affect the electric grid. This report addresses the effects caused by nuclear HEMP.

communication systems that utilize the civilian electrical infrastructure.[4] More recently, however, some government and research organizations have questioned the long-term level of impact electromagnetic events could have on the electric grid and have recommended further research and study be conducted on the effects of electromagnetic events.[5]

Most of the U.S. electric grid is owned and operated by the private sector, with federal, state, local, and other governments playing significant regulatory and other roles. The Department of Homeland Security (DHS) has the lead role in coordinating the overall federal effort to promote the security and resiliency of the nation's critical infrastructure, which includes the electricity grid. The Department of Energy (DOE)—as the sector-specific agency for the energy sector—coordinates with DHS and is also responsible for coordinating with other relevant federal agencies and for collaborating with critical infrastructure owners and operators to prioritize and coordinate federal resiliency efforts.[6] In addition, the Federal Energy Regulatory Commission (FERC), which regulates the interstate transmission of electricity, among other things, is responsible for reviewing and approving standards developed by the North American Electric Reliability Corporation (NERC)—the designated U.S. Electric

[4]See, for example, GAO, *Critical Infrastructure Protection: Federal Agencies Have Taken Actions to Address Electromagnetic Risk, but Opportunities Exist to Further Assess Risks and Strengthen Collaboration*, GAO-16-243 (Washington, D.C.: Mar. 24, 2016); and Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack—Critical National Infrastructures* (April 2008).

[5]See, for example, Scientific Applications and Research Associates (SARA), Inc., for Electric Infrastructure Security Council, *Electromagnetic Black Sky Responses of Power and Control Equipment*, #2017 018 (Colorado Springs, Colorado; July 2017); Electric Power Research Institute (EPRI), *Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid: Geomagnetically Induced Current and Transformer Thermal Analysis*, #3002009001 (Palo Alto, CA; Feb. 2017); JASON Summer Study, The MITRE Corporation, *Impacts of Severe Space Weather on the Electric Grid*, JSR-11-320, a report prepared at the request of the Department of Homeland Security, Science and Technology Directorate (McLean, VA: November 2011); and U.S. Department of Energy, Sandia National Laboratories, *Sandia Peer Review Comments for FERC on the ORNL-Metatech FERC Power Grid Reports*, SAND2016-11517 R (Albuquerque, New Mexico; 2010) (FOR OFFICIAL USE ONLY).

[6]Sector-specific agencies are the federal departments and agencies responsible for providing institutional knowledge and specialized expertise, as well as leading, facilitating, or supporting the security and resilience programs and associated activities of their designated critical infrastructure sector in the all-hazards environment. Presidential Policy Directive 21, *Critical Infrastructure Security and Resilience* (Feb. 12, 2013) (PPD-21) (identifying the 16 critical infrastructure sectors and the sector-specific agencies).

Reliability Organization (ERO)—to provide for the reliable operation of the bulk power system (the generation and transmission components of the grid).[7] The North America electric grid encompasses the United States, parts of Mexico, and most provinces of Canada. Canada has experienced the only extreme GMD event resulting in significant loss of power to the North America grid.[8] NERC's role in Canada is similar to its role in the United States and reliability standards are mandatory and enforceable in most Canadian provinces.[9]

The United States has taken steps to assess the risks posed by electromagnetic events and identified steps to mitigate these risks. For example, in April 2008 the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (EMP Commission) issued a report that included over 90 recommendations addressing the preparation for, and protection and recovery from, a possible EMP attack

[7]See 16 U.S.C. § 824o. As the FERC-designated Electric Reliability Organization (ERO) for the United States, the North American Reliability Corporation (NERC) is overseen by FERC in the United States. In this role, NERC is responsible for developing and enforcing mandatory standards to provide for the reliable operation of the bulk power system and conducting reliability assessments. The bulk power system includes the facilities and control systems necessary for operating the interconnected electricity transmission network and the electric energy from certain generation facilities needed for reliability, and excludes local distribution systems.

[8]In 1989, a severe solar storm caused wide-scale impacts on the Hydro-Quebec power system in Canada.

[9]According to NERC, while authority over electricity generation and transmission in Canada rests primarily with provincial governments, all have recognized NERC as an electric reliability standards-setting organization and have committed to supporting NERC in its standards-setting and oversight role as the North American ERO. According to NERC, while the process for approving NERC Reliability Standards varies in the different Canadian jurisdictions, standards—in some cases modified to reflect the jurisdictions' reliability regimes—are mandatory and enforceable in the provinces of Ontario, New Brunswick, Alberta, British Columbia, Manitoba, Nova Scotia, and Quebec.

against U.S. critical infrastructure.[10] The majority of these recommendations were made to DHS and DOE. In May 2013, FERC directed NERC to develop reliability (regulatory) standards requiring electricity suppliers to address the potential impact of GMD on the reliable operation of the U.S. bulk power system.[11] In June 2014, FERC approved a standard, submitted by NERC, requiring that certain suppliers prepare for the effects of GMD events by developing contingency operating plans, procedures, and processes.[12] FERC approved a second standard in

[10]Established pursuant to the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, the EMP Commission was responsible, among other things, for assessing the nature and magnitude of potential HEMP threats to the United States and the capability of the United States to prepare and recover from a HEMP attack. Pub. L. No. 106-398, §§ 1401-09, 114 Stat. 1654, 1654A-345-348 (2000). See also National Defense Authorization Act for Fiscal Year 2006, Pub. L. No. 109-163, § 1052, 119 Stat. 3136, 3434-35 (reestablishing the EMP Commission to monitor, investigate, make recommendations, and report to Congress on the evolving threat to the United States of an EMP attack resulting from the detonation of a nuclear weapon or weapons at high altitude); National Defense Authorization Act for Fiscal Year 2008, Pub. L. No. 110-181, § 1075, 122 Stat. 3, 333 (providing, among other things, that the EMP Commission and the Secretary of Homeland Security shall jointly ensure that the work of the EMP Commission and the Secretary of Homeland Security with respect to EMP attack on electricity infrastructure, and protection against such attack, is coordinated with DHS efforts on such matters); National Defense Authorization Act for Fiscal Year 2016, Pub. L. No. 114-92, § 1089, 129 Stat. 726, 1015-16 (2015) (reestablishing the EMP Commission but with an expanded purpose that includes the evolving threat from, among other things, nonnuclear and naturally occurring EMP). The EMP Commission's charter expired on June 30, 2017. *Id.* § 1089. While the commission did not specifically identify a total number of recommendations, our analysis of the commission report identified over 90 recommendations, which included key recommendations and related subareas across 10 critical infrastructure sections, including electric power, telecommunications, and emergency services among others. The National Defense Authorization Act for Fiscal Year 2018 established a new Commission to Assess the Threat to the United States from Electromagnetic Pulse Attacks and Similar Events, which is to review and assess a number of issues related to potential electromagnetic pulse events and similar events, such as the nature, magnitude, and likelihood of potential electromagnetic pulse attacks and similar events, including geomagnetic disturbances, and the capability of the United States to repair and recover from damage inflicted on United States military and civilian systems by EMP attacks and similar events. See Pub. L. No. 115-91, tit. XVI, subtit. F, § 1691 (2017)..

[11]For the purposes of this report, we define "electricity suppliers" as entities that produce and sell electricity, as in those that own or operate generation or transmission infrastructure, as well as those with responsibility for planning and overseeing the grid and for selling electricity to consumers.

[12]See NERC Reliability Standard EOP-010-1 (approved by FERC at Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014)). According to NERC, as of October 2017, this standard has also been adopted in the Canadian provinces of Manitoba, Saskatchewan, Ontario, New Brunswick, Nova Scotia, and Quebec; British Columbia has adopted the standard but it is not yet subject to enforcement and Alberta is in the process of adopting EOP-010-1.

September 2016, also submitted by NERC, requiring certain suppliers to assess the vulnerability of their transmission systems to GMD events; suppliers that do not meet certain performance requirements must develop a plan to achieve the performance requirements.[13] Also, in December 2016, the National Defense Authorization Act for Fiscal Year 2017 was enacted, requiring DHS to, among other things, conduct an intelligence-based review and comparison of the risks and consequences of electromagnetic events to the nation's critical infrastructure and to use that information to inform a recommended strategy for protecting and preparing U.S. critical infrastructure against electromagnetic threats.[14]

In 2016, we reported that key federal agencies had taken various actions to address electromagnetic risks to the electric grid—such as establishing industry standards and federal guidelines and completing related research reports—and that some of these actions aligned with recommendations made in 2008 by the EMP Commission.[15] We also found that while DHS components had independently conducted some efforts to assess electromagnetic risks, DHS had not fully leveraged opportunities to collect key risk inputs—threat, vulnerability, and consequence information—to inform comprehensive risk assessments of electromagnetic events. Moreover, we found that DHS and DOE, in conjunction with industry, had not established a coordinated approach to identifying and implementing key risk management activities to address EMP risk, such as identifying and prioritizing key research and development efforts. We recommended, among other things, that DHS identify internal roles to address electromagnetic risks and collect additional risk inputs to further inform risk assessment efforts. We also recommended that DHS and DOE engage with federal partners and industry stakeholders to identify and implement key EMP research and development priorities. DHS and DOE concurred with our recommendations. As of October 2017, DHS had addressed our recommendation regarding key EMP research and development priorities by, among other things, working with key industry stakeholders to help

[13]See NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C. ¶ 61,215, 81 Fed. Reg. 67,120 (2016)). According to NERC, as of December 2017, this standard has been adopted in the Canadian provinces of New Brunswick, Ontario, and Saskatchewan.

[14]See Pub. L. No. 114-328, § 1913, 130 Stat. 2000, 2684-87 (2016).

[15]GAO-16-243.

identify and implement EMP research and development efforts. DHS had also taken steps to identify key roles and responsibilities within the Department to address electromagnetic risks as well as work with federal and industry partners to collect additional inputs on threats, vulnerabilities, and consequences related to electromagnetic risks, which we are in the process of reviewing to determine whether they address our recommendations in these areas. DOE has also taken steps to work with industry to develop a joint government-industry EMP strategy and supporting DOE action plan to further address our recommendation regarding the identification of key EMP research and development priorities. Both DHS and DOE have reported taking some actions to identify critical electrical infrastructure assets, but have yet to fully address this recommendation. We will continue to review DHS and DOE's actions to address our open recommendations.

Given our previous work reviewing federal efforts to address electromagnetic risks, you asked us to review actions taken by the electricity industry to prepare for and mitigate impacts from electromagnetic events. Our objectives were to examine (1) to what extent U.S. and Canadian electricity suppliers have identified information about the effects of GMD and HEMP events on the electric grid, (2) what steps selected U.S. and Canadian electricity suppliers have taken to protect against GMD and HEMP events and how NERC has monitored these efforts, and (3) what opportunities exist for U.S. electricity suppliers to recover costs for protecting against GMD and HEMP events.

In conducting our work, we interviewed representatives from 13 of the 181 U.S. and Canadian electricity suppliers subject to NERC's 2014 GMD reliability standard that conduct planning and generation, transmission, and distribution operations.[16] We selected these 13 electricity suppliers based on various factors, including input from DOE, NERC, and industry organization officials familiar with suppliers' activities to prepare for

[16]According to NERC, as of October 2017, of the 181 suppliers, seven Canadian suppliers are subject to compliance with the 2014 reliability standard; the Canadian province of Alberta is in the process of adopting the standard and British Columbia has adopted the standard but it is not yet subject to enforcement.

electromagnetic events.[17] Of these 13, we conducted site visits to 6 suppliers to better understand their experiences with past GMD events and identify actions they have taken to prepare for and mitigate GMD and HEMP events, among other things. During these visits we met with officials and observed operations and facilities, such as control centers hardened to mitigate effects from HEMP events, and equipment potentially vulnerable to GMD, such as high-voltage transformers.[18] We included three Canadian electricity suppliers among the 13 suppliers we interviewed due to their (1) experiences with past GMD events, (2) research on the impacts of GMD, and (3) actions taken to prepare for and mitigate GMD events. While we cannot generalize the information we learned from these selected suppliers to all U.S. and Canadian suppliers, they provided us with examples of what suppliers may know about the potential impacts of electromagnetic events on the electric grid, as well as steps suppliers may be taking to prepare for and mitigate such impacts. The selected U.S. suppliers also identified opportunities available to them for recovering costs for protecting against electromagnetic events. Further, we interviewed representatives from six industry organizations because of these organizations' specialized knowledge and experience with electricity suppliers.

To address the first objective, we reviewed U.S. and Canadian government studies issued, or commissioned by, for example, DHS, DOE, and NERC regarding, among other things, the vulnerability of transmission and generation infrastructure and equipment to GMD and HEMP events, possible measures to mitigate the effects of GMD and HEMP, and areas requiring further research. We also reviewed relevant

[17]We also considered, among other things, the following supplier preparedness and mitigation actions and characteristics: (1) efforts or plans to install mitigation equipment or technology; (2) efforts or plans to develop specific mitigation processes, procedures, or other operational actions; (3) infrastructure, such as length and voltage of transmission lines; (4) equipment, such as high voltage (over 230kV) transformers; (4) geomagnetic latitude; and (5) experience with GMD events.

[18]Voltage is the "force" that makes electricity flow through a conductor. It is measured in "volts," with a "kilovolt" (kV) representing 1,000 volts. The classification of "high voltage" transmission varies, but generally ranges from 230 kV up to 765 kV in North America. Electricity is generally produced at between 5 to 34.5 kV and distributed at between 15 to 34.5 kV. The six United States and Canadian electricity suppliers we visited were Bonneville Power Administration (BPA), PJM Interconnection LLC, Hydro-Quebec, Peak Reliability, Western Area Power Administration (WAPA), and Dominion Energy. The remaining seven electricity suppliers we interviewed by phone or received written responses from are ATC, Exelon Corp., Southern Company, Hydro One, Manitoba Hydro, Electric Reliability Council of Texas (ERCOT), and Central Maine Power.

studies from various industry organizations—such as the Electric Power Research Institute (EPRI)—and interviewed knowledgeable officials from these organizations and government agencies to clarify our understanding of relevant research issues. We identified these studies based on feedback from all entities listed above and through references in reports and other documentation. While we did not compile a comprehensive list of all studies of the effects of GMD and HEMP on the U.S. and Canadian electric grid, industry experts indicated that we had identified relevant studies published on this subject since 2010. We assessed the methodologies used in the relevant reports and determined them to be sufficiently rigorous to provide information about the potential effects of GMD and HEMP events on the electric grid. To better understand the effects of solar weather on the electric grid, how GMD is measured, and mechanisms in place for notifying electricity suppliers of potentially dangerous solar storms, we interviewed representatives from the National Oceanic and Atmospheric Administration (NOAA) and other federal agencies and reviewed relevant documentation on processes and procedures. To identify the frequency and intensity of past GMD events, we analyzed the available historical record of GMD occurrences from 1933 through 2016 calculated and maintained by GFZ German Research Centre for Geosciences. NOAA officials confirmed that the GFZ German Research Centre for Geosciences maintains the authoritative historical record of these data. We assessed the reliability of these data by testing for missing data, outliers, or obvious errors, and found the data to be sufficiently reliable to report on the number and intensity of GMD events occurring from 1933 through 2016. With respect to ongoing HEMP research and planning efforts, we reviewed, for example, relevant U.S. government strategies and plans and interviewed relevant officials, including researchers from U.S. National Laboratories. In October 2017, we also requested an interview with a representative from the EMP Commission but did not receive a response to our requests.[19]

To address the second objective, we reviewed FERC orders and NERC reliability standards that require certain suppliers to take steps to assess and prepare for GMD impacts, and interviewed relevant officials regarding

[19]As described earlier, the EMP Commission was established in the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, which requires that the commission by composed of nine members, appointed from among private industry in the United States with knowledge and expertise in the scientific, technical, and military aspects of EMP effects. See Pub. L. No. 106-398, 114 Stat. at 1654A-345.

the standards.[20] We also obtained information from 13 U.S. and Canadian electricity suppliers regarding steps they had taken to comply with NERC reliability standards and actions to prepare for electromagnetic events. To understand how NERC has monitored electricity suppliers' steps to comply with NERC Reliability Standard EOP-010-1, we reviewed NERC monitoring processes. NERC officials provided the number of compliance audits conducted between April 2015—when NERC, through Regional Entities to which it has delegated enforcement authority, first began reviewing suppliers for compliance with EOP-010-1—and August 2017 that included the EOP-010-1 reliability standard.[21] We contrasted the number of compliance audits with the total number of suppliers potentially subject to NERC's GMD reliability standard EOP-010-1. We assessed the reliability of the data on the total number of suppliers subject to EOP-010-1 by interviewing agency officials regarding data sources, system controls, and any quality assurance steps performed by officials before the data were provided; we found the data to be sufficiently reliable to provide the number of suppliers subject to EOP-010-1 since it went into effect. We also discussed with cognizant NERC officials the organization's processes for collecting and reporting comprehensive data on the status of their overall compliance monitoring efforts.

To address the third objective, we reviewed FERC regulations and orders related to cost recovery, such as suppliers' costs for spare transmission equipment services. We also interviewed FERC officials and representatives of two state regulators whose jurisdictions include suppliers we interviewed, regarding procedures available to electricity suppliers to recover costs for actions taken to prepare for and mitigate

[20]NERC Reliability Standard EOP-010-1 requires certain suppliers to have GMD operating procedures in place to mitigate the potential effects of GMD events on the reliable operation of the transmission networks for which they are responsible. See NERC Reliability Standard EOP-010-1 (approved by FERC at Order No. 797, Reliability Standard for Geomagnetic Disturbance Operations, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014)). NERC reliability standard TPL-007-1 requires certain suppliers to assess the vulnerability of their transmission systems to GMD events; suppliers that do not meet certain performance requirements must develop a plan to achieve the performance requirements. See NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C. ¶ 61,215, 81 Fed. Reg. 67,120 (2016)).

[21]The data NERC provided on the number of compliance audits its Regional Entities had performed that included EOP-010-1 were provided by way of a one-time manual data call to the Regional Entities in response to our request for this information. Because NERC does not routinely collect these data, nor were the data produced by an automated data system, we did not separately assess the reliability of the data.

electromagnetic effects. We asked these officials to discuss previous, current, and potential future regulatory actions—orders or rate cases they have overseen—involving recovery of costs for actions taken to protect against GMD and HEMP events. Further, we interviewed DHS and DOE officials to identify the extent to which financial incentives—such as preparedness grants—are available to U.S. electricity suppliers to offset the costs of preparation and mitigation efforts. We interviewed officials from the 10 selected U.S. suppliers regarding the extent to which they had recovered costs expended on preparedness and mitigation efforts and what, if any, options they were considering to recover such costs in the future.[22] While the information provided by these selected electricity suppliers is not generalizable to the U.S. electricity industry, it illustrates examples of actions selected suppliers have taken to recover costs for GMD and HEMP mitigation and preparedness efforts. Additional details on our scope and methodology are contained in appendix I.

We conducted this performance audit from May 2016 to February 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

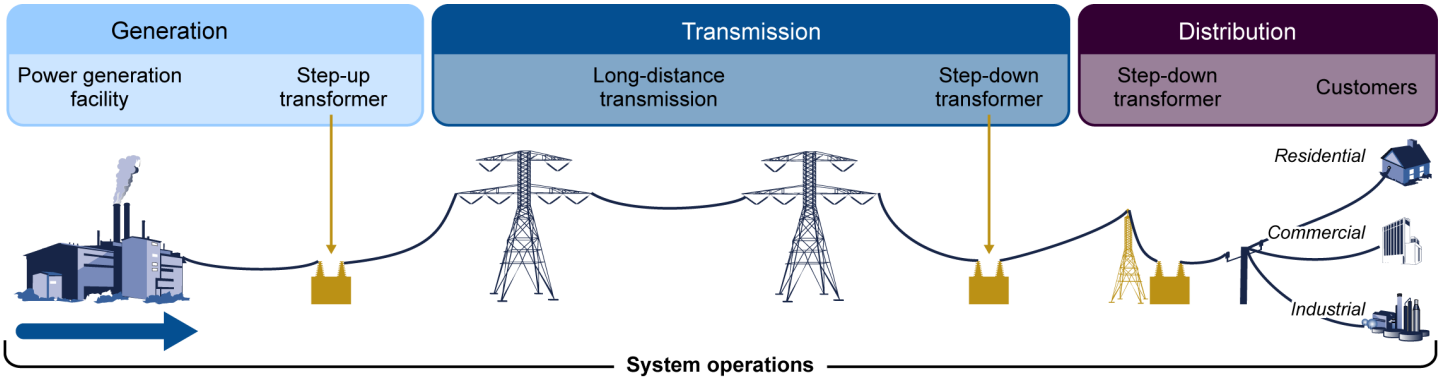
Electricity Operation and Delivery in the United States and Canada

The electricity operation and delivery system—collectively referred to as the grid—in the United States and Canada includes four functions: generation, transmission, distribution, and system operations (see fig. 1). Electricity is generated at power plants by burning fossil fuels; through nuclear fission; or by harnessing renewable sources such as wind, solar, geothermal energy, or hydropower. Once wholesale electricity is generated, it enters the bulk power system—a network of high-voltage, high-capacity transmission systems—where it is transformed to a higher voltage and flows through transmission lines, generally over long distances, to areas where it is transformed to a lower voltage and sent

[22]We did not interview Canadian electricity suppliers regarding cost recovery issues because of differences in the U.S. and Canadian wholesale and retail markets.

through the local distribution system for use by various customers. Throughout this process, system operations are managed by a system operator, such as a local utility.[23]

Figure 1: Functions of the Electricity System



Source: GAO; Art Explosion (clip art). | GAO-18-67

Below is additional information on the functions of the electric grid, including equipment that may be vulnerable to GMD and HEMP.

- **Electricity generation.** Power plants generate electricity by converting energy from other forms—such as coal, natural gas, or wind—into electricity.[24] While they produce electricity once operating they are vulnerable when power outages occur because initially starting a power plant after an outage typically requires an external source of electricity to operate the control systems—electronics that

[23]In some regions of the United States, the system (grid) operator and electricity supplier are the same entity, which is often referred to as an "electric utility." In other parts, different entities fill these roles. In this report, the term "system operator" includes "electricity supplier," which refers to owners and operators who have responsibility for planning and/or operating the electric power system.

[24]The initial form of energy can be mechanical (hydro, wind, or wave), chemical (hydrogen, coal, petroleum, refuse, natural gas, petroleum coke, or other combustible fuel), thermal (geothermal or solar), or nuclear. Power plants use generators to transform these initial energy forms into rotational mechanical energy, such as occurs in a turbine, and then into electrical power. Additionally, radiant energy (solar) power stations use photo-voltaic cells to transform the solar energy into electrical power.

are integral to their operations.[25] Some power plants have the capability to restore operations by employing a "black start," which is the process of restoring a plant to operation without relying on off-site sources of electricity, usually through using dedicated diesel generators to provide the electricity needed. However, not all plants have this capability and in the event of a power outage could therefore be vulnerable to lengthy system disruptions.

- **Electricity transmission.** Power plants are generally geographically distant from the areas where electricity is consumed. To move electricity from where it is produced to where it is used, electricity is sent over transmission lines; together, these lines form a network, or grid. To transport energy over long distances with reduced power losses, suppliers increase voltages—the "force" that makes electricity flow through a conductor—and utilize high-voltage transmission lines, operating from 230 up to 765 kilovolts (kV) in North America. According to the Quadrennial Energy Review, as of January 2017, there were approximately 240,000 miles of high-voltage transmission circuit lines in the contiguous United States.[26] During a solar storm, high-voltage transmission lines can act as "antennae" that allow GMD to enter the electric system.[27]

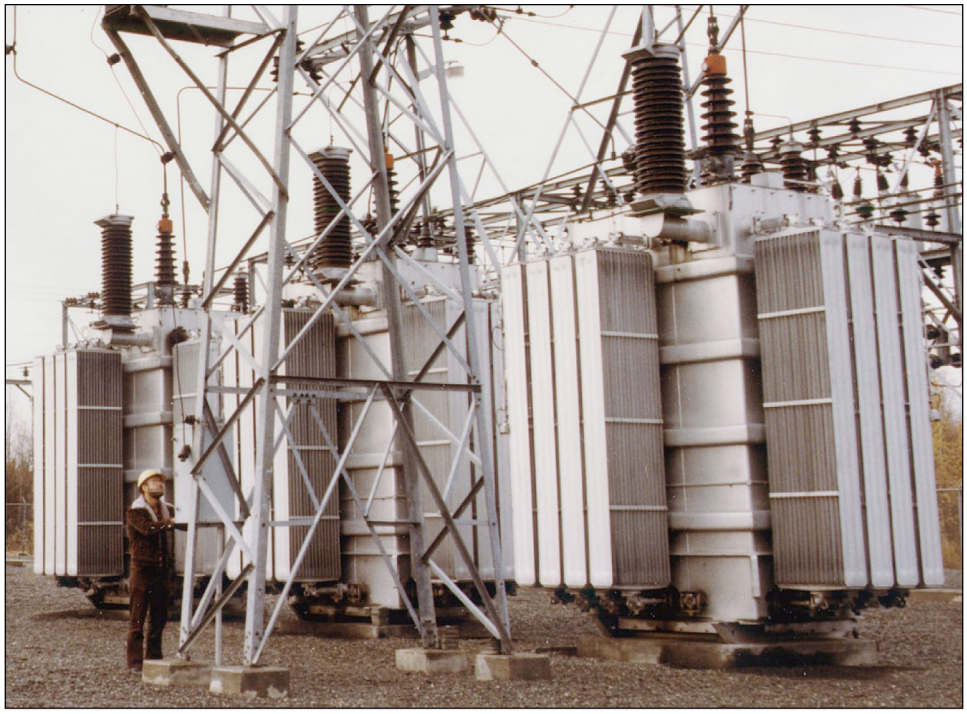
[25]Power outages are of particular concern for nuclear power plants since the loss of external power sources could impact safety operations. In June 1990, in response to a severe 1989 GMD event, the Nuclear Regulatory Commission (NRC)—which regulates the commercial operation of nuclear power plants—issued Information Notice 90-42 to inform plant licensees of the potential damage GMD could cause to the grid. In 2009 and 2010, the NRC, based on the results of several research studies, concluded that nuclear power plants can achieve safe shutdown following EMP or GMD events. In 2015, as part of actions initiated following the March 2011 Fukushima Dai-ichi incident, the NRC issued a proposed rule that would codify a 2012 order requiring nuclear plants to implement strategies in the event of a prolonged loss of offsite power, similar to what could be caused by a GMD or EMP event. See Mitigation of Beyond-Design-Basis Events, 80 Fed. Reg. 70,610 (proposed Nov. 13, 2015) (to be codified at 10 C.F.R. pts. 50 and 52). According to the proposed rule, NRC plans to take additional actions to consider these issues, including participating in an interagency task force developing a National Space Weather Strategy and associated action plan, and will reevaluate the need for additional actions to address the impact of geomagnetic storms on nuclear power plants within this context.

[26]Quadrennial Energy Review (QER) Task Force, *Transforming the Nation's Electricity System: The Second Installment of the QER* (January 2017). A circuit-mile is 1 mile of one circuit of transmission line.

[27]High-voltage transmission lines vary in terms of their vulnerability to GMD. In general, lines that conduct alternating current—in which the direction of the current reverses, or alternates—are more vulnerable to GMD at higher voltages.

- **Transformers.** Transformers are critical to the efficient and effective delivery of electricity to customers and, under certain circumstances, can be vulnerable to the effects of GMD and HEMP. Transformers facilitate the efficient transfer of electricity over long distances through the transmission system by converting electricity to different voltages along the delivery system—either up or down, depending on the design and function of the transformer (see sidebar).[28] Figure 2 depicts a large power transformer.

Figure 2: Large Power Transformers



Source: Department of Energy (DOE). | GAO-18-67

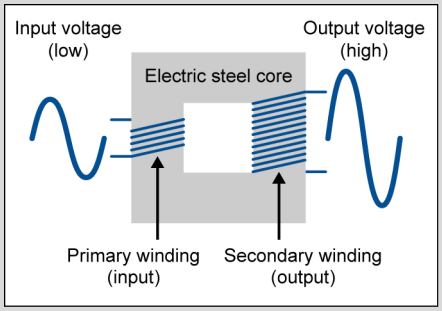
Transformers can be temporarily disabled or damaged by electromagnetic events, which in turn can lead to an interruption in electricity service to customers. To protect them from damage during an electromagnetic event or other circumstances, transformers could be

[28]Power transformers consist of two main active internal parts—the core, which is made of electrical steel, and windings, which are coils of wire wound around the core to change voltage and current levels.

Transformers

Transformers play a critical role in the electric power system because they enable electricity to be transmitted over very long distances by increasing or decreasing voltage—the force that makes electricity flow through a wire—as necessary. They come in a wide variety of sizes and configurations and serve highly specific functions within the electricity delivery system. For example, generator step-up transformers—see illustration below—are used to convert low-voltage power produced by power plants into high voltages needed to transmit power over long-distance transmission systems. One common type of transformer is the single phase, which contains two windings–coils of wire wound around the core (made of highly permeable electric steel) to change voltage levels. According to the Department of Energy (DOE), high-voltage (230 kilovolts or greater) transformers can be especially vulnerable to geomagnetic disturbance (GMD), depending on condition, design, and age, among other factors. DOE has reported that the U.S. population of large power transformers is aging: in 2011, the average age of installed U.S. large power transformers was about 38 to 40 years, with 70 percent being 25 years or older.

Single-Phase Step-Up Transformer



Source: DOE; GAO (illustration). | GAO-18-67

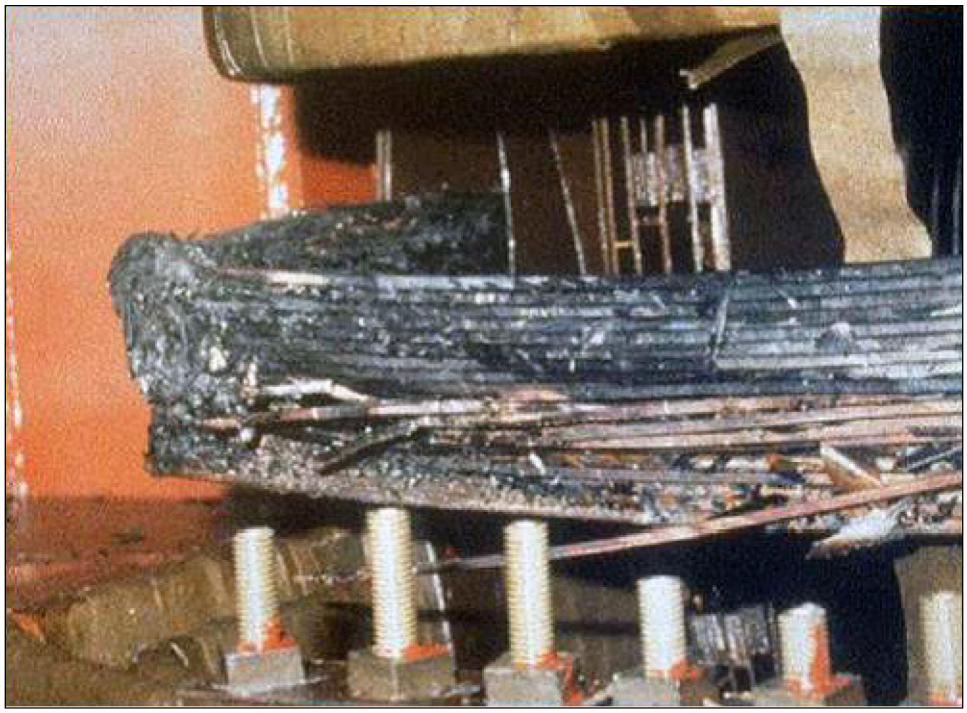
paired with equipment—for example, a protective relay—that is designed to take them out of service temporarily when the effects of an electromagnetic event reach the grid. If transformers were temporarily taken out of service for preventative purposes, it could lead to an interruption of electricity service to consumers. However, if transformers—especially those more vulnerable due to age, condition, or design—are not taken out of service during an electromagnetic event they are at risk of being permanently damaged when additional electrical current flows into them, causing excessive localized heating and damage to internal components. (See fig. 3 for an example of transformer windings that were damaged from localized heating associated with a GMD event.) Transformers that become permanently damaged during an electromagnetic event can also contribute to interruptions in service. According to DOE, replacing a damaged transformer can be challenging because they are custom-designed and interchangeability and availability of spares is limited. If a usable spare transformer is not immediately available, obtaining a replacement transformer is often a long and costly process, usually involving long delivery lead times due to their size and weight, limited inventory, a complex procurement and manufacturing process, and other factors.[29] According to DOE, in 2014 the average lead time to obtain a large power transformer was between 5 and 16 months, but could take more than 20 months in the event of supply disruptions or delays in procuring raw materials or key parts; larger, more sophisticated models are generally manufactured abroad.[30] According to a transformer manufacturer, depending on the function of the transformer, the voltage rating, and the model, in 2017 the approximate price of a large power

[29]Shortages in transformer inventory and manufacturing materials can result from, among other things, increased global demand in grid-developing countries, limited domestic manufacturing capabilities, and limited interchangeability due to differing specifications.

[30]U.S. Department of Energy, Infrastructure Security and Energy Restoration, Office of Electricity Delivery and Energy Reliability, *Large Power Transformers and the U.S. Electric Grid*, April 2014 Update (Washington, D.C.: April 2014). According to DOE, the United States has limited production capability to manufacture large power transformers. DOE estimated that in 2010, 15 percent of the nation's power transformers (with a capacity rating of greater than or equal to 60 megavolt-amperes—MVA) were produced domestically; domestic production of extra high-voltage power transformers (with a capacity rating greater than or equal to 345 MVA) was estimated to be less than 15 percent. However, DOE also reported that since 2010 four new or expanded facilities had begun producing large power transformers. According to DOE, from 2011 to 2013, seven countries accounted for 88 percent of imported large power transformers: South Korea (28 percent), Austria (15 percent), Mexico (13 percent), Canada (12 percent), Netherlands (11 percent), Brazil (5 percent), and Germany (3 percent).

transformer, weighing from 170 to 410 tons, ranged from approximately $2 to $7.5 million in the United States.[31]

Figure 3: Damaged Transformer Winding Attributed to an Electromagnetic Event



Source: Public Service Electric and Gas Company (PSE&G). | GAO-18-67

Note: The transformer winding in this photograph was damaged from localized heating attributed to extreme geomagnetic disturbance (GMD) and illustrate the possible impact GMD can have on a transformer. Although this transformer did not fail and there was no resulting power interruption, it was replaced following the GMD event. According to officials with the North American Electric Reliability Corporation (NERC), the transformer may have been vulnerable to GMD effects due to its design. The degree to which a transformer is damaged by GMD depends on many factors, including the design of the transformer and the intensity of the GMD, and therefore the impact GMD has on transformers can vary.

- **Distribution system.** The final stage in the electric power system is the distribution system, which carries electricity out of the transmission system to industrial, commercial, residential, and other

[31]Transformer labor costs and material prices vary by manufacturer, market condition, and by location of the manufacturing facility. These cost estimates do not include transportation, installation and other associated expenses, which in 2014 DOE estimated generally added 25 to 30 percent to the total cost of a transformer.

consumers.[32] The distribution system includes equipment that can be damaged during electromagnetic events, but the extent of the risk is limited because distribution lines are generally too short and of too low voltage to pose a risk to distribution equipment.

- **System operations:** Operation of the electricity system is managed by entities such as a local utility, which this report collectively refers to as system operators. Because electric energy is not typically stored in large quantities, system operators must constantly balance the generation and consumption of electricity to maintain reliability. To do this, system operators utilize a system of sensors and controls to monitor power consumption and generation from a centralized location. Operators use computerized systems to send signals to power plants and other grid components to adjust their output to match changes in consumption. Electromagnetic events can interrupt or damage some of the equipment system operators use, which can cause a disturbance in control systems (for example, such events can cause relays to unintentionally operate, which can disable system protection equipment). Because the electric power system increasingly operates at or near reliability limits during peak demand periods, a relatively modest disturbance to the system can potentially pose a risk to system reliability.

In the United States, the electrical infrastructure is primarily operated by private industry, which owns approximately 85 percent of the nation's critical electrical infrastructure. In contrast, Canada's electrical infrastructure is primarily organized along provincial lines with large, government-owned, integrated public utilities playing a leading role in the generation, transmission, and distribution of electricity.

Electromagnetic Events – GMD and HEMP

Based on our review of relevant studies and interviews with cognizant government and industry officials, there are differing opinions on the potential impact electromagnetic events could have on the electric grid and the risk of long-term, widespread damage. However, they generally agree that more study on the effects of electromagnetic events is needed. The following section describes (1) the nature and potential impact of

[32]According to the Energy Information Administration (1) the industrial sector encompasses manufacturing, agriculture, mining, and construction; (2) the commercial sector consists of businesses, institutions, and organizations that provide services such as schools, stores, office buildings, and sports arenas; (3) the residential sector includes households and excludes transportation; and (4) other includes electricity users not captured in the other three categories, including transportation.

GMD, U.S. efforts to monitor it, and the frequency of past occurrences; and (2) the nature and potential impact of HEMP events.

GMD – Description, Potential Impact, Monitoring, and Historical Occurrences

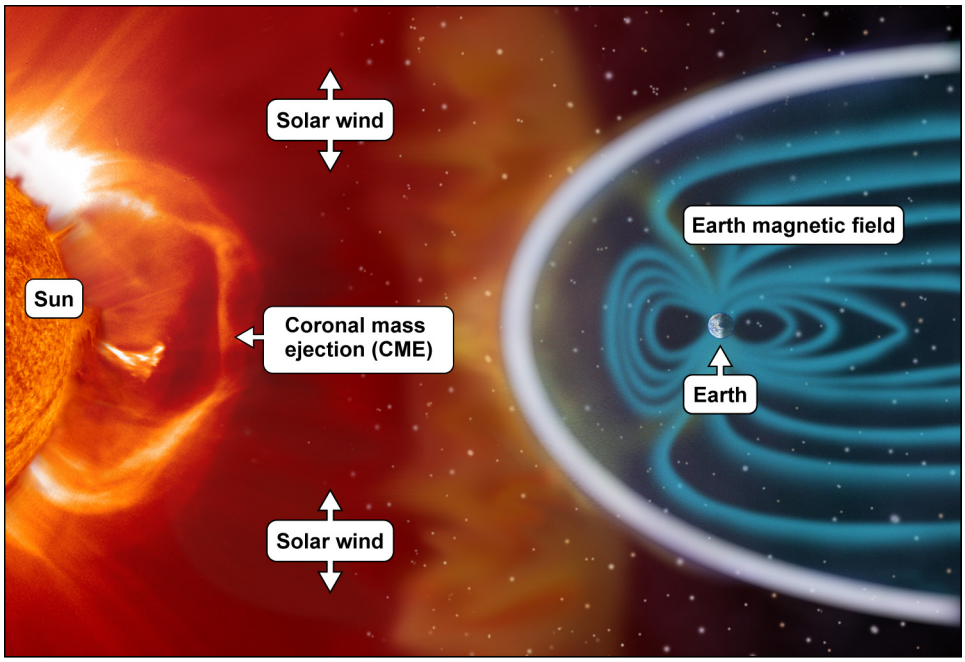
Naturally occurring solar weather events can create electromagnetic impacts—or GMD—of sufficient intensity that can adversely affect the electric power system. Solar weather events include, for example, large coronal mass ejections (CME), which are energetic eruptions in the sun's atmosphere that can cause the release of a large mass of charged particles from the sun into space.[33] When a large CME travels from the Sun to the Earth it can interact with and create disturbances in the Earth's geomagnetic field, referred to as a geomagnetic storm; the resulting impact on Earth is commonly referred to as a geomagnetic disturbance, or GMD.[34] Figure 4 illustrates how solar weather can create a GMD. Strong GMDs can create large geomagnetically induced current (GIC) on the grid. The degree to which GMD and accompanying GIC affect the electric power system depends on several factors, including the magnitude of the GMD, design and geomagnetic latitude of the power system, and geology of the local area, among other things.[35] According to NERC, the most likely consequence of a strong GMD and the accompanying GIC is the loss of voltage stability, although GMD can also damage components of the system, including high-voltage transformers.

[33]Coronal mass ejections (CME) are energetic eruptions of charged solar particles—magnetized plasmas—that are ejected from the sun's corona. Space weather, originating from solar activity, affects the Earth's upper atmosphere, potentially causing disruption of the electric power system. While space weather affects space assets and communications systems, this report addresses how certain aspects of space weather can affect electric power transmission systems.

[34]CMEs generally take 2 to 3 days to reach Earth although the fastest transit time on record is 14.6 hours.

[35]Geomagnetic latitude is a system of latitude determined like geographical latitude but along the geomagnetic meridians from the geomagnetic equator. The potential impact of GMD events is generally more acute for electric power systems in more northern geomagnetic latitudes. Additional factors that can affect the electric grid include the directional orientation, resistance, and length of transmission lines; orientation of the GMD; electrical conductivity of the Earth in the local area; proximity of the system to an ocean or large salt water bodies; and design of the power system equipment.

Figure 4: Coronal Mass Ejection (CME)



Source: National Aeronautics and Space Administration (illustration). | GAO-18-67

Note: Figure is not to scale.

In the United States, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service manages the Space Weather Prediction Center (SWPC), which is responsible for monitoring and providing services on space weather, including geomagnetic storms.[36] SWPC uses a variety of ground and space-based sensors, as well as imaging systems, to monitor conditions on the Sun and to observe and forecast geomagnetic activity around the world. SWPC uses this information to issue Watches, Warnings, and Alerts for geomagnetic storms through e-mail and website postings to those who are impacted by space weather, such as owners and operators of the electric grid, spacecraft operations, users of radio signals, and others. In addition, SWPC provides immediate telephone notification and confirmation of

[36]The National Oceanic and Atmospheric Administration (NOAA) is part of the U.S. Department of Commerce. The Space Weather Prediction Center (SWPC) provides monitoring and forecasting of solar and geophysical events that affect satellites, power grids, communications, navigation, and many other technological systems. In Canada, responsibility for monitoring space weather rests with Natural Resources Canada's Canadian Space Weather Forecast Service.

imminent and ongoing geomagnetic storms to all NERC reliability coordinators through a NERC hotline.[37]

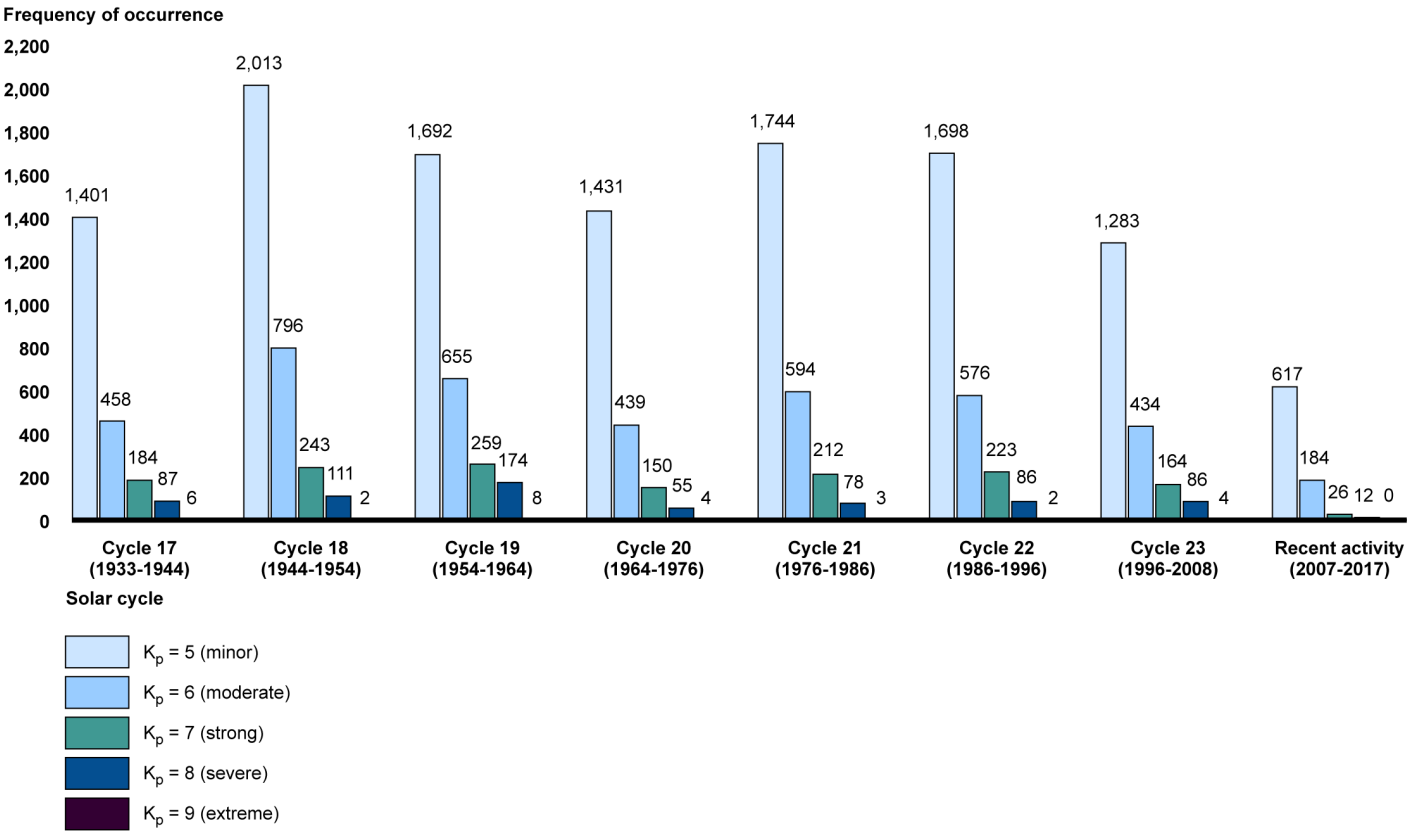
To communicate the magnitude of geomagnetic storms (disturbances in Earth's magnetic field) and to determine whether geomagnetic alerts and warnings should be issued, SWPC relies on a real-time estimate of the Planetary K-index (Kp-index), which ranges from Kp = 0, or quiet, to Kp = 9, or extreme storm intensity.[38] (See appendix II for more information on SWPC's notification system as well as their estimates of overall impact of geomagnetic storms to the electric power system, by storm level.) Figure 5 shows the range of planetary geomagnetic activity, by solar cycle and Kp level, from 1933 through 2017.[39] As shown in this figure, recent activity—between 2007 and 2017, approximately equivalent to the average length of a solar cycle—exhibited the fewest occurrences of GMD events (minor, moderate, strong, severe, and extreme) of any solar cycle in nearly a century.

[37]NERC reliability coordinators are to redistribute voice notification information to all applicable electricity suppliers (generation and transmission). SWPC provides similar phone notification to the NERC bulk power system awareness group—which monitors ongoing storms that may impact the bulk power system—when severe or extreme geomagnetic storm conditions are forecast. According to NOAA, similar notification processes are in place to notify the Federal Emergency Management Agency of expected or ongoing geomagnetic storming.

[38]According to SWPC, their real-time Estimated Planetary K-index (K_p-index) data show the maximum fluctuations in the magnetic field observed from a network of selected magnetometers—instruments that measure relative change of a magnetic field at a particular location—relative to a quiet day.

[39]Solar activity—including CME—is commonly tracked across solar cycles. Solar cycles reflect changes in the Sun's activity levels (e.g., levels of solar wind and CMEs) and appearance (primarily changes in the number of sunspots—dark, low temperature regions on the surface of the Sun caused by magnetic activity) about every 11 years.

Figure 5: Planetary Geomagnetic Disturbance (GMD) Intensity by Solar Cycle, 1933 - 2017



Source: GAO analysis of GFZ German Centre for Geosciences data. | GAO-18-67

Note: The Planetary K-index (denoted Kp-index) records GMD across 13 global magnetic observatories. Readings are averaged and reported over 3-hour intervals. Historical Kp-index records are grouped according to solar cycle, which are periods of solar activity—including coronal mass ejections—that reflect changes in the Sun's activity levels (e.g., levels of solar wind and coronal mass ejections) and appearance (primarily changes in the number of sunspots—dark, low temperature regions on the surface of the Sun caused by magnetic activity) about every 11 years.

The only extreme GMD event that has resulted in significant loss of power to the North America grid occurred in 1989, when a Kp-9 solar storm caused wide-scale impacts on the Hydro-Quebec power system in

Canada—the regional electric grid witnessed a severe disruption which left 6 million customers without power for up to 9 hours.[40]

HEMP – Description and Potential Impact

According to the 2008 EMP Commission, a nuclear EMP is the burst of electromagnetic radiation that results from the detonation of a nuclear device, which can disrupt or destroy electronic equipment.[41] The threat primarily focused on by the 2004 and 2008 EMP Commissions, and specifically addressed in this report, is the high-altitude EMP (HEMP). A HEMP event is caused by the detonation of a nuclear device above the atmosphere, from about 40 to 400 kilometers (approximately 25 to 250 miles) above the Earth's surface.[42] A HEMP attack does not cause direct physical impacts at the Earth's surface, such as injury or damage directly from heat, blast, or ionizing radiation, but instead creates an intense electromagnetic pulse.[43] The components of HEMP—commonly identified as E1, E2, and E3—can disrupt or damage critical electrical infrastructure, such as computers, electronics, and transformers. EMP can also be produced using nonnuclear weapons, but these generally have a short range and are not a focus of this report.

Electricity System Regulation and Oversight

Responsibility for regulating electricity is divided between states and the federal government. Most electricity consumers are served by retail markets that are regulated by the states, generally through state public utility commissions or equivalent organizations. As the primary regulator of retail markets, state commissions approve many aspects of utility operations, such as the siting and construction of new power plants, as well as approving the prices consumers pay and how those prices are

[40]During the event, NOAA issued an Alert based on observations recorded in Boulder, Colorado, for a storm of K_p of greater-than-or-equal-to 6, which at the time was the highest tier of NOAA GMD alert. In the United States, while there has been damage to transformers attributed to GMD, there have been no reported electrical service interruptions resulting from GMD. North America has experienced three notable geomagnetic storms, occurring in 1940, 1958, and 1989.

[41]Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack—Critical national Infrastructures* (April 2008).

[42]The higher the altitude or the larger the yield of the nuclear device, the greater is the radius of EMP effect.

[43]Ionizing radiation is any type of particle or electromagnetic wave that carries enough energy to ionize—or remove electrons from—an atom.

set.[44] Prior to being sold to these retail consumers, such as households and businesses, electricity is bought, sold, and traded in wholesale electricity markets by companies that own power plants, as well as utilities and other companies.

Wholesale interstate electricity markets are regulated by FERC. Historically, FERC-approved wholesale electricity rates based on utilities' costs of production plus a rate-of-return that it determined to be reasonable.[45] Beginning in the late 1990s, FERC took a series of significant steps to restructure the wholesale electricity markets to increase the role of competition—market forces of supply and demand—in setting wholesale electricity prices, a process referred to as electricity restructuring. Subsequently, FERC has provided authority for many entities—for example, independent owners of power plants—to sell electricity in wholesale markets at prices determined by supply and demand. These entities can now compete with existing utilities and one another to sell electricity in wholesale markets, but have no assurance that their costs will be recovered. While electricity restructuring has introduced a measure of market-based pricing to the generation of electricity, transmission (and distribution, regulated by states) are still subject to regulation on a cost-recovery basis. FERC has jurisdiction over transmission rates on the federal level, and state regulators have jurisdiction over the charges that utilities incorporate in customers' rates in order to recover their transmission costs.

As part of the restructuring process, FERC also encouraged the voluntary creation of new entities called Regional Transmission Organizations (RTO) and Independent System Operators (ISO) to manage regional networks of electric transmission lines as grid operators—functions that,

[44]The price consumers pay for electricity is often a combination of rates determined by regulators and prices determined by markets. Rates are generally approved by regulators and set to recover the cost of providing a service plus a rate-of-return. For the purposes of this report, we generally use "prices" to refer to both rates and prices, except when specifically discussing FERC's oversight authority.

[45]The Federal Power Act does not define "reasonable," but FERC and the Supreme Court have interpreted it to mean that rates must fall within "a zone of reasonableness" that balances the interests of electricity suppliers and customers. See 16 U.S.C. §§ 824d–824e; see also Fed. Power Comm'n v. Hope Natural Gas Co., 320 U.S. 591 (1944); Fed. Power Comm'n v. Conway Corp., 426 U.S. 271 (1976).

in these areas, had traditionally been carried out by local utilities.[46] These RTOs, in many cases, established and manage wholesale electricity markets for electricity buyers and sellers to participate in. As grid operators, RTOs are also responsible for managing transmission in their regions, which includes establishing and implementing rules and pricing related to transmission, among other things. As we reported in 2003, 24 states also introduced retail competition to electricity markets they regulate and allow former utilities and new companies to compete to serve customers; since then, the states where retail competition is occurring have changed.[47] In states with retail competition, in general, electricity rates for generators other than the original utility are not structured to guarantee recovery of generation-related costs.

In addition to its role in regulating aspects of the electricity market, FERC is also responsible for reviewing and approving standards to ensure the reliability of the bulk power system. FERC designated NERC to develop and enforce these reliability standards, subject to FERC review and approval. These standards outline general requirements for planning and operating the bulk power system to ensure reliability. (See appendix III for information on NERC reliability standards requiring electricity suppliers to address the potential impact of GMD on the reliable operation of the U.S. electric grid.) NERC and its Regional Entities, along with FERC, can all independently enforce reliability standards.[48] Within the boundary of each

[46]Prior to the creation of RTOs, FERC approved the creation of entities called Independent System Operators (ISO). ISOs perform many similar functions to RTOs and for the purposes of this report, we refer to all ISOs and RTOs as "RTOs". However, many RTOs that originally took on names that include "ISO" have maintained them.

[47]GAO, *Lessons Learned from Electricity Restructuring: Transition to Competitive Markets Underway, but Full Benefits Will Take Time and Effort to Achieve*, GAO-03-271 (Washington, D.C.: Dec. 17, 2002). According to a report published by Christensen Associations Energy Consulting LLC, as of 2016, eight states have suspended or rescinded retail choice for some or all customers. See Christensen Associates Energy Consulting LLC, *Retail Choice in Electricity: What Have We Learned in 20 Years?* (Madison, WI: Electric Markets Research Foundation, 2016). Some states allow non-utility providers to compete with the regulated utilities in supplying electric power to retail electricity customers. More recently, the American Coalition of Competitive Energy Suppliers, a trade association of competitive energy suppliers, identified 18 states that have some aspect of their retail electricity markets open for competitive suppliers. According to this entity, competition in these states may be limited to some customers, such as larger customers (for example, industrial companies), that are allowed to purchase electricity from competitive suppliers.

[48]NERC carries out its responsibilities through 8 Regional Entities covering the continental United States, Canada, and the northern portion of Baja Mexico.

regional entity, there are one or more NERC-certified reliability coordinators. Reliability coordinators are charged with the task of continuously assessing the reliability of the transmission system. The coordinator has the authority to direct stakeholders—transmission operators, generators, and others involved with the electric grid's operations—to take action to preserve the reliability and integrity of the bulk power system.

U. S. and Canadian Electricity Suppliers We Contacted Have Identified Information about GMD Effects, but Have Less Information about HEMP Effects

Electricity Suppliers Have General Information about GMD Effects and Some Selected Suppliers Have Taken Steps to Evaluate Their Networks

U.S. and Canadian government and industry organizations have studied and publicly reported on potential GMD effects on the electric grid. These studies have covered the general threats to the nation's electric grid from GMD but do not cover the unique aspects of individual suppliers' generation and transmission networks that could potentially make them more or less vulnerable to GMD events.[49] In addition, these studies typically identified areas in which more research is needed regarding the GMD threat and potential mitigation measures that would inform suppliers' own assessments of the potential impact of GMD events on their unique networks.

These select studies we identified included those performed by NERC, DOE, EPRI, and other private industry groups and generally examined the areas of vulnerability for the grid with respect to GMD events, potential impact on the grid from these events, possible mitigation

[49]The aspects of a supplier's generation or transmission system that may affect its level of vulnerability to GMD include the types of transformers used, length, and voltage levels of transmission lines, etc.

measures, and areas needing further research.[50] While noting the need for further research, some of these studies vary with regard to their assessment of the likelihood of long-term, widespread damage to the grid from these events. The following is a summary of some of these selected studies performed since 2010 and grouped by the entities responsible for performing them:

- **NERC.** In June 2010, NERC issued a report, based on a joint effort with DOE, which included a plan to form a task force of government and industry efforts to examine GMD.[51] This resulted in the formation of the NERC GMD Task Force consisting of government and industry officials to examine the GMD threat to the nation's power grid. The task force's work in evaluating the potential impact of GMD events resulted in NERC's subsequent February 2012 report which outlined its plans for working with industry on new reliability standards for protecting the grid against GMD events.[52] This report concluded, among other things, that the failure of a large number of transformers during a severe GMD event was unlikely, although certain older transformers, along with generator step-up transformers, could be particularly susceptible. As a result of this work, and as directed by FERC, NERC developed the EOP-010-1 and TPL-007-1 GMD reliability standards.[53] Also, as a result of this work, NERC issued a GMD Planning Guide for electricity suppliers, which assists the suppliers in carrying out studies of their individual vulnerabilities to a GMD event.

[50]We identified these studies for review based on feedback from government and industry officials regarding relevant studies on GMD and HEMP published since 2010. We also identified some of these studies through references in other reports and documentation. These studies do not represent an exhaustive list of all the research that has been performed on GMD and HEMP events and their potential impact on the U.S. and Canadian electric grid.

[51]North American Electric Reliability Corporation and U.S. Department of Energy, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System* (Washington, D.C.: June 2010).

[52]North American Electric Reliability Corporation, *2012 Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System* (Atlanta, GA.: February 2012).

[53]Two of the three requirements under the EOP-010-1 standard went into effect on April 1, 2015, with the remaining requirement on reliability coordinators' dissemination of space weather information going into effect on April 1, 2017 (after retirement of a prior reliability standard dealing with that topic). The TPL-007-1 standard will go into effect in stages from 2017 to 2022.

- **DOE/National Labs.** Since 2010, DOE has been engaged in a number of efforts regarding GMD. For example, in 2011, DOE enlisted the Pacific Northwest National Laboratory (PNNL) to study the potential effect of GMD on long, high-voltage transmission lines and associated mitigation measures that could potentially be employed. Also, in April 2014, DOE reported on the results of its study of the vulnerabilities of large power transformers to GMD and other threats and the challenges facing the replacement of these transformers in the wake of such events.
- **EPRI.** In conducting research for its private industry membership, the Electric Power Research Institute engaged in a number of studies from October 2010 to March 2014. These efforts began with an effort to examine potential impacts from GMD through an assessment of various risk factors. EPRI's later efforts involved the development of approaches for modeling the impacts from GMD on the grid to allow suppliers to better protect their networks from these events.
- **Other private industry.** Private entities conducted studies in January 2010 and November 2011 for Oak Ridge National Laboratory and DHS, respectively, that examined prior GMD events and assessed the potential future impact of these events on the grid along with areas of vulnerability and potential mitigation measures. Other private studies included those examining which regions of North America are most vulnerable to GMD events in addition to the potential impact on the insurance industry and society in general from these events.

See appendix IV for additional details on these and other select studies performed by government and industry regarding protection of the grid from GMD events.[54]

These past research efforts have generally identified the degree to which the electric power system is affected by a GMD event. The level of impact from these events can depend on various factors including, among other things, magnitude of the event, design and geomagnetic latitude of the power system, and geology of the local area. Further, these studies identified that GMD can have a broad range of impacts when it is introduced to a power system, ranging from minor events such as radio

[54]As part of an ongoing effort in response to provisions of the National Defense Authorization Act for Fiscal Year 2017, DHS officials said they are examining the risks and consequences of both GMD and EMP events in order to develop a strategy for protecting and preparing U.S. critical infrastructure against these events. See Pub. L. No. 114-328, § 1913, 130 Stat. 2000, 2684-87 (2016). DHS officials said that, as of September 2017, they expect to complete this strategy and present it to Congress by December 23, 2017.

interference and control malfunctions to wide-scale disruptions. NERC has identified two predominant risks to the system: (1) potential voltage instability in the transmission system caused by insufficient reactive power support and (2) possible damage to system components.

The first risk and, according to NERC, the most likely consequence of a strong GMD event and accompanying GIC, is the insufficient reactive power support, which can lead to voltage instability and power system collapse. Reactive power support is necessary to stabilize the transfer of electricity through the electric power system, from generation to consumption.[55] With regard to the second risk, several components of the electric system are susceptible to damage from GMD and GIC, but government and industry officials agree that the vulnerable components with the greatest potential consequence in the event of loss are transformers, which typically exist at substations throughout suppliers' transmission networks.[56] High-voltage transmission lines act as "antennae," allowing GIC to enter the electric power system, disrupting normal operations and, in some cases, damaging equipment. Transformers, in turn, run the risk of overheating during a GMD event.[57] According to NERC, restoration times for these two risk scenarios are significantly different. Restoration time from voltage collapse—i.e., system blackout—would be a matter of hours to days, while the replacement of transformers, as previously discussed, could take months or potentially years. Therefore, the failure of large numbers of transformers, while less likely, would have considerable impacts on portions of the electric power system.

[55]In this risk scenario, as transformers absorb high levels of reactive power, protection and control systems may disconnect supporting reactive equipment due to the harmonic distortion of waveforms. Reactive power is usually measured in terms of volt-ampere-reactive (VAR).

[56]Capacitor banks—devices that maintain voltage in power lines and improve system efficiency—are also vulnerable to GMD and geomagnetically induced current (GIC). Also vulnerable are reactive power devices critical to maintaining system stability.

[57]According to research officials, the design of a transformer, along with the magnitude and duration of GIC, are key factors in the amount of heating that develops in the structural parts of a transformer during a GMD event. The extent to which this heating might damage the condition, performance, and insulation life of a transformer is also a function of the transformer's design, as well as operational demand during GMD. In high-voltage transformers, GIC can cause, among other things, unwanted heating of transformer components which, if sufficiently high and sustained for long enough, can reduce the life span of the transformer. The transformer's lifespan can also be reduced when GIC causes insulation in the transformer to break down.

While general information on the potential impact of GMD events on the electric grid is available from the aforementioned government and industry reports, individual suppliers must assess the potential impact on their own, unique networks. For example, of the 13 selected suppliers we spoke with,[58] 11 reported performing analyses to evaluate the potential impact of GMD on their specific generation systems or transmission networks.[59] The 11 suppliers that had performed these analyses did so in advance of all suppliers being required to analyze the vulnerabilities of their networks as part of their compliance with NERC's second-stage GMD reliability standard TPL-007-1.[60] The nature of the analyses the 11 suppliers engaged in required the use of modeling software to determine the specific vulnerabilities of their networks which further allowed them to design their own mitigation measures, if warranted, to address any vulnerabilities identified and prevent equipment damage or power outages. Suppliers we contacted noted that potential GMD mitigation measures included installation of specific equipment to assist with network stability and voltage regulation.

As noted previously, past research efforts have indicated that GMD events can have a variety of impacts ranging from minor malfunctions to wide-scale disruptions. For example, 3 of the 11 suppliers we contacted that had performed an analysis of their networks' potential vulnerabilities had also reported prior impacts on their networks from a GMD event. Of these three suppliers, two (including Hydro-Quebec) reported major power interruption or equipment damage from the event.[61] The remaining supplier reported a brief power outage on one transmission line during the same 1989 GMD event that caused a major power outage for Hydro-Quebec; however, this power outage did not result in any significant loss of electricity to the supplier's customers. Outside of the 1989 event, this

[58]These results reflect only those suppliers we contacted during our review and are not generalizable to all electricity suppliers.

[59]Of the two suppliers who did not report performing analyses to determine the potential impact of GMD on their networks, one supplier reported it was relying on the NERC region to perform this assessment which had yet to be completed and another supplier had yet to complete their assessment.

[60]TPL-007-1 is scheduled to be implemented in stages from 2017 to 2022.

[61]The March 1989 GMD event led to the collapse of Hydro-Quebec's system, leaving 6 million people without power for 9 hours. Another supplier, which was a network operator, reported damage to a generator step-up transformer during the same event.

same supplier reported minor power fluctuations and voltage drops from smaller GMD events.

Most suppliers we contacted that had assessed their networks' vulnerabilities to GMD expressed confidence in their ability to avoid major damage or power interruptions from future GMD events. Specifically, 6 of the 11 selected suppliers that had performed analyses of their networks' vulnerabilities to GMD reported that, going forward, they expected that any effects from a future GMD event on their networks would likely be minimal (i.e., no significant damage or power interruption).[62] Six suppliers also thought that procedures and technology currently in place afforded better protection from these events than in the past.[63] For example, one northern U.S. supplier we contacted had, after acquiring new GMD analysis software, studied its system and concluded that it could easily withstand the GMD "benchmark event" established by NERC in its TPL-007-1 reliability standard and that its current technology and procedures were adequate to deal with the threat.[64] Also, another supplier studied its system and is using the results to inform future decisions on transformer purchases to obtain technology that is more resistant to GMD.

Government and Industry Are Taking Steps to Better Understand Effects of HEMP on the Grid

According to U.S. government and industry officials we spoke with, completed research and available information on the vulnerability of the grid to HEMP, along with its potential effects, is less extensive and lags behind industry understanding of GMD. These officials noted that the understanding of HEMP and how it can affect the electricity system is general in nature and not specific to the commercial electric grid. Specifically, the Department of Defense has developed information

[62]Of the remaining five suppliers, four did not characterize what their studies revealed with respect to the potential severity of the impact and one supplier had not completed its study.

[63]Of the remaining five suppliers, four did not express a view as to whether they thought present day procedures and technology provided better protection from GMD events. One supplier was uncertain as to whether this was the case.

[64]The "benchmark event" referred to by NERC in its TPL-007-1 Reliability Standard refers to a hypothetical GMD event against which the performance of a supplier's network is to be evaluated. At the direction of FERC, as of October 2017, NERC is performing research to revise this benchmark due to FERC's concerns over the efficacy of the benchmark in the current standard.

regarding the potential effects of HEMP on military assets and facilities.[65] According to DOE, the most detailed HEMP testing has been performed on military communication and weapons systems, not on the commercial electric grid.[66] In a number of studies since 2010, both government and private industry have examined the HEMP threat to the grid while also noting the need for further research to fully understand the specific threats to components of the grid that would allow suppliers to protect against these events.[67] While noting the need for further research, some of these studies vary with regard to their assessment of the likelihood of long-term, widespread damage to the grid from HEMP. See appendix IV for additional details on government and industry studies on the threat to the grid from EMP events including HEMP.

The government and private industry studies generally note the threat to the grid presented by the E1, E2, and E3 pulse components of HEMP as follows:

- **E1.** The E1 pulse is capable of destroying microelectronics (such as computers), communication and control systems, and other electronic equipment that can disrupt the grid and other critical sectors. According to DOE, E1 can also generate very large and damaging voltage surges in power lines. Figure 6 depicts the potential impact from an E1 pulse, and shows the higher the altitude the greater the potential radius of the impact from an E1 pulse.[68]

[65]Several U.S. high-altitude nuclear tests in the 1950s and 1960s explored impacts to the military and communications. The most famous of these was the "Starfish Prime" test in the South Pacific that disrupted some long-distance communications, damaged several satellites, and impacted streetlights and burglar alarms in Hawaii.

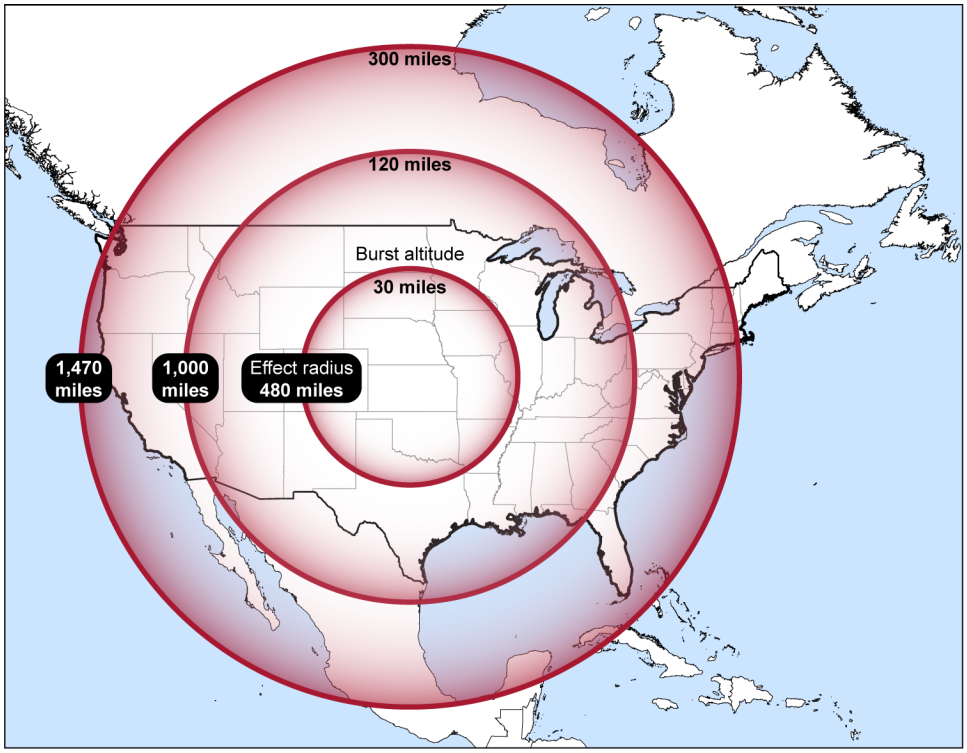
[66]DOE further stated that the electric industry lacks experience on exactly how EMPs affect the high-voltage, heavy-duty equipment in substations and generation plants that are essential to grid operation. DOE added that DOD has the most experience and best database on EMP effects, but their system focus has been on command, control, communication, and computer systems which are comparable to the electric power grid monitoring and control systems, but different from the high voltage systems organic to generation facilities and substations.

[67]We did not review any classified research or information on HEMP during the course of our review.

[68]Prior nuclear testing by both the United States and former Soviet Union has involved the detonation of nuclear devices at various altitudes which can affect the radius of the area impacted as shown in figure 6. For example, the U.S. Starfish Prime test in 1962 was detonated at an altitude of 250 miles and another test conducted by the Soviet Union in the same year was detonated at an altitude of 180 miles. The potential radius may also vary based on the yield of the nuclear device.

- **E2.** The E2 pulse, similar to lightning, has an ability to impair or destroy control features that are not protected from lightning. However, the grid typically has protections in place to address the lightning threat to major components.
- **E3.** The E3 pulse is similar to GMD and also creates similar disruptive currents in transmission lines which can cause grid instability and heating that damages transformers.

Figure 6: Estimated Impact Area of High-Altitude Electromagnetic Pulse (HEMP), by Height of Burst



Source: Gary Smith, "Electromagnetic Pulse Threats," Testimony before the House Committee on National Security (July 16, 1997); MapInfo (map). | GAO-18-67

Few electricity suppliers we contacted reported taking steps to examine how HEMP could impact their systems.[69] Specifically, 3 of 11 selected suppliers who responded to our inquiry on this topic reported performing a study of the potential impact of HEMP events on their network

[69]These results reflect only those suppliers we contacted during our review and are not generalizable to all electricity suppliers.

infrastructure.[70] Two of these three suppliers reported studying the potential impact of HEMP events on their network in conjunction with these suppliers' design of hardened control centers expected to be resistant to HEMP and other hazards. One of the two suppliers that designed control centers resistant to HEMP did so due to a concern over being able to maintain power to certain critical customers for which the loss of power would have national security implications. The other supplier that had designed an HEMP-resistant control center did so as part of an "all hazards" approach to protecting its transmission infrastructure. The third supplier that had studied the potential impact of HEMP on its system did so as part of a combined study, required by its state legislature, on the threats posed by both GMD and HEMP. Specifically, this supplier examined the potential impact of the HEMP E3 pulse on its system which is similar to GMD, and, therefore, is expected to involve similar mitigation measures.[71] The supplier stated that the lack of available modeling and analysis tools prevents them from fully understanding the potential impact of all components of HEMP—particularly the E1 and E2 pulses.

Four of the 8 suppliers we contacted who stated they had not studied the potential impact of HEMP on their networks indicated a desire to see EPRI complete its ongoing EMP research before engaging in studies of their own networks. Further, all eight suppliers who stated they had not performed any studies of the potential impact of HEMP on their networks also noted a lack of key information on the nature and risk of the HEMP threat that would allow them to complete studies of their networks and develop corresponding mitigation measures. Six of the suppliers cited the classified nature of much of the available information maintained by the federal government on the EMP threat—particularly HEMP—as a contributing factor to the industry's lack of needed information on the threat. In addition, according to NERC officials, while they have developed reliability standards directing suppliers to study the vulnerabilities of their networks to GMD and establish procedures for

[70]An additional 2 suppliers (among our total of 13 suppliers contacted) did not respond to our follow-up inquiries regarding whether they had studied the potential impact of HEMP on their networks.

[71]The E3 pulse of HEMP and GMD are similar in that they both enter electricity transmission systems by driving electrical currents in the earth which result in the GIC that impacts these systems. However, they differ in that the GMD waveform is of a lower amplitude than E3 HEMP and occurs over a longer period of time—a matter of roughly a day for GMD compared to seconds or minutes for E3 HEMP.

dealing with those events, it has yet to produce similar standards for EMP or HEMP due to the lack of information available to industry on the EMP threat and how it may impact the grid.

According to DOE, more research is needed to fully investigate and evaluate how an electric utility could protect itself from, or mitigate the effects of, HEMP on its systems. DOE also noted that government and industry have ongoing research efforts to better understand these potential effects and develop possible mitigation measures. For example, DOE has three ongoing research efforts related to HEMP. First, DOE is collaborating with DHS to advance the understanding of HEMP effects on the grid through research at the Los Alamos National Laboratory.[72] Second, DOE has funded efforts underway at the Idaho National Laboratory focused on developing potential HEMP strategies, protections, and mitigations for the electric grid—including hardening of infrastructure, blocking of currents, developing a strategy for stocking and prepositioning of spare parts, as well as developing operational and emergency planning tools. Finally, DOE has enlisted the Oak Ridge National Laboratory in analyzing the vulnerability of the grid to a HEMP event, along with the potential damage from such an event, and how it would impact on the reliability and delivery of electric power. The analysis will examine resilience options such as hardening some facilities, stockpiling some parts, and contingency planning. In addition to these research projects, DOE officials told us both Los Alamos National Laboratory and Lawrence Livermore National Laboratory are working to produce unclassified information on the characteristics of the electromagnetic signals associated with HEMP that could be shared with electricity suppliers to better inform their planning efforts.

In addition to its ongoing research efforts, DOE and industry have taken steps to enhance understanding of HEMP issues. In particular, DOE and industry issued the *Joint Electromagnetic Pulse Resilience Strategy* (Joint Strategy) in July 2016 to study HEMP and improve the sharing of

[72]Los Alamos issued the first report based on this research in November 2016 which provides an overview of EMP hazards and potential impacts. The next two phases of this work are due to be completed by the end of January 2018 and will include (1) the categorization of all possible EMP and GMD events into classes that cover the full range of nuclear EMP and natural GMD events considered plausible, (2) classification of these events into events of "concern" and "no-concern," and (3) development of a preliminary catalog of data, models, and methods anticipated to carry out a study of EMP events.

information on HEMP that would be useful to industry.[73] According to DOE, central to development of the Joint Strategy was an effort to enhance shared government-industry understanding of the current status of risks from, and preparedness for, HEMP events. DOE added that this effort is important because what is currently known about HEMP effects to the grid has been developed from computer models designed for other purposes (e.g., understanding Department of Defense system effects), or is classified and thus difficult to share with industry. Specifically, the Joint Strategy includes five strategic goals to guide DOE and industry in minimizing HEMP impacts and improving resilience of the grid to these events. These strategic goals are (1) improving and sharing understanding of HEMP: threat, effects, and impacts, (2) identifying priority infrastructure, (3) testing and promoting mitigation and protection approaches, (4) enhancing response and recovery capabilities relating to a HEMP attack, and (5) sharing best practices across government and industry both nationally and internationally.

Following development of the Joint Strategy, both DOE and EPRI (working with DOE, on industry's behalf) committed to developing separate, but coordinated, action plans that would implement the five strategic goals for studying HEMP and providing needed information to industry. DOE's *Electromagnetic Pulse Resilience Action Plan* (DOE Action Plan), issued in January 2017, delineates the steps that DOE will take to address HEMP risks and emphasizes the federal government's ability to clarify and communicate HEMP threats and impacts, reduce HEMP vulnerabilities, and facilitate the energy sector's response and recovery after HEMP events.[74] DOE stated that its Action Plan also considers the over 90 recommendations made in the 2008 EMP Commission report and at least partially addresses 10 of the 15 recommendations directly related to the electric power system made by

[73]U.S. Department of Energy, *Joint Electromagnetic Pulse Resilience Strategy: A Collaborative Effort of the U.S. Department of Energy and the Electric Power Research Institute* (Washington, D.C.: July 2016).

[74]U.S. Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan* (Washington, D.C.: Jan. 2017).

the EMP Commission in their report.[75] See appendix V for additional detail on the DOE Action Plan, including its relationship to the EMP Commission's work.

As noted in the Joint Strategy, EPRI's industry action plan—initiated in April 2016—is a complement to the DOE Action Plan and includes research to be performed to (1) detail the potential impacts of HEMP on the bulk power system, (2) examine potential industry actions to mitigate HEMP risks, and (3) inform industry investment decisions regarding those mitigation options.[76] According to DOE and EPRI, the research that is outlined in the industry action plan is ongoing and scheduled for completion over a 3-year period with the first two reports being issued in September 2016 and February 2017.[77] EPRI officials added that this research is intended to provide the electric industry with what it needs—specifically, an unclassified, science-based approach to HEMP with regard to (1) threat characterization, (2) testing results, (3) modeling and simulation, and (4) recommended strategies for mitigating the impacts of HEMP including prudent and practical hardening and recovery options. To meet these goals, EPRI, together with participating suppliers, have undertaken this 3-year long research effort and expect to complete this work in 2019. This research effort is comprised of the following tasks:

- **HEMP threat characterization.** For the first part of this task, EPRI is identifying the state of knowledge of unclassified HEMP research for all three components of the HEMP environment (i.e., the E1, E2 and E3 pulse components of HEMP). This portion of EPRI's research was

[75]Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack—Critical national Infrastructures* (April 2008). DOE concluded that the remaining 5 recommendations related to the electric power system would be better addressed by industry or other agencies. These include (1) the evaluation and implementation of quick fixes, (2) assuring availability of crucial communication channels, (3) assuring protection of high-value generation assets, (4) assuring protection of high-value transmission assets, and (5) assuring sufficient numbers of adequately trained recovery personnel.

[76]According to EPRI, in conducting its research under the plan it is collaborating closely with DOE, the national laboratories, and DOD.

[77]This first report issued in September 2016 was a compendium describing the state of knowledge of HEMP research that is relevant to the electric power industry as well as a suite of unclassified HEMP environments that can be used in power system assessments. The second report issued in February 2017 detailed an evaluation of the potential impacts of the E3 pulse from a HEMP event on bulk-power transformers. The E3 pulse is similar to a severe GMD event.

achieved by the issuance of the aforementioned September 2016 report. The remaining two components of this task are ongoing and include (1) identifying characteristics of the electromagnetic signals associated with HEMP that can be used to assess the potential impacts on bulk power system components, and (2) investigating the physics of HEMP's transmission to, and impact on, power system infrastructure.

- **Electric infrastructure EMP vulnerability.** This task involves identifying the vulnerability of transmission systems and support assets (e.g., protection and controls systems, communications, transformers, etc.) exposed to the HEMP threat by performing laboratory tests. EPRI will test various infrastructure components at two EMP test labs by subjecting them to E1 pulses. According to EPRI, initial results for this task are possible by the end of 2017.
- **Electric infrastructure impacts.** For this task, EPRI is assessing the potential impacts of a HEMP attack on the bulk power system by combining the system modeling-related efforts in the first task above with the equipment testing results of the second task above. Under this task, EPRI is also developing assessment techniques, models, and tools for assessing the impacts of a HEMP attack. The aforementioned February 2017 report assessing the potential effects of the E3 pulse component of HEMP on U.S. bulk-power transformers represents a portion of the work under this task. In this report, EPRI found that a small number of geographically-dispersed transformers (14 out of the tens of thousands included in EPRI's analysis) were potentially at risk for thermal damage from the E3 pulse. EPRI produced a companion report assessing the potential impacts of the E3 pulse on the stability of the bulk-power system (i.e., the potential for voltage collapse) in December 2017 to be followed by the results of the first E1 pulse assessment at a later date.
- **Mitigation, hardening, and recovery.** Under this task, EPRI is assessing various mitigation and hardening approaches that can be employed to reduce the impacts of HEMP on bulk-power system reliability—including examinations of potential unintended consequences of these approaches and cost effectiveness. As an initial step, EPRI is developing interim guidance on hardening substations based on military and international standards that is scheduled to be completed by the third quarter of 2017.
- **Risk-based decision support.** For this task, EPRI is developing methodologies and tools to support risk-informed decisions regarding the implementation of HEMP hardening and mitigation measures.

- **Trial implementation.** Once hardening measures have been identified, EPRI's supporting member utilities will have the opportunity to evaluate implementation of these measures on aspects of their networks. This task will develop a collection of leading industry practices with regards to HEMP mitigation and hardening. EPRI is to communicate the effectiveness of these measures including lessons learned.
- **Project member and stakeholder communication.** Under this task, EPRI will communicate the results of its research project to its supporting members and stakeholders in order to share new learning in a timely manner.

U.S. and Canadian Electricity Suppliers Have Made Improvements to Provide Protection against GMD and HEMP Events, Including Some That NERC Requires and Monitors

Selected Suppliers Have Made Technology Improvements Primarily to Enhance Overall Network Reliability which Can Also Help Protect Against GMD and HEMP Events

Overall, 10 of the 13 selected suppliers we contacted reported making technological improvements to provide a range of system reliability benefits, some of which can also provide collateral benefits for protecting against GMD and HEMP events.[78] These 10 suppliers purchased and maintained their own transmission-related equipment, while the remaining three suppliers were reliability coordinators who did not purchase or own their equipment.[79] Various examples of these technological improvements for improved system reliability—that had the added benefit of protecting against GMD or HEMP events—were reported by the suppliers we contacted and include the following:[80]

- **Replacement of older transformers for various reasons, including susceptibility to GMD.** Overall, 7 of the 13 suppliers we

[78]Of the 13 suppliers we contacted, one had installed equipment to specifically address concerns over the vulnerability of its network to GMD as opposed to general reliability upgrades that had the collateral benefit of protecting against GIC.

[79]For the three reliability coordinators we contacted, purchase and ownership of such equipment would be the responsibility of the generator and transmission owners and operators they oversee.

[80]This is not an exhaustive list of all possible technology-related actions suppliers might take and represents only examples of such actions identified and employed by the 10 suppliers we contacted who purchased their own equipment.

contacted noted that transformer replacement occurs for a variety of reasons, including increased efficiency.[81] However, seven of the ten suppliers that purchased their own equipment added that, when they acquire new transformers, they generally selected models that have the added benefit of being more resilient to the effects of GIC during a GMD event. These seven suppliers reported that their specifications for the acquisition of new transformers specifically included qualities to make them more resilient to GIC.[82] The suppliers also told us they are adhering to these specifications whenever they replace an older, less resilient, transformer as part of ongoing system upgrades. One supplier reported that they have undertaken a broad review of the transformers used in their system and taken steps to systematically reduce the number of unique units as part of a broader effort to make their system more consistent. They told us they have worked, to the extent possible, to standardize their transformer designs since implementing a new transformer purchasing program in 2008 which included upgrades such as more stringent specifications for protection against GMD. This supplier told us these efforts would also make it easier and less costly to maintain spares and to replace individual transformers that could be damaged from GMD or HEMP events.

- **Participation in spare transformer programs to facilitate timely recovery of suppliers' networks after transformer failures, including those caused by GMD and HEMP events.** Of the 10 selected suppliers we contacted who purchased their own equipment, 6 reported having participated in at least one spare transformer program. For example, five of these suppliers participated in the Edison Electric Institute's (EEI) Spare Transformer Equipment Program (STEP) which was intended as a coordinated approach to developing a shared inventory of spare transformers and streamlining the process of sharing transformers with affected companies. This program requires participating utilities to maintain a specific number of transformers up to 500 kV to be made available to other utilities in case of a critical substation failure. According to program documentation, any investor-owned, government-owned, or rural

[81]Two of these seven suppliers were reliability coordinators who did not purchase their own equipment, including transformers. However, these two reliability coordinators were aware of reasons for replacing transformers based on the experiences of the other suppliers they oversee in their role as reliability coordinators.

[82]As noted previously, 3 of our 13 selected suppliers were reliability coordinators who did not acquire or own any generation or transmission-related equipment. Therefore, only 10 of the 13 selected suppliers would be involved in purchasing new equipment such as transformers.

electric company in the U.S. or Canada may participate in the EEI STEP.[83] The sixth supplier did not participate in an outside spare transformer program such as EEI's, but, instead, maintained its own, in-house program.

- **Investment in series capacitors to enhance network efficiency.** Eight of the 10 selected suppliers we contacted, who purchased their own equipment, stated that they had added series capacitors to their networks.[84] Seven of these eight suppliers told us they had acquired series capacitors to enhance the efficiency of their networks and help with network stability and voltage regulation. These suppliers stated that these devices offer the added benefit of mitigating the impacts of GMD and HEMP events because series capacitors block GIC, therefore preventing GIC from affecting certain parts of the

[83]In addition to the Spare Transformer Equipment Program and other individual efforts by various reliability coordinators for the suppliers they oversee, several other spare transformer programs exist as collaborative efforts among members of the electric industry. These include (1) SpareConnect, (2) Grid Assurance, (3) Wattstock, and (4) Restore. SpareConnect is a program that provides an online platform that allows industry members to reach out to other members during an emergency to borrow spare equipment. SpareConnect is a communication conduit only and does not manage a database of spare transformers as is the case with other programs. Grid Assurance is a company formed by utilities and energy companies to more cost-effectively procure an inventory of spare equipment instead of utilities trying to acquire this equipment on their own. The equipment can be rapidly deployed to subscribers in an emergency. Grid Assurance is not expected to be fully functional until January 2018. Wattstock is an independent, private company building an inventory of spare transformers located at regional distribution centers. Participants pay an enrollment fee as well as an annual membership and rental fee for the usage of any spares. Restore is a regionally-focused initiative by several electricity suppliers to establish a voluntary program in which participants identify spare transformers and other equipment that would be made available for purchase by other participants in the event of a widespread disaster or physical attack within their service area. Also, looking forward, DOE submitted a Strategic Transformer Reserve Report to Congress in March 2017 that evaluated options for establishing a strategic transformer reserve and recommended supporting an industry-based option driven by voluntary industry actions and NERC requirements. DOE further stated that, one year from the date of this report, it would reassess whether sufficient progress has been made through this approach to warrant continuation or alternative actions by government.

[84]Of the two suppliers who did not report installing series capacitors, one supplier stated they were not necessary for its network and the other did not respond to our inquiry on this topic.

transmission system.[85] For example, one Canadian supplier, whose customers were almost totally dependent on electricity for heat during the winter, reported installing these technologies to improve overall network reliability but recognized the benefits of the technology for helping alleviate the threat of GMD events—which, according to DOE, is particularly acute at its far northern latitude.

- **Installation of digital relays with enhanced functionality.** Four of the 10 suppliers we contacted who acquired their own equipment had replaced, or were in the process of replacing, older electro-mechanical protective relays used in their grid control systems with newer digital relays. Unlike electro-mechanical relays—which can fail to operate properly under certain conditions resulting from a GMD event—digital relays can be programmed to properly respond to these conditions. FERC officials confirmed that digital relays may offer some degree of protection during GMD events, but cautioned that they are likely more susceptible than the older electro-mechanical relays to the E1 pulse of HEMP events.
- **Construction of hardened control centers to protect against a variety of threats, including HEMP.** Two of the 10 suppliers we contacted that purchased their own equipment had built, or were planning to build, control centers specifically designed to be resilient to the effects of EMP and other threats. For example, one electricity supplier's customers included critical national security agencies and others in the Washington, D.C. area—resulting in the supplier's desire to protect against the HEMP threat. The second supplier was in the process of designing its own hardened control center to guard against both EMP and other threats posed by extreme weather events occasionally occurring in its area of the country.

In addition to technological improvements to provide a range of system reliability benefits, some suppliers are considering investments in technology specifically focused on blocking harmful GIC produced during GMD events. This GMD mitigation technology is referred to as a "GIC

[85]According to DOE, series capacitors primarily improve power transfer efficiency by potentially allowing more power to be transmitted over existing lines. According to three of these seven suppliers, while series capacitors block the flow of GIC in certain parts of the transmission system, these devices can affect the level of GIC in other parts of the supplier's transmission system. Therefore, their ability to mitigate GIC impacts depends on the network topology relative to transmission lines and transformers that may be vulnerable to GIC.

blocking device" and is still being tested.[86] Since this technology is for the sole purpose of blocking GIC produced during GMD events, its cost may be directly attributed to GMD mitigation.[87] One of our 13 selected electricity suppliers had installed such a prototype device on its high-voltage transmission system as part of an ongoing field trial to assess its performance and overall system impact in order to determine the effectiveness of the device under different operating conditions. Four selected suppliers expressed concern that GIC blocking devices can have unintended consequences on the stability or reliability of their transmission networks which could limit their overall benefits. Two of these suppliers stated that, before considering the installation of these blocking devices, they would perform analysis to determine their effectiveness in suppressing GIC at the system level and the impact on the functioning of their transmission system.[88]

[86]Specifically, the GIC-blocking device blocks the flow of GIC between the ground and transformer in order to protect it from any thermal or electrical impacts of a GMD event.

[87]Officials representing the designer of the blocking device stated that the device can also help protect suppliers' networks from the E3 pulse during HEMP events.

[88]Executive Order 13744 directs the Department of Energy, in consultation with the Department of Homeland Security, to work with private industry to test devices, such as GIC blockers, on the active grid. Coordinating Efforts to Prepare the Nation for Space Weather Events, Exec. Order No. 13744, 81 Fed. Reg. 71,573 (Oct. 13, 2016). DOE expects the work to be conducted in two phases with the first phase being development of a testing plan (due 12 months following contract award) and the second phase would be the actual testing. Other aspects of the executive order include defining the roles and responsibilities of various federal agencies in dealing with the threat presented by space weather. In October 2017, DOE stated that the study to define a potential pilot program for GIC blocking devices, or other similar technology, had just begun and could result in implementation of a pilot project in late 2018 or 2019 if funding is available.

Suppliers Have Developed Operating Procedures for the Initial GMD Reliability Standard and Recognize They May Need to Take Further Steps for the Next Standard

NERC's initial reliability standard EOP-010-1 requires certain suppliers to have GMD operating procedures to mitigate the potential effects of GMD events on the reliable operation of the transmission networks for which they are responsible.[89] As of May 2017, the 13 suppliers we contacted told us they were all subject to the requirements of the EOP-010-1 standard and had GMD operating procedures in place to comply with the standard. Moreover, three of the 13 suppliers functioned as reliability coordinators and told us that all of the suppliers they oversaw in their territory also had operating procedures in place in accordance with EOP-010-1. Officials with the reliability coordinators stated they reviewed their suppliers' operating procedures to ensure they did not conflict with the procedures of other electricity suppliers in the coordinators' geographic areas of responsibility.

In addition, NERC's Compliance Registry indicates that 188 electricity suppliers in the United States and Canada are potentially subject to the EOP-010-1 standard.[90] NERC officials stated that, based on audit reports reviewed from its Regional Entities that included EOP-010-1, suppliers with transformers fitting the criteria specified in EOP-010-1 have developed the operating procedures required by the standard. NERC officials also stated that the EOP-010-1 standard requires electricity suppliers' operating plans and procedures to mitigate the effects of GMD events on the reliable operation of the grid—as well as for the reliability coordinators to coordinate these plans and procedures within their area of responsibility. NERC officials stated that, as part of their compliance review for the standard, the NERC regions will assess the reasonableness of these plans and procedures. According to NERC, the standard provides the suppliers the flexibility to develop the procedures

[89]See NERC Reliability Standard EOP-010-1 (approved by FERC at Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014)). Suppliers subject to the requirements of EOP-010-1 include reliability coordinators and transmission operators utilizing power transformers with a specific type of grounding and voltage greater than 200 kV.

[90]NERC lists these 188 suppliers in its compliance registry under the functional responsibility of either reliability coordinators or transmission operators. While these are the entities potentially subject to EOP-010-1 based on their functional responsibility, the determination of whether they are actually subject to the standard is dependent on the types of transformers they employ—as specified in the standard (i.e., transformer with high side, wye-grounded winding with terminal voltage greater than 200 kV). According to NERC, this information on the type of transformers employed is not maintained in the NERC Compliance Registry, and is, instead, maintained by NERC's regions.

they think they need for their respective networks.[91] NERC officials added that the quality of the measures put in place to address vulnerabilities to GMD would be further addressed under NERC's second-stage GMD standard, TPL-007-1.

NERC's initial GMD-related reliability standard, EOP-010-1, went into effect in April 2015.[92] NERC's next reliability standard, TPL-007-1, includes requirements that will be phased in over a 5-year period from July 2017 to January 2022. The TPL-007-1 standard lists a total of seven requirements of which all but one are directed at planning coordinators and transmission planners whose planning area includes certain high-voltage transformers.[93] In general, these requirements detail further steps suppliers must take to periodically model their networks and assess the vulnerable points of their networks to GMD.

Depending on the vulnerabilities suppliers identify in conducting future assessments in accordance with TPL-007-1, suppliers will be required to develop corrective action plans, starting in January 2022, to ensure their generation or transmission networks meet certain performance requirements during a GMD event (e.g., no cascading blackouts).[94] According to NERC, corrective actions in each plan may include (1) operational procedures, (2) enhanced training, (3) installation of devices (e.g., GIC blocking devices), (4) modification of devices (e.g., modifying equipment for greater GIC resilience), (5) removing vulnerable devices (e.g., old transformers), and (6) spare transformer programs. See

[91]NERC plans to support suppliers' efforts to develop these operational processes and procedures by identifying and sharing operating plans, processes, and procedures found to be the most effective.

[92]As noted previously, two of the three requirements under EOP-010-1 went into effect on April 1, 2015, while the remaining requirement on reliability coordinators' dissemination of space weather information went into effect on April 1, 2017.

[93]One of the seven requirements under TPL-007-1 is directed at transmission and generator owners. Also, with regard to the types of transformers detailed in the TPL-007-1 standard, these are transformers with a "high side wye-grounded winding with terminal voltage greater than 200 kV."

[94]FERC has directed NERC to further revise the requirements for corrective action plans in this standard. FERC Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C.¶ 61,215, 81 Fed. Reg. 67,120 (2016). Specifically, FERC has directed NERC to revise the TPL-007-1 standard to require suppliers to prepare a corrective action plan within 1 year and to complete actions called for in such plans within 2 to 4 years.

appendix III for additional detail on TPL-007-1's 7 requirements for certain electricity suppliers along with implementation dates for each.

NERC Has a Process to Verify Compliance with Reliability Standards, Including Those Related to GMD

NERC has an established process to verify electricity suppliers' compliance with reliability standards, including EOP-010-1 and TPL-007-1. Annually, NERC identifies and prioritizes risks based on the potential impact to reliability across its eight North American regions and the likelihood that such an impact might be realized. This process results in an annual compilation of risk elements for the coming year that are reflected in NERC's implementation plan for compliance monitoring of reliability standards throughout its eight regions. In this implementation plan, NERC obtains input from the regions on risks inherent in their geographic areas of responsibility, and NERC links these areas of risk with specific reliability standards. For example, since becoming effective in 2015, NERC officials stated that the EOP-010-1 standard has been an annual area of focus in the implementation plan under the "extreme physical events" risk area.

NERC's overarching implementation plan provides a template for the regions to follow in developing their own regional implementation plans. NERC's eight Regional Entities build on NERC's guidance on risks facing all regions by assessing risks to the reliable operation of the bulk power system in their specific geographic areas of responsibility and identifying the reliability standards associated with those local areas of risk that they will focus on in their compliance monitoring efforts for the upcoming year. Further, according to NERC officials, each NERC Regional Entity performs individual risk assessments for each of the electricity suppliers in their areas of responsibility which further inform their approach to compliance monitoring for each of these suppliers—including which tools to use when assessing compliance.[95] According to NERC, these

[95]NERC's Regional Entities use a variety of compliance monitoring tools including on-site compliance audits of each supplier at least once every 3 years for suppliers responsible for complying with EOP-010-1 and TPL-007-1. These audits evaluate compliance with reliability standards identified as part of the compliance oversight plan for each supplier which incorporates the reliability standards identified by NERC in its overarching and regional implementation plans. Regional Entities may also use other tools including spot checks for more focused reviews on a limited number of reliability standards or other topics, and compliance investigations for system disturbances. NERC also relies on self-identification of non-compliance with the reliability standards, including EOP-010-1, either by supplier self-reports or through supplier self-certifications of compliance. NERC or its Regional Entities may also receive complaints alleging violations of reliability standards which will be reviewed to determine if the complaint provides sufficient basis for the initiation of another compliance monitoring or enforcement process.

individual risk assessments, along with the overarching and region-specific risks, inform the regions compliance monitoring oversight plan for each supplier. At the end of this planning process, NERC approves each region's implementation and audit plans and submits the audit plans to FERC.

As of August 2017, NERC's regions had conducted 63 compliance audits of suppliers that included the EOP-010-1 reliability standard out of the total of 188 electricity suppliers potentially subject to the standard in the United States and Canada.[96] According to NERC officials, the EOP-010-1 reliability standard went into effect in April 2015, and, as noted previously, NERC Regional Entities conduct compliance audits of individual suppliers—including those that must comply with EOP-010-1—at least once every 3 years.[97] Therefore, due to this reason and the fact that these audits are just one of several options for NERC to consider in compliance monitoring, not every supplier subject to EOP-010-1 has been the subject of a compliance audit that included that standard in its scope as of the date of this report. NERC regions conducted these compliance audits on both reliability coordinators and transmission operators registered in the U.S. that were subject to EOP-010-1. As of September 2017, NERC had reported a total of two instances of non-compliance with the EOP-010-1 standard since its inception in April 2015. Electricity suppliers self-reported these two instances of non-compliance to NERC, and they were not the result of a compliance audit. NERC concluded that these incidents posed minimal risk to the reliability of the bulk power system. The two suppliers engaged in mitigation activities (e.g., training of personnel and modification of procedures) to address their non-compliance with the standard, which was verified by NERC's Regional

[96]In evaluating a supplier's compliance with a reliability standard, the NERC Regional Entity is to review the extent to which the supplier has complied with the specific requirements detailed in each standard. For example, with respect to Reliability Standard EOP-010-1, the NERC Regional Entity assesses (1) whether each reliability coordinator has a current GMD operating plan coordinating GMD operating procedures within its area of responsibility and whether the plan has been implemented, (2) whether each reliability coordinator can provide evidence to indicate that forecasted and current space weather information was disseminated as stated in its operating plan, and (3) whether each transmission operator has implemented a GMD operating procedure that includes the following: tasks related to receiving space weather information, system operator actions to be initiated based on predetermined conditions, and conditions for terminating the GMD operating procedures.

[97]According to NERC officials, they have not yet initiated efforts to review suppliers' compliance with their second stage Reliability Standard, TPL-007-1, since its implementation will be staggered over the next several years.

Entities. NERC concluded that no further action was needed in these two cases.

Selected Suppliers Reported that Costs for Protecting against GMD and HEMP Events Have Been Relatively Small to Date, and Most U.S. Suppliers Are Expected to Be Able to Recover Costs through Charges to Electricity Customers

Selected Suppliers Told Us Costs for Protecting against GMD and HEMP Events Have Been Relatively Small to Date, but Costs May Increase as Suppliers Comply with Future NERC Requirements

Selected electricity suppliers told us the costs they have incurred to date for protecting against GMD and HEMP events have been small relative to their overall system costs. One supplier said that the costs they have incurred are generally associated with projects that provide broader system reliability or other benefits not specific to GMD or HEMP events. Based on interviews with selected suppliers, there are several types of projects that protect against GMD and HEMP events at different levels of costs:

- **Projects providing collateral GMD or HEMP protection at no specific, incremental cost.** As noted previously in this report, selected suppliers have installed several types of equipment for the purposes of transmission efficiency or benefits of general stability, and this equipment also provides collateral protection against GMD or HEMP events. This equipment has included series compensation systems installed on transmission lines, replacement of older electro-mechanical protective relays used in the suppliers' grid control systems with newer digital relays, and acquisition of spare transformers or participation in shared spare transformer programs which improves their ability to quickly restore transmission systems

from any cause, including GMD or HEMP events. Total project costs may vary widely depending on the amount and type of equipment suppliers choose to install, but according to suppliers we interviewed and information from transformer manufacturers, costs for this equipment can range from thousands of dollars per digital relay to tens of millions of dollars for a series compensation system.

- **Projects providing supplemental GMD or HEMP protection at minimal added cost.** As also noted previously in this report, some suppliers we interviewed said they have added specifications for improved protection against GMD or HEMP events as part of larger equipment procurement or construction projects and that this improved protection typically came at a relatively small increase in total project price. For example, several suppliers told us that transformers and other transmission equipment used to control voltage levels can be made more resistant to GIC by using certain designs or materials, and one supplier said this would increase equipment costs by 2 to 3 percent or less. In addition, the two suppliers we interviewed who have designed new control centers that are to be hardened against a range of hazards—including extreme weather (earthquakes, tornadoes, hurricanes, lightning), physical attacks, and HEMP events—told us that adding HEMP protection to the design of new control centers has increased total project costs from about 5 to approximately 20 percent.[98]
- **Projects built primarily for GMD or HEMP protection.** As also noted previously in this report, one supplier has installed a prototype GIC-blocking device, designed specifically to protect against GMD events, as part of a pilot effort to test its operational impacts. The costs of deploying these devices are expected to be better understood after the pilot effort is completed, but based on its initial results, the supplier expects that the total cost for a well-designed GIC-blocking device would be at least $500,000, excluding installation and other costs and one device could be required to protect each transformer.

[98]One supplier, which completed a new hardened systems operation center in August 2017, told us that for this center "hardening" consists of various physical reinforcements and operational redundancies—such as encasing the core in concrete-encased steel, with inner and outer steel doors that cannot be operated concurrently—and redundancy of key services, such as double diesel generators in the event of power loss, two telecommunications systems, and two computing facilities. According to the supplier, estimating the costs of retrofitting a systems operation center against HEMP threats would be extremely difficult, given the many variables involved.

Suppliers we interviewed told us they have also developed plans or procedures to mitigate for GMD. According to suppliers, in general these plans emphasize reducing the (1) level of power provided by individual power plants and (2) amount of power flowing over power lines to levels below their operating limits. For example, the plan for one coordinator—a grid operator—requires that they immediately take action to reduce the transfer of power down to GMD Operating Plan-designated limits; if these limits are approached or exceeded, selected power plants are directed to reduce the levels of power provided and, if necessary, the grid operator modifies the levels of power flowing through the system until designated transfer limits are reached.[99] According to suppliers, lowering these power levels can reduce the temperatures of key equipment such as transformers and provide for greater flexibility to operate the system during an event. In some cases, such plans can require increased use of power plants that are more costly to operate, potentially increasing overall system costs. The costs of emergency operating procedures implemented in response to electromagnetic events are likely to vary considerably on a case-by-case basis, depending on such factors as the level of demand and the generation resources available during the event.

In terms of customer costs, U.S. suppliers we interviewed said that the costs they have incurred for GMD or HEMP protection thus far would represent a negligible increase in rates paid by customers. For example, one supplier we interviewed serves about 4.5 million retail customers, and officials from that supplier estimated the cost of hardening a planned control center against HEMP to be at least $10 million. If this cost is fully passed on to customers and paid for in a single year, we calculated that it would amount to a total of about $2 for the average customer's electric bill for that year.

In the future, suppliers could face increased costs for protecting against GMD, depending on the corrective actions needed to address vulnerabilities, which suppliers are to identify in accordance with reliability standard TPL-007-1. The standard does not require suppliers to complete

[99]According to the GMD Operating Plan for this grid operator, emergency actions are required when GIC measurements at one transformer exceed 10 amperes for 10 minutes. At that point, the system is to be operated at GMD Operating Plan-designated "transfer limits" that have been pre-determined based on, among other things, studies modeling various GMD scenarios, including actual GMD events. Once GIC levels at all monitored transformers fall below 10 amperes, the operator is to continue to operate the system at the GMD Operating Plan-designated transfer limits for 3 hours, at the end of which, if GIC levels still remain below 10 amperes, operations are restored to appropriate levels.

vulnerability assessments and develop corrective action plans until 2022, and suppliers told us it is too early to know what types of corrective actions may be required. However, the costs associated with some types of potential actions could be high. In particular, examples of potential corrective actions provided in the standard, such as installing new equipment or modifying existing equipment for improved GIC resilience, could be costly according to some suppliers we interviewed. For example, high-voltage transformers can cost tens of millions of dollars each. If suppliers identify multiple transformers that are vulnerable to thermal impacts from GIC flows, replacing or modifying them would be costly. Similarly, a supplier may need to install GIC-blocking devices throughout their network to effectively protect against a GMD event because the devices re-direct GIC flows elsewhere in the network. Therefore, a blocking device strategy could be costly if suppliers determine that large numbers of their transformers are vulnerable.

Based on our prior review of federal efforts to enhance electric grid resiliency and federal emergency management programs, and interviews with agency and industry representatives, there are no sources of direct federal funding specifically to reimburse suppliers for costs they incur for protecting against GMD or HEMP events.[100] DHS officials told us there are two DHS grant programs that could be used to indirectly support suppliers' efforts to prepare for GMD or HEMP events.[101] However, DHS directly awards these grants to state, local, or tribal governments, and DHS officials told us that it is rare for these grant funds to be passed through to private companies and they have no record of instances in which electricity suppliers received funding for grid preparedness efforts.[102]

[100]GAO-17-153.

[101]The Federal Emergency Management Agency administers the State Homeland Security Program, which provides assistance for state, tribal, and local preparedness activities that address high-priority preparedness gaps where a nexus to terrorism exists—potentially including EMP preparedness. In addition, the agency's Emergency Management Performance Grants Program provides grants to states to assist state, local, territorial, and tribal governments in preparing for all hazards, which could include GMD and EMP events.

[102]According to DHS officials, data are self-reported by grant recipients and DHS does not review the data for accuracy.

Regulated U.S. Suppliers' Costs for Protecting against GMD are Generally Recoverable, but Cost Recovery is Less Certain for HEMP Events

Federal and State Regulators Have Made Specific Assurances about Recovering GMD-Related Costs

At the federal level, in FERC's September 22, 2016, order approving NERC's TPL-007-1 reliability standard, FERC stated that cost recovery for prudent costs associated with or incurred to comply with the standard would be available to suppliers for whom FERC approves rates.[103] Two suppliers we interviewed said that because FERC requires suppliers to comply with the standard and has provided specific assurance that prudent costs will be recoverable, they do not expect challenges recovering such costs. According to FERC officials, FERC determines whether suppliers' investments are prudent on a case-specific basis, in part by considering whether the supplier acted reasonably given industry norms.[104] FERC officials also stated that for most transmission rates, it does not conduct in-depth reviews of the reasonableness and prudence of each cost item unless a stakeholder such as a ratepayer advocacy group, large customer, or state public utility commission challenges the

[103]See NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C. ¶ 61,215, 81 Fed. Reg. 67,120 (2016)). As previously discussed, while electricity restructuring introduced a measure of market-based pricing to electricity generation, transmission and distribution are still subject to regulation on a cost-recovery basis. FERC has jurisdiction over transmission rates on the federal level, and state regulators have jurisdiction over the charges that utilities incorporate in customers' rates in order to recover their transmission costs.

[104]In addition, FERC requires that equipment be "used and useful" in order for its costs to be recoverable through transmission rates. See, e.g., *Transcontinental Gas Pipe Line Corp.,* 59 F.P.C. 1237 (1977), *aff'd sub nom., Tennessee Gas Pipeline Co. v. FERC,* 606 F.2d 1094, 1123 (D.C. Cir. 1979), *cert. denied,* 445 U.S. 920 and 447 U.S. 922 (1980). According to FERC officials, equipment is used and useful if it is providing the service it is supposed to be providing. Officials said that GMD and HEMP mitigation equipment is similar to other types of protective equipment that may never be called upon to operate in a protective mode, but that is considered used and useful for purposes of cost recovery if it can provide protection when needed.

suppliers' rate filing with FERC.[105] FERC officials told us they were not aware of any cases in which stakeholders challenged GMD-related costs.

Some suppliers we interviewed said that the revisions to TPL-007-1 that FERC required in Order 830—particularly, revisions to the benchmark GMD event suppliers must use in their vulnerability assessments—could result in added costs for suppliers. For instance, one supplier expressed concern that they could have to begin work to assess vulnerabilities and protect against the first version of the benchmark event, and that the revised standard would require them to re-do such work using a new benchmark event, at additional cost. In response to such concerns, FERC stated that it could not yet determine what impacts the revisions might have on the actions suppliers would have to take to comply, because NERC had not yet developed or proposed the revisions.[106] However, FERC re-affirmed that cost recovery for prudent costs associated with or incurred to comply with reliability standard TPL-007-1, and future revisions to the standard, will be available to regulated suppliers.

Representatives from the state regulators we interviewed said they allow recovery of prudent generation or distribution costs for regulated utilities for improvements needed to meet federally-required reliability standards, such as NERC's GMD reliability standards. In addition, some of the selected suppliers told us that they use federally-required reliability standards to justify necessary investments when filing a rate case with state regulators. As with FERC, state regulators we interviewed said they determine the prudence and reasonableness of costs on a case-specific basis.

[105]According to FERC officials, transmission costs, including costs for complying with Reliability Standards, are recoverable through annually-updated "formula" rates that FERC keeps on file and reviews periodically. These rates are based on aggregated transmission costs, including GMD- or EMP-specific costs—though these costs are generally not listed separately from other costs, according to officials. Formula rates are not typically subject to a detailed review of individual cost items. However, FERC's policy is that utilities include safeguards in their transmission formula rate protocols to provide transparency and to ensure that the data and calculations are correct. Among these safeguards is a requirement for utilities to file annual updates to their rates with FERC and share them, with appropriate support, with all interested parties.

[106]Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events

Suppliers' Ability to Recover Future HEMP-Related Costs is Uncertain Due to Limited Understanding of HEMP Risks and Mitigation Efforts

To the extent suppliers and regulators determine that HEMP events pose a risk to bulk power system reliability, FERC may allow recovery of prudent costs for protecting against EMP events. However, according to FERC officials, determining prudence for costs associated with new, emerging areas such as HEMP mitigation could be challenging because regulators and suppliers have limited understanding of HEMP risks. In 2004, FERC publicly assured suppliers that it will allow for recovery of prudent costs necessary for ensuring the reliability of the bulk power system. Specifically, FERC issued a policy statement assuring public utilities that FERC will approve applications to recover prudently-incurred costs necessary to ensure bulk power system reliability, including prudent expenditures for compliance with good utility practices—practices engaged in or approved by a significant portion of the electricity industry or that could be expected to accomplish the desired result at a reasonable cost.[107] Two suppliers we interviewed said that they expect FERC would allow them to recover transmission costs they deemed necessary for protecting against HEMP events. FERC officials told us that they are not aware of any cases to date where suppliers have sought recovery of transmission costs associated with HEMP protection through FERC-approved rates, so they do not know what challenges they might encounter in determining whether these costs are prudent. Also, unlike GMD events, suppliers and electricity industry stakeholders told us there are not yet tools for assessing suppliers' vulnerability to HEMP events, standards for protecting against these events, or tools for assessing the effectiveness of protective remedies.

Suppliers and state regulators we met with said more information is needed to understand HEMP risks and mitigation efforts in order to determine to what extent costs would be recoverable. Electricity industry stakeholders and suppliers told us that they are sensitive to the fact that their costs are typically borne by customers, and more complete knowledge of HEMP risks would allow them to invest responsibly in HEMP protection from both a reliability and cost perspective. Similarly, one state regulator we interviewed has not yet received any rate filings

[107]FERC Policy Statement on Matters Related to Bulk Power System Reliability, April 19, 2004. FERC Order No. 888 defined ''Good Utility Practice." Order No. 888, *Promoting Wholesale Competition Through Open Access Non-Discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities*, 75 F.E.R.C. ¶ 61,080, 61 Fed. Reg. 21,540 (1996).

from suppliers that include costs associated with HEMP protection.[108] However, one supplier said that their state regulators prioritize reliability, and they expect the regulators would allow recovery of costs for HEMP protection if suppliers determined such protection was needed. As with FERC, state regulators said that when rate filings involve new technologies or practices, there is more uncertainty regarding costs and benefits and it can be more difficult for regulators to determine prudency. For example, one state regulator told us that DHS is doing work to understand risks associated with HEMP events, and what protections such events may necessitate. The regulator said they would like to see the results of this work before suppliers invest in mitigation equipment, so there can be more certainty that the costs will be considered prudent.

Independent Generators May Face Challenges Recovering Costs for Protecting Against GMD and EMP Events

Independent generators—generators that sell power in wholesale electricity markets and are not part of an integrated utility—do not have a mechanism assuring cost recovery for reliability improvements, including such as GMD and HEMP protection. FERC officials stated that these generators sell electricity at prices determined by supply and demand in markets that FERC has determined are sufficiently competitive or that have adequate procedures in place to mitigate the effect of companies to manipulate prices, such as could be the case for a company with a large market share. As such, according to electricity industry and FERC officials, independent generators do not have the assurances of cost recovery that traditionally-regulated suppliers do. If they invest in protecting their facilities from the potential effects of GMD and HEMP, the prices independent generators obtain for selling electricity so as to be competitive in the wholesale markets may be too low to allow them to fully recover their costs.[109] According to data from DOE's Energy Information Administration, independent generators represented nearly 47 percent of

[108]According to supplier officials, they have not yet applied for a rate adjustment to recover the costs of constructing the new control center.

[109]Sellers in wholesale markets—such as owners of power plants—place offers with RTOs to supply an amount of electricity at a specific price. Potential buyers of this electricity also place bids with RTOs defining their willingness to pay for it. RTOs periodically "stack" the offers to supply electricity from lowest offered price to highest until the RTO estimates that it has sufficient electricity to meet the total demand. The market clearing price, or the highest supply bid needed to satisfy the last unit of demand, is paid for each unit of electricity produced for that time period.

electric generation facilities and generated about 39 percent of utility-scale electricity in the U.S. in 2015.[110]

FERC officials said they recognize that independent generators could face challenges recovering costs for step-up transformers—generator equipment which, if it is vulnerable to GMD, may need to be replaced or modified in accordance with NERC standard TPL-007-1. Independent generators must balance the need to recover costs associated with these transformers with the need to offer prices for their electricity that are competitive in wholesale markets. According to suppliers, until studies are completed to identify how companies will comply with TPL-007-1 it is unclear the extent of the risk to step-up transformers owned by independent generators and the extent of the challenges of paying for steps to mitigate those risks.

Agency Comments

We provided a draft of this report to DOE, DHS, NOAA, NRC, FERC, and NERC for their review and comment. DOE, DHS, NRC, FERC, and NERC provided technical comments, which we incorporated as appropriate.

[110]DOE, Energy Information Administration, *Electric Power Annual,* 2015*,* and *Electric Power Monthly*, April 2017.

We are sending copies of this report to the Secretaries of Commerce, Energy, and Homeland Security, the Chairmen of the Federal Energy Regulatory Commission and the Nuclear Regulatory Commission, and the Chief Executive Officer of the North American Electric Reliability Corporation. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact Chris Currie at (404) 679-1875 or curriec@gao.gov or Frank Rusco at (202) 512-3841 or ruscof@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VI.

Chris P. Currie
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List of Requesters

The Honorable Ron Johnson
Chairman
The Honorable Claire McCaskill
Ranking Member
Committee on Homeland Security and Governmental Affairs
United States Senate

The Honorable Michael McCaul
Chairman
Committee on Homeland Security
House of Representatives

The Honorable Scott Perry
Chairman
Subcommittee on Oversight and Management Efficiency
Committee on Homeland Security
House of Representatives

Appendix I: Scope and Methodology

In conducting our work, we interviewed representatives from 13 of the 181 U.S. and Canadian electricity suppliers—entities that own or operate generation or transmission infrastructure—subject to the North American Electric Reliability Corporation's (NERC) 2014 geomagnetic disturbance (GMD) reliability standard and which conduct planning and generation, transmission, and distribution operations.[1] We selected these 13 electricity suppliers based on input from the U.S. Department of Energy (DOE), NERC, industry associations, and research institutions as to which suppliers had taken steps to prepare for and mitigate impacts from electromagnetic events. We also considered, among other things, the following supplier preparedness and mitigation actions and characteristics: (1) efforts or plans to install mitigation equipment or technology; (2) efforts or plans to develop specific mitigation processes, procedures, or other operational actions; (3) infrastructure, such as length and voltage of transmission lines; (4) high-voltage equipment, including transformers over 230 kilovolts (kV); (5) geomagnetic latitude; and (6) experience with GMD-related service disruptions.[2] We included 3 Canadian electricity suppliers among the 13 suppliers we interviewed due to their (1) experiences with past geomagnetic disturbance (GMD) events, (2) research on the impacts of GMD, and (3) actions taken to prepare for and mitigate GMD events.

We conducted site visits to 6 of the 13 suppliers to better understand their experiences with past GMD events and identify actions they have taken to prepare for and mitigate GMD and High-Altitude Electromagnetic Pulse (HEMP) events, among other things. During these visits we met with organization officials; observed operations and facilities, such as control centers hardened to mitigate effects from HEMP events; and viewed equipment potentially vulnerable to GMD, such as high-voltage

[1]For the purposes of this report, we define "electricity suppliers" as entities that own or operate generation or transmission infrastructure, as well as those with responsibility for planning and overseeing the grid and for selling electricity to consumers. According to NERC, as of October 2017, of the 181 suppliers, 7 Canadian suppliers are subject to compliance with the 2014 reliability standard; the Canadian province of Alberta is in the process of adopting the standard and province of British Columbia has adopted the standard but is not yet subject to enforcement.

[2]Voltage is the "force" that makes electricity move through a conductor. It is measured in "volts," with a "kilovolt" (kV) representing 1,000 volts. The classification of "high voltage" transmission varies, but generally ranges from 230 kV up to 765 kV in North America.

transformers.[3] While we cannot generalize the information we learned from these selected suppliers to all U.S. and Canadian suppliers, they provided insight on what electricity suppliers may know regarding the potential impacts of electromagnetic events on the electric grid, as well as steps suppliers may be taking to prepare for and mitigate such impacts. The selected U.S. suppliers also identified opportunities available to them for recovering costs for protecting against electromagnetic events. Based on input from DOE, NERC, supplier, and industry officials, and because of these organizations' specialized knowledge and experience with the electricity industry, we also interviewed representatives from six industry organizations—five industry associations and one industry research organization—two transformer manufacturers, one software modelling company specializing in simulations of high-voltage power system operations, and one designer of a prototype geomagnetically induced current (GIC)-blocking device.[4]

To determine the extent to which U.S. and Canadian electricity suppliers have identified information about the effects of GMD and HEMP on the electric grid, we reviewed selected U.S. and Canadian government studies issued—or commissioned by—DHS, DOE, U.S. National Laboratories, Natural Resources Canada, the Federal Energy Regulatory Commission (FERC), and NERC since 2010 regarding, among other things, the vulnerability of transmission and generation infrastructure and equipment to GMD and HEMP events, possible measures to mitigate the

[3]The six U.S. and Canadian electricity suppliers we visited are Bonneville Power Administration (BPA), Dominion Energy, PJM Interconnection LLC, Hydro-Quebec, Peak Reliability, and Western Area Power Administration (WAPA). The seven electricity suppliers we interviewed by phone or received written responses from, are American Transmission Co., Central Maine Power, Electric Reliability Council of Texas (ERCOT), Exelon Corp., Hydro One, Manitoba Hydro, and Southern Company.

[4]The six industry organizations we met with are Edison Electric Institute (EEI), the Electric Power Supply Association, the National Association of Regulatory Utility Commissioners, the National Electrical Manufacturers Association, the National Rural Electric Cooperative Association, and the Electric Power Research Institute (EPRI). We also met with representatives from ABB and Mitsubishi Electric Power Products, Inc., two manufacturers of large power transformers with facilities in the United States. We met with representatives of PowerWorld, a grid software modelling company, to discuss model simulations of geomagnetic disturbance (GMD) impact on high-voltage networks. We also met with officials from Emprimus, the designer of a prototype device for blocking geomagnetically induced currents (GIC).

effects of GMD and HEMP, and areas requiring further research.[5] We also reviewed relevant studies published since 2010 from the Electric Power Research Institute (EPRI) and private contractors referred to us by government, supplier, and industry representatives. We identified these studies based on feedback from all entities listed above and through references in reports and other documentation. While we did not compile a comprehensive list of all studies of the effects of GMD and HEMP on the U.S. and Canadian electric grid, industry experts indicated that we had identified relevant studies published on this subject since 2010. We also interviewed knowledgeable officials from these U.S. and Canada government agencies, national laboratories, and industry organizations to clarify our understanding of the issues addressed in these studies. We assessed the methodologies used in the relevant reports and determined them to be sufficiently rigorous to provide information about the potential effects of GMD and HEMP events on the electric grid.

To better understand the effects of solar weather on the electric grid, how GMD is measured, and mechanisms in place for notifying electricity suppliers of potentially dangerous solar storms, we interviewed representatives from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service, the U.S. Geological Survey (USGS), and the National Aeronautics and Space Administration (NASA). We also reviewed relevant documentation on processes and procedures.

To identify data on the frequency and intensity of past GMD events, we analyzed data on GMD occurrences, from 1933 through 2016, the available record of occurrences maintained by the GFZ German Research Centre for Geosciences. According to NOAA officials, the GFZ German Research Centre for Geosciences maintains the authoritative historical record of these data.[6] We assessed the reliability of these data by testing for missing data, outliers, or obvious errors. We found the data to be sufficiently reliable to report on the number and intensity of GMD

[5]The Department of Energy (DOE) oversees 17 national laboratories that perform scientific research on a range of large-scale, complex issues for the federal government and other entities. Natural Resources Canada is a federal government department in Canada responsible for natural resources, energy, minerals and metals, forests, earth sciences, and mapping.

[6]According to National Oceanic and Atmospheric Administration (NOAA), its Estimated Planetary K-index (K_p-index) is a near real-time estimate of the official Planetary K_p-index maintained by the GFZ German Research Centre for Geosciences.

events occurring from 1933 through 2016. We also interviewed Department of Homeland Security (DHS) officials regarding the Department's efforts to address requirements in the National Defense Authorization Act for Fiscal Year 2017.[7]

To obtain perspectives on efforts individual electricity suppliers have taken to better understand the effects of GMD and HEMP, we interviewed officials from 13 U.S. and Canadian suppliers regarding the extent to which they had evaluated the impact of electromagnetic events on their specific generation systems or transmission networks and what they had learned from these evaluations. With respect to ongoing efforts to research the effects of HEMP, we reviewed DOE and EPRI's *Joint Electromagnetic Pulse Resilience Strategy* and *the* U.S. Department of Energy *Electromagnetic Pulse Resilience Action Plan* and interviewed relevant DOE and EPRI officials regarding these plans.[8] Further, we interviewed officials from various national laboratories regarding their ongoing efforts to fully investigate and evaluate how an electric utility could protect itself from, or mitigate the effects of, HEMP on its systems.[9] We also interviewed officials from the Nuclear Regulatory Commission (NRC) regarding efforts to assess the ability of a nuclear power plant to achieve safe shut down following a GMD or EMP event and the extent to which plants are required to implement strategies or guidelines in the event of a prolonged loss of offsite power, similar to what could be caused by a GMD or EMP event. Finally, we reviewed the 2008 Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (EMP Commission) report with recommendations on preparing for and recovering from a possible EMP

[7]Pub. L. No. 114-328, § 1913, 130 Stat. 2000, 2684-87 (2016).

[8]U.S. Department of Energy, *Joint Electromagnetic Pulse Resilience Strategy*, (Washington, D.C.; July 2016) and U.S. Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, (Washington, D.C.: January 2017).

[9]We interviewed officials from the following U.S. National Laboratories: Idaho National Laboratory, Sandia National Laboratory, Los Alamos National Laboratory, and Oak Ridge National Laboratory.

attack.[10] In October 2017, we also requested an interview with a representative from the EMP Commission but did not receive a response to our requests.[11]

To identify steps selected U.S. and Canadian electricity suppliers have taken to protect against GMD and HEMP events and understand how NERC has monitored these efforts, we reviewed FERC orders and NERC reliability standards that require certain suppliers to take steps to assess

[10]Established pursuant to the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, the EMP Commission was responsible, among other things, for assessing the nature and magnitude of potential HEMP threats to the United States and the capability of the United States to prepare and recover from a HEMP attack. Pub. L. No. 106-398, §§ 1401-09, 114 Stat. 1654, 1654A-345-348 (2000). See also National Defense Authorization Act for Fiscal Year 2006, Pub. L. No. 109-163, § 1052, 119 Stat. 3136, 3434-35 (reestablishing the EMP Commission to monitor, investigate, make recommendations, and report to Congress on the evolving threat to the United States of an EMP attack resulting from the detonation of a nuclear weapon or weapons at high altitude); National Defense Authorization Act for Fiscal Year 2008, Pub. L. No. 110-181, § 1075, 122 Stat. 3, 333 (providing, among other things, that the EMP Commission and the Secretary of Homeland Security shall jointly ensure that the work of the EMP Commission and the Secretary of Homeland Security with respect to EMP attack on electricity infrastructure, and protection against such attack, is coordinated with DHS efforts on such matters); National Defense Authorization Act for Fiscal Year 2016, Pub. L. No. 114-92, § 1089, 129 Stat. 726, 1015-16 (2015) (reestablishing the EMP Commission but with an expanded purpose that includes the evolving threat from, among other things, nonnuclear and naturally occurring EMP). The EMP Commission's charter expired on June 30, 2017. Id. § 1089. While the commission did not specifically identify a total number of recommendations, our analysis of the commission report identified over 90 recommendations, which included key recommendations and related subareas across 10 critical infrastructure sections, including electric power, telecommunications, and emergency services among others. The National Defense Authorization Act for Fiscal Year 2018 established a new Commission to Assess the Threat to the United States from Electromagnetic Pulse Attacks and Similar Events, which is to review and assess a number of issues related to potential electromagnetic pulse events and similar events, such as the nature, magnitude, and likelihood of potential electromagnetic pulse attacks and similar events, including geomagnetic disturbances, and the capability of the United States to repair and recover from damage inflicted on United States military and civilian systems by EMP attacks and similar events. See Pub. L. No. 115-91, tit. XVI, subtit. F, § 1691 (2017).

[11]As described earlier, the EMP Commission was established in the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, which requires that the commission by composed of nine members, appointed from among private industry in the United States with knowledge and expertise in the scientific, technical, and military aspects of EMP effects. See Pub. L. No. 106-398, 114 Stat. at 1654A-345.

and prepare for GMD impacts.[12] We interviewed FERC and NERC officials to discuss these standards and reviewed public comments submitted by stakeholders during the FERC rulemaking process. We also interviewed officials from 13 U.S. and Canadian electricity suppliers to identify steps they had taken to comply with NERC reliability standards as well as any additional actions to prepare for and mitigate potential GMD and HEMP effects, such as replacement of older equipment or investment in spare transformer programs. Additionally, we reviewed relevant federal guidance on preparing for GMD and HEMP events, such as DHS's Electromagnetic Pulse protection guidelines and NERC's Geomagnetic Disturbance Planning Guide.[13]

To identify the extent to which NERC has monitored electricity suppliers' steps to comply with NERC reliability standard EOP-010-1, we reviewed NERC monitoring processes, including procedures for developing an annual, nationwide implementation plan for conducting monitoring activities. NERC officials provided the number of compliance audits conducted between April 2015—when NERC, through Regional Entities to which it has delegated enforcement authority, first began reviewing suppliers for compliance with EOP-010-1—and August 2017 that included the EOP-010-1 reliability standard.[14] We contrasted the number of

[12]The North American Electric Reliability Corporation (NERC) Reliability Standard EOP-010-1 requires certain suppliers to have GMD operating procedures in place to mitigate the potential effects of GMD events on the reliable operation of the transmission networks for which they are responsible. NERC Reliability Standard EOP-010-1 (approved by FERC at Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014). NERC Reliability Standard TPL-007-1 requires certain suppliers to assess the vulnerability of their transmission systems to GMD events; suppliers that do not meet certain performance requirements must develop a plan to achieve the performance requirements. NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C. ¶ 61,215, 81 Fed. Reg. 67,120 (2016).

[13]The U.S. Department of Homeland Security's (DHS) guidelines were initially developed for use by the Federal Executive Branch Continuity Communications Managers Group but, according to DHS, have wide applicability to help protect any electronic equipment, facilities, and communications/data centers. These guidelines were made available in mid-2015 but, as of November 2015, have not been widely implemented by any federal agency.

[14]The data NERC provided on the number of compliance audits its Regional Entities had performed that included EOP-010-1 were provided by way of a one-time manual data call to the Regional Entities in response to our request for this information. Because NERC does not routinely collect these data, nor were the data produced by an automated data system, we did not separately assess the reliability of the data.

compliance audits with the total number of suppliers potentially subject to NERC's GMD reliability standard EOP-010-1. We assessed the reliability of the data on the total number of suppliers subject to EOP-010-1 by interviewing agency officials regarding data sources, system controls, and any quality assurance steps performed by officials before the data were provided; we found the data to be sufficiently reliable to provide the number of suppliers subject to EOP-010-1 since it went into effect. We also discussed with cognizant NERC officials the organization's processes for collecting and reporting comprehensive data on the status of their overall compliance monitoring efforts.

To identify what opportunities exist for U.S. electricity suppliers to recover costs for protecting against GMD and HEMP events, we reviewed FERC regulations and orders related to cost recovery, such as suppliers' costs for spare transmission equipment services. We also interviewed FERC officials and representatives of selected state regulators whose jurisdictions include suppliers we interviewed, regarding procedures available to electricity suppliers to recover costs for actions taken to prepare for and mitigate GMD and HEMP effects.[15] We asked these officials to discuss previous, current, and potential future regulatory actions—orders or rate cases they have overseen—involving recovery of costs for actions taken to protect against GMD and HEMP events. Further, we interviewed cognizant DHS and DOE officials to identify the extent to which financial incentives—such as preparedness grants—are available to U.S. electricity suppliers to offset the costs of preparation and mitigation efforts. As part of our review of actions taken by ten selected U.S. electricity suppliers to prepare for and mitigate the impact of electromagnetic events, we interviewed officials regarding the extent to which they had recovered costs expended on preparedness and mitigation efforts and what, if any, options they were considering to recover such costs in the future.[16] While the information provided by these selected electricity suppliers is not generalizable to the U.S. industry, it illustrates examples of actions selected suppliers have taken to recover costs for GMD and HEMP mitigation and preparedness efforts. In addition, we interviewed representatives from various trade

[15]We met with representatives from the Virginia Division of Public Utility Regulation and Maine Public Utility Commissions.

[16]We did not interview Canadian electricity suppliers regarding cost recovery issues because of differences in the U.S. and Canadian wholesale and retail markets.

associations to identify challenges suppliers face in recovering costs for mitigation and preparedness efforts.

We conducted this performance audit from May 2016 to February 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Appendix II: National Oceanic and Atmospheric Administration (NOAA) Notifications for Geomagnetic Disturbances

In the United States, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service manages the Space Weather Prediction Center (SWPC), which is responsible for monitoring and providing services on space weather, including geomagnetic storms.[1] SWPC uses a variety of ground and space-based sensors, as well as imaging systems, to view and estimate geomagnetic activity around the world, and to issue Watches, Warnings, and Alerts for geomagnetic storms through e-mail and website postings to those who are impacted by space weather. Additionally, in the event of imminent geomagnetic storms, SWPC issues immediate voice notification and confirmation to all North American Electric Reliability Corporation (NERC) reliability coordinators through a special hotline.[2]

SWPC relies on a real-time estimate of the Planetary K-index (Kp-index) to communicate the magnitude of geomagnetic storms. This index is an indicator of the magnitude of disturbances in the Earth's magnetic field.[3] SWPC uses its Estimated K_p-index—which runs from $K_p = 0$ (quiet) to K_p

[1]The National Oceanic and Atmospheric Administration's (NOAA) is part of the U.S. Department of Commerce. The Space Weather Prediction Center (SWPC) provides monitoring and forecasting of solar and geophysical events that affect satellites, power grids, communications, navigation, and many other technological systems. In Canada, responsibility for monitoring space weather rests with Natural Resources Canada's Canadian Space Weather Forecast Service.

[2]NERC reliability coordinators are to redistribute voice notification information to all applicable electricity suppliers (generation and transmission). SWPC provides similar phone notification to the NERC bulk power system awareness group—which monitors ongoing storms that may impact the bulk power system—when severe or extreme geomagnetic storm conditions are forecast. According to NOAA, similar notification processes are in place to notify the Federal Emergency Management Agency of expected or ongoing geomagnetic storming.

[3]According to NOAA, scientists also use other measures of geomagnetic disturbance (GMD) intensity. For example, the Disturbance Storm Time (D_{st}) index records geomagnetic field disturbance across four near-equatorial magnetic observatories. Both the K_p and D_{st} indices exclude regular fluctuations in magnetic activity. Whereas K_p is a "range index"—a measure of variation that saturates at $K_p = 9$—D_{st} is an unbounded measure of solar storm effects on the Earth's magnetic field. In this report, we use the K_p-index, the history of which spans three solar cycles more than the D_{st}-index.

= 9 (extreme)—to determine whether geomagnetic alerts and warnings should be issued.[4]

SWPC's primary notifications include:

- **Watches:** Watch forecasts for impending geomagnetic storms—coronal mass ejections (CME)—are issued when the highest predicted Kp-index for a day is between K_p = 5 or higher and are posted approximately 1 to 2 days before a storm reaches Earth. According to SWPC, Watch forecasts are less reliable in predicting storm intensity and timing than other types of forecasts, but are considered useful for longer-range notification. Watch forecasts are based primarily on space and ground-based solar observations as well as modelling predictions.[5]
- **Warnings:** Warnings of geomagnetic storms are issued when estimated K_p-indices of K_p = 4 or higher are expected; they are generally issued 20 to 40 minutes in advance and are based on real-time observations of the solar wind conditions affecting earth.[6] SWPC considers Warning notices as more reliable than Watch forecasts in terms of measuring storm intensity and timing.

[4]According to SWPC, their real-time Estimated K_p-index data show the maximum fluctuations in the magnetic field observed from a network of selected magnetometers—instruments that measure a magnetic field at a particular location—relative to a quiet day. SWPC calculates a near real-time estimate of readings from eight magnetometers located in the United States, Canada, Germany, the United Kingdom, and Australia. To present the significance of the effects of geomagnetic storms in a way that is easier for users to understand, SWPC also communicates the magnitude of geomagnetic storms according to the NOAA Space Weather Scale (NOAA G-scale). The G-scale was designed to correspond in a straightforward way to the significance of effects of geomagnetic storms; SWPC uses the Estimated K_p-index to determine the G-scale level (G1 through G5), in which "K_p = 5" corresponds to "G1" and "K_p = 9" corresponds to "G5." A K_p of 0 to 4 is below storm levels and is labeled as "G0." For purposes of consistency, we use the K_p-index in this report.

[5]According to NOAA, Watch notifications are primarily based on solar observations from solar coronagraphs—telescopes that are used to view the sun's corona—as well as solar x-ray emissions, solar extreme ultraviolet imagery, and solar radio emissions. Additionally, Watch forecasts are informed by data from NOAA's large-scale prediction model that provides physics-based projections on the evolution of coronal mass ejections (CME).

[6]Continuous solar wind observations are provided by NOAA's Deep Space Climate Observatory (DSCOVR) satellite, which orbits approximately 1 million miles from Earth. During a recent extreme storm—the October 2003 "Halloween storm"—the CME arrived at the Earth about 14 minutes after passing the spacecraft (at that time the National Aeronautics and Space Administration's (NASA) Advanced Composition Explorer spacecraft).

- **Alerts:** Alerts are near real-time indications that a specific storm threshold—K_p = 4 or above—is reached; they are based on SWPC's minute-by-minute estimate of GMD activity. Alerts are derived from ground-based magnetometer observations from eight locations around the world.

According to SWPC, Watches, Warnings, and Alerts are to be issued as activity occurs and therefore can be issued very frequently during high-activity intervals and not at all during quiet periods.[7] SWPC issues these notifications when storm levels reach a specific estimated K_p level. Table 1 shows the estimated K_p-indices that trigger each SWPC notification product as well as the estimated impacts to the electrical power system.

Table 1: National Oceanic and Atmospheric Administration (NOAA) Solar Storm Levels, Notifications, and Estimated Impacts

K_p – Index level	Notification	Estimated impact on power systems
K_p = 5	Watch	Weak fluctuations may occur
	Warning	
	Alert	
K_p = 6	Watch	High-latitude power systems may be affected
	Warning	
	Alert	
K_p = 7	Watch	Power system voltage effects may occur
	Warning	
	Alert	
K_p = 8	Watch	Possible widespread voltage control problems and some protective systems may mistakenly disconnect key assets from the grid
	Warning	
	Alert	
K_p = 9	Alert	Some grid systems may experience collapse or blackout, some transformers may experience damage

Source: National Oceanic and Atmospheric Administration (NOAA). | GAO-18-67

Note: The estimated impacts listed are approximate. Actual observed effects will vary depending on the specific power system configuration at the time of the disturbance. In addition, effects vary with location due to regional variability of any given storm as well as the high variability of earth conductivity. SWPC stated that it is developing improved, regional measures, which as of October 2017 were being tested; SWPC expects them to be fully operational in 2019.

[7]According to SWPC, Watches are typically issued up to twice per day while other, non-alert bulletins are generally issued once a day. SWPC also issues products that summarize weekly activity and provides a 27-day forecast for space weather.

Appendix III: North American Electric Reliability Corporation (NERC) Geomagnetic Disturbance (GMD) Reliability Standards

In May 2013, the Federal Energy Regulatory Commission (FERC) directed NERC to develop reliability standards requiring electricity suppliers to address the potential impact of GMD on the reliable operation of the U.S. bulk power system.[1] In June 2014, FERC approved standard EOP-010-1, submitted by NERC, requiring that certain suppliers prepare for the effects of GMD events by developing contingency operating plans, procedures, and processes.[2] FERC approved a second standard—TPL-007-1—in September 2016, also submitted by NERC, requiring certain suppliers to assess the vulnerability of their transmission systems to GMD events; suppliers that do not meet certain performance requirements must develop a plan to achieve the performance requirements.[3] Table 2

[1]See Federal Energy Regulatory Commission (FERC) Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 F.E.R.C. ¶ 61,147, 78 Fed. Reg. 30,747 (2013). FERC's order directed the North American Electric Reliability Corporation (NERC) to implement the directive in two stages: in the first stage, NERC was to submit reliability standards requiring owners and operators of the bulk-power system to develop and implement operational procedures to mitigate the effects of a geomagnetic disturbance (GMD); in the second stage, NERC was to submit reliability standards requiring owners and operators of the system to conduct initial and on-going assessments of the potential impact of benchmark GMD events on the bulk-power system as a whole and mitigate any vulnerabilities identified.

[2]See NERC Reliability Standard EOP-010-1 (approved by FERC at Order 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014)).

[3]See NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events*, 156 F.E.R.C.¶ 61,215, 81 Fed. Reg. 67,120 (2016). In accordance with FERC Order 779, the second stage of GMD Reliability Standards are to identify benchmark GMD events that responsible entities must assess for potential impacts on the bulk electric system. FERC directed NERC to technically support its choice of benchmarks based on certain factors, such as varying severity of the GMD (i.e., the rate of change in the GMD's magnetic fields), duration, geographic footprint of the GMD, how the GMD's intensity varies with latitude, system configuration, and the orientation of the magnetic fields produced by the GMD. Further, FERC Order No. 779 states that if these assessments identified potential impacts from benchmark GMD events, the Reliability Standards should require owners and operators to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the bulk-power system, caused as a result of a benchmark GMD event. Such a plan could not be limited to operational procedures or enhanced training alone but should contain strategies for protecting against the potential impact of GMDs based on factors such as the age, condition, technical specifications, system configuration or location of specific equipment. Finally, the order states that these strategies could include automatically blocking geomagnetically induced currents (GIC) from entering the bulk-power system, instituting specification requirements for new equipment, inventory management, isolating certain equipment that is not cost effective to retrofit or a combination thereof. See FERC Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 F.E.R.C. ¶ 61,147, 78 Fed. Reg. 30,747 (2013).

summarizes the specific requirements in NERC's stage 1—EOP-010-1—and stage 2—TPL-007-1—standards, the electricity industry entities responsible for them, and their effective dates for the requirements.

Table 2: Requirements, Responsible Parties, and Effective Dates for the North American Electric Reliability Corporation's (NERC) Geomagnetic Disturbance (GMD) Reliability Standards

Requirement	Responsible parties	Effective date
Stage 1 – EOP-010-1[a]		
R1: Each reliability coordinator shall develop, maintain, and implement a GMD operating plan that coordinates GMD operating procedures or processes within its area. At a minimum, the plan shall include (1) a description of activities designed to mitigate the effects of GMD and (2) a process for the reliability coordinator to review the GMD operating procedures or processes of transmission operators within the area.	Reliability coordinators.[b]	April 1, 2015
R2: Each reliability coordinator shall disseminate forecasted and current space weather information to recipients identified in the reliability coordinator's GMD operating plan.	Reliability coordinators.	April 1, 2017
R3: Each transmission operator shall develop, maintain, and implement a GMD operating procedure or process to mitigate the effects of GMD events on the reliable operation of its respective system. At a minimum, the procedure or process shall include: steps or tasks to receive space weather information; system operator actions to be initiated based on predetermined conditions; and conditions for terminating the procedure or process.	Transmission operators whose operating area includes certain high-voltage transformers.	April 1, 2015
Stage 2—TPL-007-1[c]		
R1: Each planning coordinator, in conjunction with its transmission planner(s), shall identify their individual and joint responsibilities for completing geomagnetic disturbance (GMD) vulnerability assessment(s).	Planning coordinators and transmission planners whose planning areas include certain high-voltage transformers.[g]	July 1, 2017
R2: Each responsible entity shall maintain system models and geomagnetically induced current (GIC) system models of their planning area for performing GMD vulnerability assessment(s).	Responsible entities identified in R1 above.	July 1, 2018
R3: Each responsible entity shall have criteria for acceptable system steady state voltage performance for its system during NERC's 1-in-100 year benchmark GMD event.[d]	Responsible entities identified in R1 above.	January 1, 2022
R4: Each responsible entity shall complete a GMD vulnerability assessment once every 60 calendar months. This vulnerability assessment must use a study or studies based on models identified in requirement R2, and document assumptions and summarized results. The assessment will be based on NERC's 1-in-100 year benchmark event to determine whether the system meets certain performance requirements outlined in R4, including avoidance of voltage collapse.[e]	Responsible entities identified in R1 above.	January 1, 2022

Requirement	Responsible parties	Effective date
R5: Each responsible entity shall provide GIC flow information to be used for the transformer thermal impact assessment[f] specified in requirement R6 to each transmission owner and generator owner that owns an applicable power transformer.	Responsible entities identified in R1 above.	January 1, 2019
R6: Each transmission owner and generator owner shall conduct a thermal impact assessment for its solely and jointly owned applicable power transformers based on a maximum effective GIC value of 75 amps per phase or greater.f The assessment will describe suggested actions and supporting analysis to mitigate the impact of GIC, if any.	Transmission owners and generation owners that own certain high-voltage transformers.[g]	January 1, 2021
R7: Each responsible entity that concludes—through the GMD vulnerability assessment conducted in requirement R4—that their system does not meet specified performance requirements, shall develop a corrective action plan. The plan must meet certain requirements outlined in R7, including that it must be reviewed in subsequent GMD vulnerability assessments until it is determined that the system meets the performance requirements.	Responsible entities identified in R1 above.	January 1, 2022

Source: GAO analysis of North American Electric Reliability Corporation (NERC) reliability standards EOP-010-1 and TPL-007-1. | GAO-18-67

Notes: In Order No. 830, the Federal Energy Regulatory Commission (FERC) directed NERC to develop certain modifications to the second stage standard, including (1) modifying the benchmark GMD event definition used for GMD vulnerability assessments, which also affects requirements pertaining to transformer thermal impact assessments, (2) requiring collection of GMD-related data, and for NERC to make the data publicly available, and (3) requiring deadlines for corrective action plans and GMD mitigating actions. FERC Order No. 830, Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, 156 F.E.R.C.¶ 61,215, 81 Fed. Reg. 67,120 (2016). The deadline for these modifications to the second stage standard is 18 months from the effective date of Order No. 830, which is May 29, 2018.

[a]See NERC Reliability Standard EOP-010-1 (approved by FERC at Order 797, Reliability Standard for Geomagnetic Disturbance Operations, 147 F.E.R.C. ¶ 61,209, 79 Fed. Reg. 35,911 (2014)).

[b]The NERC reliability functional model defines the set of functions that must be performed to ensure the reliability of the bulk electric system, and it explains the relationship among the entities responsible for performing the tasks within each function. The functional model includes the following definitions for the responsible parties listed in the table:

- Generation owners: These are the entities that own and maintain generating units.
- Planning coordinators: These are the entities that coordinate and integrate transmission facility and service plans, resource plans, and protection systems.
- Reliability coordinators: These entities are the highest level of authority that is responsible for the reliable operation of the bulk electric system, have the wide area view of the bulk electric system, and have the authority to direct other functional entities within their area of responsibility to take whatever action is necessary—either in advance or in real time—to ensure the reliable operation of the grid.
- Transmission operators: These entities are responsible for the reliability of their "local" transmission system, and operate or direct the operation of the transmission facilities.
- Transmission owners: These entities own and maintain transmission facilities.
- Transmission planners: These entities develop long-term (generally one year and beyond) plans for the reliability (adequacy) of the interconnected bulk electric transmission systems within their portion of the planning authority area.

[c]See NERC Reliability Standard TPL-007-1 (approved by FERC at Order No. 830, Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events, 156 F.E.R.C. ¶ 61,215, 81 Fed. Reg. 67,120 (2016).

[d]NERC's GMD reliability standards drafting team developed a benchmark GMD event representing an event not expected to occur more than once in a 100-year period as determined by a statistical analysis of recorded geomagnetic data.

[e]Voltage collapse is characterized by a loss of control of the voltage levels, which gradually decline in a power system, potentially leading to blackouts.

[f]A transformer thermal impact assessment is an assessment of the heating that transformers experience when GIC is introduced into the transmission system. GIC is known to create conditions that lead to transformer overheating, which can damage transformers and potentially cause them to fail.

[g]The NERC standards apply to transformers with a "high side wye-grounded winding with terminal voltage greater than 200 kilovolts (kV)."

Appendix IV: Select Government and Industry Studies on Electromagnetic Events

An electromagnetic event can result from a naturally occurring, large-scale geomagnetic disturbance (GMD), caused by severe solar weather, or from human-made sources, such as the high-altitude detonation of a nuclear device to create a high-altitude electromagnetic pulse (HEMP). Table 3 provides details on a select number of geomagnetic-related studies performed since 2010 with respect to their objectives, findings, and recommendations.[1] These studies include details on (1) areas of vulnerability for the grid with respect to GMD events, (2) potential impact on the grid from these events, (3) possible mitigation measures, and (4) areas needing further research. For example, as shown in the table, the North American Electric Reliability Corporation's (NERC) and the Department of Energy's (DOE) June 2010 report included a plan to form a task force of government and industry efforts to examine GMD. This resulted in the formation of the NERC GMD Task Force, consisting of government, industry, and academic experts, to examine the GMD threat to the nation's power grid. The task force's work in evaluating the potential impact of GMD events resulted in NERC's subsequent February 2012 report (also shown in table 3) which outlines its plans for working with industry on new reliability standards for GMD events, among other things. As a result of this work, and as directed by the Federal Energy Regulatory Commission (FERC), NERC developed the EOP-010-1 and TPL-007-1 GMD reliability standards.[2] Also as a result of this work, NERC issued a GMD Planning Guide for electricity suppliers, which assists the suppliers in carrying out studies to assess the effects of GMD on their individual networks.[3]

[1]We identified these studies for review based on feedback from government and industry officials regarding relevant studies on GMD and HEMP published since 2010. We also identified some of these studies through references in other reports and documentation. These studies do not represent an exhaustive list of all the research that has been performed on GMD events and their potential impact on the U.S. and Canadian electric grid.

[2]See FERC Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 F.E.R.C. ¶ 61,147, 78 Fed. Reg. 30,747 (2013). The EOP-010-1 standard went into effect in April 2015, with R2 of this standard going into effect on April 1, 2017, and the TPL-001-1 standard will go into effect in stages from 2017 to 2022.

[3]NERC, *Geomagnetic Disturbance Planning Guide* (Atlanta, GA: December 2013). For the purposes of this report, we define "electricity suppliers" as entities that own or operate generation or transmission infrastructure, as well as those with responsibility for planning and overseeing the grid and for selling electricity to consumers.

Table 3: Select Government and Industry Studies on the Geomagnetic Disturbance (GMD) Threat

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Geomagnetic Storms and Their Impacts on the U.S. Power Grid	Metatech Corporation – January 2010	Prepared for the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory, this report describes the threat of geomagnetic storms on the Earth caused by solar activity and further discusses their impacts (past and future) on the U.S. power grid.	According to the authors, this report provides the baseline for determining the future recommendations for protecting the U.S. power grid from this threat in the future. Widespread, prolonged outages are possible from GMD events due to potential damage to key grid components—chiefly transformers—which have long lead time for replacement. Operational contingencies must be planned for to avoid cascading collapse of the grid. Impacts from these events can be exacerbated by aging network infrastructure—particularly transformers.
High-Impact, Low-Frequency Event Risk to the North American Bulk Power System	North American Electric Reliability Corporation (NERC)/DOE – June 2010	NERC and DOE organized a workshop of industry and government experts to identify next steps for several risks to the bulk power system, including GMD and electromagnetic pulse (EMP) events. Topics included (1) approaches to measure and monitor the risks, (2) potential mitigation steps, and (3) formulation of effective public/private partnerships.	"Proposals for Action" for GMD and EMP included: (1) the formulation, by NERC of a task force consisting of government and industry experts to examine mitigation options for both GMD and EMP among others, (2) a call for government authorities in both the U.S. and Canada to develop a long-term research, development, and deployment roadmap on mitigation options to be coordinated with NERC and the electric sector, and (3) the need for NERC and government entities in the U.S. and Canada to develop more timely and accurate information on impending GMD events. As a result of this study, NERC formed the NERC GMD Task Force.

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Approaches for Minimizing Risks to Power System Infrastructure Due to Geomagnetic Disturbances	Electric Power Research Institute (EPRI) – October 2010	This white paper presented an overview of methodologies and approaches to predicting and reducing the impact of GMDs on the electric grid in addition to identifying open research areas.	This paper details potential impacts of GMD on the grid including loss of transformers or other equipment due to overheating. It further states that, in the rare extreme, a large GMD could potentially damage a significant number of transformers and interrupt service for many customers for extended periods. In addition, the paper details various risk factors for GMD impacts on the grid including: (1) line length and orientation, (2) latitude, (3) line and ground resistance, and (4) transformer design. The paper also includes possible operational steps for utilities to minimize risk such as closer monitoring of system voltages in addition to mitigation options such as working with transformer manufacturers to design transformers more resistant to geomagnetically induced current (GIC).
Geomagnetic Storms: An Evaluation of Risks and Risk Assessments	Department of Homeland Security (DHS) Office of Risk Management and Analysis – May 2011	This report was an issue brief intended to promote discussion of critical risk management subjects among homeland security enterprise partners. Specifically, the brief (1) focused on the risk that GMD events present, (2) examined the state of the art for geomagnetic storm risk assessments, (3) outlined lessons and challenges from geomagnetic storm literature, (4) summarized federal government and DHS initiatives on storms, and (5) presented areas for consideration and additional study by DHS.	According to this report, a geomagnetic storm that degrades the grid would affect not only the energy sector, but the transportation, communication, banking, and finance sectors, as well as government services and emergency response capabilities. Without a sense of the likelihood of such events or a mechanism for relative comparisons, cost benefit analyses have been unable to demonstrate the utility of investing either in hardening or in testing and maintaining operational procedures. The Federal government lacks comprehensive national-level geomagnetic storm risk management assessments and strategies, and no standing entity exists to coordinate cross-federal government geomagnetic storm risk analysis. The federal government should consider whether it is appropriate to conduct formal, comprehensive risk assessment regarding severe geomagnetic storms.

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Impacts of Severe Space Weather on the Electric Grid	JASON, published by MITRE Corporation – November 2011	This study was performed by MITRE, under a contract with DHS, to (1) assess the impacts of space weather on the electric grid, (2) understand how previous solar storms have affected some grids, and (3) determine what cost-effective methods are available to protect the grid, among other topics.	Key findings and recommendations included the need for a rigorous risk assessment to determine how plausible a worst-case scenario may be and additional research to better understand how transformers may be impacted by GMD. This report also recommended the potential installation of blocking devices to minimize the impacts of GIC.
Geomagnetic Storms and Long-Term Impacts on Power Systems	DOE/Pacific Northwest National Laboratory (PNNL) – December 2011	PNNL was commissioned to study the potential impact of a GIC event on the western United States/Canada power grid focusing on long transmission lines (over 150 miles) that did not include series capacitors.	This report discusses the March 1989 Hydro-Quebec power failure resulting from a GIC event with respect to the specific causes of the failure and lessons learned. In addition, the report covers preventive measures that can be implemented to minimize damage and power outages including the installation of technology such as series capacitors and protective relays. PNNL concluded in this report that the western United States/Canada power grid was not substantially at risk to GIC due to the relatively small number of long transmission lines exceeding 150 miles.
Effects of Geomagnetic Disturbances on the Bulk Power System	NERC GMD Task Force – February 2012	This report produced by the NERC GMD task force in response to findings from the June 2010 report (see above).	The task force concluded that a severe GMD event will not likely result in failure of a large number of transformers as indicated by other studies, although certain older transformers could experience damage and generator step-up transformers could be particularly vulnerable. Voltage instability is a more likely result than failing transformers. This report provided industry participants with procedures and methods to better manage risks from geomagnetic disturbances but cautioned that these are dependent on factors such as individual suppliers' equipment characteristics, system design, and operating philosophy, among others. Recommended actions for NERC included: (1) development of improved tools for GMD mitigation strategies and management of GMD impacts, (2) enhancement of information exchanges between researchers and industry, and (3) review of the need for enhanced NERC reliability standards.

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Solar Storm Risk to the North American Electric Grid	Lloyd's — 2013	The report discusses the likelihood of extreme geomagnetic storms, specific vulnerabilities of the North American power grid, the regions at highest risk from this complex natural hazard and the implications for the insurance industry and society generally.	The report found that: (1) an extreme GMD event (i.e., "Carrington-level event") is almost inevitable in the future, (2) as the grid ages and dependence on electricity increases, the risk of a catastrophic outage also increases with the peak of each solar cycle, (3) the highest risk of storm-induced power outages in the United States is along the Atlantic corridor between Washington, D.C., and New York City, (4) total U.S. population at risk during an event is between 20 and 40 million with a duration of between 16 days to 1 to 2 years (exact duration largely dependent on the availability of spare transformers, and (5) less severe GMD events could still adversely impact highly-populated areas if concentrations of transformers servicing those areas are affected.
Study of the Impact of Geomagnetically Induced Currents on the North American Eastern and Western Interconnects	EPRI – October 2013	This project addresses the modeling of power system impacts of GMDs and GICs, incorporating them into the power flow framework.	Among various findings related to system modeling for GIC, the study found that GIC tends to concentrate at network edges and is also predominant in higher voltage networks. Voltage collapse analysis of large-scale models examined in this study shows the level of GIC and reactive power losses required to cause the system to experience a voltage collapse.
Electromagnetic Transient-Type Transformer Models for Geomagnetically-Induced Current (GIC) Studies	EPRI – November 2013	This report detailed an analysis of the modeling of different transformer types to determine potential impacts from GIC.	The report proposed a new model of transformer for GIC simulation studies.
Update on Studies of Extreme Geomagnetically-Induced Current Event Scenarios	EPRI – December 2013	This was a study of extreme geomagnetic storm and GIC scenarios, including different ground-conductivity structures and geomagnetic latitudes, intended to further power engineering analyses to assess the risk space weather poses to high-voltage transmission systems.	Among other things, study found that, in the most extreme storms, geomagnetic latitude threshold may propagate down to about 40 degrees of geomagnetic latitude.
Analysis of Geomagnetic Disturbance (GMD) Related Harmonics	EPRI – March 2014	This report describes the characteristics of harmonic distortion caused by transformers during a GMD event and an assessment of tools needed by industry to perform an adequate assessment of GMD-related impacts.	This study concluded that industry needs new tools and additional guidance to fill gaps in capabilities and knowledge in order to include harmonic issues related to transformers in GMD impact assessments.

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Large Power Transformer Study	DOE – April 2014	This report was an update by DOE to a 2012 report on large power transformers and U.S. electric grid that assessed the procurement and supply environment of large power transformers. In this report, DOE examined the characteristics and procurement of large power transformers, and the availability of global and domestic suppliers, and assessed the potential risks facing these transformers, among other things. The report also discussed new government and industry efforts to augment risk management options for critical infrastructure, including power transformers.	This study concluded that the demand for large power transformers will remain strong worldwide and challenges continue to exist in acquiring these transformers given this strong demand. These challenges include (1) limited supply sources for raw materials—particularly copper and electrical steel, (2) long lead times to acquire and associated transportation challenges, and (3) limited production capability in the United States. However, the report noted that new domestic manufacturers are coming on line that will provide some relief to the U.S. dependence on foreign manufacturers.
Assessing the Impact of Space Weather on the Electric Power Grid Based on Insurance Claims for Industrial Equipment	Lockheed Martin – July 2014	This study details a statistical analysis of 11, 242 insurance claims from 2000 to 2010 for equipment losses and related business interruptions in North America that are associated with damage to, or malfunction of, electrical and electronic equipment.	In this peer-reviewed journal article, researchers found that insurance claim rates are elevated on days with increased geomagnetic activity. Also, when focusing on the claims explicitly attributed to electrical surges (more than half of the total sample), researchers found that claim rates on geomagnetic activity is correlated with major disturbances in the U.S. high-voltage electric power grid.

Source: GAO based on review of various GMD studies. | GAO-18-67

Table 4 provides details on a select number of unclassified HEMP-related studies performed since 2010 with respect to their objectives, findings, and recommendations.[4] These studies include details on (1) areas of vulnerability for the grid with respect to HEMP events, (2) potential impact on the grid from these events with respect to all three HEMP pulses (E1, E2, and E3), (3) possible mitigation measures, and (4) areas needing further research.

[4]We identified these studies for review based on feedback from government and industry officials regarding relevant studies on HEMP published since 2010. We also identified some of these studies through references in other reports and documentation. These studies do not represent an exhaustive list of all the research that has been performed on HEMP events and their potential impact on the U.S. and Canadian electric grid.

Table 4: Select Government and Industry Studies Related to the High-Altitude Electromagnetic Pulse (HEMP) Threat

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
Five Technical Reports Addressing EMP Impacts on the U.S. Power Grid	Oak Ridge National Laboratory – January 2010	These reports were authored by external industry experts and examined the EMP threats and their potential impacts in addition to potential solutions for preventing and mitigating their effects.	Findings and recommendations included efforts to develop, test, and deploy mitigation technologies to automatically protect the power grid from costly damage and improve reporting and monitoring of the grid.
Electromagnetic Pulse (EMP) Impacts on Extra High Voltage Power Transformers	DHS – April 2010	This study addressed (1) how realistic the threat from EMP is, (2) the level of vulnerability of transformers to each of the three pulses produced by an EMP event (E1, E2, and E3), (3) the impact of an EMP incident on the grid, and (4) technologies or methodologies available to harden and protect transformers.	Key findings included (1) control systems could lose functionality or fail completely, primarily due to early-time, high frequency E1 pulse effects, (2) an E3 pulse from and EMP event is a major threat to transformers, and (3) generator step-up transformers usually operate near full load and are, therefore, more sensitive to the E3 pulse. The report also discussed various technology options for mitigating the impact of E3 pulse on transformers such as installing series capacitors or specific transformer design specifications.
Strategies, Protections, and Mitigations for the Electric Grid from Electromagnetic Pulse Effects	DOE, Idaho National Laboratories – January 2016	DOE chose Idaho National Laboratory to conduct an EMP study due to its capabilities and experience in setting up EMP experiments on the grid, conducting vulnerability assessments, and developing innovative technologies to increase infrastructure resiliency.	This study examined various sources on EMP effects and concluded that they were lacking due to the age of the tests, general lack of data, and the fact that they were not based on modern grid technologies. In addition, the report noted that most sources on the impact of EMP are decades old and do not include communications technologies for control of the grid. Also, most previous mitigation advice does not take into account protection from all 3 EMP pulses (E1, E2,and E3). The number of unknowns prevents industry from knowing where to direct investments in EMP protection. The report concluded that baselining the threat, impacts to the grid, and the effectiveness of the mitigation options for all EMP pulses is needed to most effectively inform the electric power industry.

Name of study	Organization and date	Description/Objectives of study	Findings, recommendations, and any results from study
EMP/GMD Phase 0 Report: A Review of EMP Hazard Environments and Impacts	Los Alamos National Laboratory – November 2016	This report provides an overview of EMP hazard environments and potential impacts on components of the electric grid.	The study concluded that EMP could cause widespread, long-term outages. However, the report added that many outages, even those that are widespread, are restored within 1 to 2 days. Future phases of this study will seek to define "events of concern," describe how to analyze consequences of these events, and perform initial work to demonstrate the viability of this analysis.
Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid	EPRI – February 2017	This report details an assessment of the U.S. transformer fleet to determine the potential for widespread damage resulting from the E3 pulse component of a HEMP event.	EPRI found that a small number of geographically-dispersed transformers were potentially at risk for thermal damage from the E3 pulse. However, the study did not assess the potential impact on the grid of the loss of these transformers and EPRI expected that aspect to be examined in future studies.
Electromagnetic Black Sky Responses of Power and Control Equipment	SARA, Inc. for the Electric Infrastructure Security Council – July 2017	The focus of this report is an attempt to survey the responses of various electric power system equipment and controls to HEMP and GMD including transformers and control equipment such as relays and sensors.	Overall, the report noted minimal effects from HEMP on most power system components, including transformers. However, the report noted that most digital relays not incorporating EMP protection suffered damage. The report also noted areas needing further study with respect to other power system components.
Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid	EPRI – December 2017	This report evaluated the potential for the E3 pulse to cause instability in the bulk power system and is a continuation of the previous EPRI assessment of the potential of GIC from E3 to cause thermal damage to transformers.	The results of this assessment indicate that voltage collapse due to E3 alone is possible for several of the target locations that were evaluated. EPRI further reported that, while the geographic extent of the impact was estimated to be on the order of several states or larger, none of the scenarios that were evaluated resulted in a nationwide grid collapse.

Source: GAO based on review of various HEMP studies. | GAO-18-67

Appendix V: Details on the U.S. Department of Energy's (DOE) Electromagnetic Pulse (EMP) Resilience Action Plan

DOE's EMP Action Plan (DOE Action Plan), issued January 2017, describes 19 actions to be taken by September 30, 2021, to enhance the resilience of the electric power grid to high-altitude electromagnetic pulse (HEMP) effects.[1] DOE stated that its Action Plan considers the over 90 recommendations made in the 2008 Commission to Assess the Threat of the United States from Electromagnetic Pulse (EMP) Attack (EMP Commission) report and at least partially addresses 10 of the 15 recommendations directly related to the electric power system made by the EMP Commission in their report.[2] See table 5 for these 10 EMP

[1]U.S. Department of Energy, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan* (Washington, D.C.: Jan. 2017).

[2]Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack—Critical National Infrastructures* (April 2008). The Department of Energy (DOE) concluded that the remaining 5 recommendations related to the electric power system would be better addressed by industry or other agencies. These include (1) the evaluation and implementation of quick fixes, (2) assuring availability of crucial communication channels, (3) assuring protection of high-value generation assets, (4) assuring protection of high-value transmission assets, and (5) assuring sufficient numbers of adequately trained recovery personnel.

Commission recommendations from 2008 and corresponding components of DOE's 2017 Action Plan.[3]

Table 5: Ten Electromagnetic Pulse (EMP) Commission Recommendations from 2008 Related to the Electric Power System and Corresponding Components of the Department of Energy's (DOE) 2017 Action Plan

Commission recommendation	Commission explanation of recommendation	Department of Energy (DOE) action plan item corresponding to commission recommendation[a]
Need to understand system and network-level vulnerabilities, including cascading effects	Encouraged research to identify system vulnerabilities and cost effective and necessary modifications to improve system performance with respect to Electromagnetic Pulse (EMP) and other threats.	(1) Generating a shared understanding of potential EMP effects, (2) identifying gaps in EMP knowledge, and (3) developing an understanding of the susceptibility of specific grid components.
Developing national and regional restoration plans	Prioritize rapid restoration of power, particularly critical areas identified by the government.	Identifying and evaluating critical infrastructure and functions and any specific differences related to EMP.

[3]Established pursuant to the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, the EMP Commission was responsible, among other things, for assessing the nature and magnitude of potential HEMP threats to the United States and the capability of the United States to prepare and recover from a HEMP attack. Pub. L. No. 106-398, §§ 1401-09, 114 Stat. 1654, 1654A-345-348 (2000). See also National Defense Authorization Act for Fiscal Year 2006, Pub. L. No. 109-163, § 1052, 119 Stat. 3136, 3434-35 (reestablishing the EMP Commission to monitor, investigate, make recommendations, and report to Congress on the evolving threat to the United States of an EMP attack resulting from the detonation of a nuclear weapon or weapons at high altitude); National Defense Authorization Act for Fiscal Year 2008, Pub. L. No. 110-181, § 1075, 122 Stat. 3, 333 (providing, among other things, that the EMP Commission and the Secretary of Homeland Security shall jointly ensure that the work of the EMP Commission and the Secretary of Homeland Security with respect to EMP attack on electricity infrastructure, and protection against such attack, is coordinated with DHS efforts on such matters); National Defense Authorization Act for Fiscal Year 2016, Pub. L. No. 114-92, § 1089, 129 Stat. 726, 1015-16 (2015) (reestablishing the EMP Commission but with an expanded purpose that includes the evolving threat from, among other things, nonnuclear and naturally occurring EMP). The EMP Commission's charter expired on June 30, 2017. Id. § 1089. While the commission did not specifically identify a total number of recommendations, our analysis of the commission report identified over 90 recommendations, which included key recommendations and related subareas across 10 critical infrastructure sections, including electric power, telecommunications, and emergency services among others. The National Defense Authorization Act for Fiscal Year 2018 established a new Commission to Assess the Threat to the United States from Electromagnetic Pulse Attacks and Similar Events, which is to review and assess a number of issues related to potential electromagnetic pulse events and similar events, such as the nature, magnitude, and likelihood of potential electromagnetic pulse attacks and similar events, including geomagnetic disturbances, and the capability of the United States to repair and recover from damage inflicted on United States military and civilian systems by EMP attacks and similar events. See Pub. L. No. 115-91, tit. XVI, subtit. F, § 1691 (2017).

Commission recommendation	Commission explanation of recommendation	Department of Energy (DOE) action plan item corresponding to commission recommendation[a]
Assuring availability of replacement equipment	Ensure adequate, timely supply of parts to repair or replace damaged power system components to allow for rapid restoration.	Analyze the unique types of EMP damage to inform protection and mitigation strategies, including a stockpile of components to facilitate recovery.
Expanding and extending emergency power supplies	The number of stand-alone back-up and emergency power supplies for critical services during restoration of the grid should be increased.	Assess the impacts of EMP on generators commonly used for backup power generation and preparation of a report on issues, concerns, and potential mitigation and protection options.
Extending black start capability	Require all power plants above a certain size have "black start" capability which allows them to start up without power from the grid.	Analyze suppliers' challenges to startup following EMP-induced damage. Ensure suppliers' response and recovery plans include EMP events.
Prioritizing and protecting critical nodes	Require government entities to identify critical areas for electricity service and recovery including elements that facilitate a rapid and effective recovery of the grid.	Identify and evaluate methodologies for identifying critical infrastructure and formulating recommendations.
Expanding and assuring intelligent islanding capability	Develop the capability to compartmentalize the electrical grid to minimize the impact of an EMP event and provide for more rapid and widespread recovery.	Studying the options available to island the grid and reporting on its effectiveness.
Simulating, training, exercising, and testing the recovery plan	Develop multiple centers for the purpose of simulating EMP and other major system threatening attacks in order to (1) identify weaknesses, (2) provide training for personnel, and (3) coordinate industry and agency activities.	Develop materials for identifying unique challenges of recovering from EMP that can be used in training modules and in preparing EMP exercises.
Developing and deploying system test standards and equipment	Test and evaluate multiple system components to ensure that system vulnerability to EMP is identified and mitigation and protection efforts are effective.	(1) Examine the susceptibility of specific critical electric grid components, (2) highlight the levels of EMP that various components can withstand, and (3) use and assess existing models to identify potential impacts on grid components.
Establishing installation standards	The government should set hardening standards for electric power protective systems and provide fiscal assistance to industry in implementing them.	Analyze the need for a pilot program to harden substations and generation equipment to a range of EMP scenarios, and evaluate the effectiveness of hardening measures.

Source: GAO analysis of similarities between select 2008 EMP Commission recommendations and DOE's 2017 Action Plan. | GAO-18-67

[a]For each 2008 EMP Commission Report recommendation detailed in the first two columns of this table, we reviewed the various items in DOE's Action Plan and identified (in this third column) which of those Action Plan items fit within the scope of each Commission recommendation.

As of November 2017, based on our review of implementation dates for specific actions in DOE's plan, the agency had yet to complete 15 of the 19 actions detailed in the Action Plan but had initiated efforts under the plan to identify gaps in HEMP knowledge and coordinate government and

industry information sharing with the electricity sector and other critical industry sectors. Future work DOE expects to address under the plan will include (1) evaluating existing models used to estimate EMP impacts to the grid, (2) the adequacy of backup power generation in the wake of an EMP event, (3) establishing a national capability for conducting EMP testing of existing grid components, (4) identifying and evaluating mitigation and protection measures for various grid components, and (5) assessing the feasibility of testing different hardening techniques for substations for EMP scenarios. The DOE Action Plan includes deliverables and due dates for the 19 action items detailed in the plan which, according to DOE, are subject to the availability of necessary funding. See table 6 for details on these deliverables, and associated dates, for each action item.

Table 6: Action Items, Deliverables, and Completion Dates for Components of the Department of Energy's (DOE) 2017 Action Plan for Carrying Out Its Responsibilities under the DOE-Industry Joint Strategy for Electromagnetic Pulse (EMP)

Department of Energy (DOE)-Industry joint strategy goal	DOE action item	Deliverable	Projected date for completion
Improve and share understanding of electromagnetic pulse: Threat, Effects, and Impacts	1.1 Generate a shared understanding of potential electromagnetic pulse effects	1.1.1 Maintain classified and unclassified briefing materials that address the current understanding of the potential impacts of high and low impact electromagnetic pulse events on the electric grid.	12/31/16 (DOE reports preparing both classified and unclassified briefings and has conducted both during 2017.)
		1.1.2 Create a schedule of industry, interagency, and cross-sector briefings using these materials.	3/31/17 (DOE reports providing both classified and unclassified briefings as needed.
	1.2 Identify gaps in EMP knowledge	1.2.1 Establish a working group of the Mission Execution Council to identify current gaps in electromagnetic pulse knowledge among the National Laboratories and other federal agencies.	10/31/16 (DOE reports this working group has been established.)
		1.2.2 Produce a report documenting Mission Executive Council findings.	12/31/16 (DOE reports that, as of November 2017, the draft report is being reviewed by Mission Executive Council principals.)

Department of Energy (DOE)-Industry joint strategy goal	DOE action item	Deliverable	Projected date for completion
	1.3 Coordinate government-industry information sharing	1.3.1 Establish an electromagnetic pulse information working group in coordination with the Electric Power Research Institute, the Electricity Subsector Coordinating Council, and appropriate stakeholders.	12/31/16 (DOE reports that no formal working group has been formed. However, DOE meets with Electric Power Research Institute and DHS partners more than once monthly and with the Electricity Subsector Coordinating Council quarterly.)
	1.4 Develop unclassified composite E1/E2/E3 waveforms for use by industry in modeling/testing their systems	1.4.1 Develop and disseminate unclassified E1 waveforms.	12/31/17 (DOE reports this deliverable will not be completed until at least December 2018 due to contractual issues.)
		1.4.2 Develop and disseminate unclassified composite E1/E2/E3 waveforms.	12/31/19
		1.4.3 Develop and disseminate a set of unclassified waveforms for coupled currents and voltages for transmission and distribution lines.	12/31/20
	1.5 Provide an understanding of the susceptibility of specific critical electric grid components to EMP waveforms	1.5.1 Develop a report that highlights past test results, including data sheets showing the estimated levels of EMP that various equipment and sub-systems can withstand, as necessary to supplement current data available from equipment suppliers.	5/31/19
	1.6 Evaluate interactive EMP system and component modeling capabilities	1.6.1 Develop a report on the evaluation and comparison of existing EMP models of EMP effects, coupling, and impacts, including recommended areas where new models or validation are needed, or where existing models should be refined.	3/31/18
	1.7 Develop realistic risk-based EMP planning scenarios for use by industry for planning purposes and assess/model expected damage for each scenario	1.7.1 In coordination with the Department of Homeland Security (DHS), develop a set of EMP planning scenarios that can serve as the basis for threat waveform specifications and assessments of EMP impacts and protection requirements for the grid as well as supporting infrastructure.	10/31/17 (DOE reports this work is ongoing and the completion date has been revised to October 2018.)

Department of Energy (DOE)-Industry joint strategy goal	DOE action item	Deliverable	Projected date for completion
		1.7.2 In coordination with DHS and industry partners, use the EMP planning scenarios of concern as inputs into available models of EMP impacts to the electric grid. The results will be analyzed.	10/31/19
		1.7.3 In coordination with DHS, issue a report on the findings from the analysis on the use of the EMP planning scenarios to model EMP impacts to the electric grid.	1/31/20
	1.8 Report on potential issues of concern for critical infrastructure from the loss of off-site utility power from EMP	1.8.1 Assess the impacts of EMP on generators commonly used for backup power generation and prepare a report on issues, concerns, and potential mitigation and protection operations to ensure critical assets can continue to safely function during a long term power outage due to EMP.	12/31/18
Identify priority infrastructure	2.1 Identify and evaluate methodologies for identifying critical infrastructure and functions and any differences related to EMP	2.1.1 Prepare a report that identifies and evaluates methodologies for identifying critical infrastructure, reviews findings and includes recommendations.	3/31/17 (Completed. DOE reported identifying and reviewing FERC's existing methodology and concluding that no new methodology was necessary.)
		2.1.2 Collaborate with the Federal Energy Regulatory Commission (FERC), DHS, and industry to improve methodologies as recommended in the report to reflect changing technologies and conditions.	9/30/20
Test and promote mitigation and protective approaches	3.1 Establish a national capability to conduct EMP testing of grid components, systems, and protection technologies	3.1.1 Develop and validate EMP test requirements, including design and planning considerations.	9/30/18
		3.1.2 Advance long-term capabilities for providing testing of individual electric components and the grid system as a whole in a realistic environment.	12/31/18
		3.1.3 Document test results of individual components and appropriately dissemble analysis describing vulnerabilities and impacts, which may include disruption thresholds and points at which components and equipment are damaged or destroyed.	6/30/19
		3.1.4 Document test results of the electric grid as a system and validate models for industry use.	6/30/20

Department of Energy (DOE)-Industry joint strategy goal	DOE action item	Deliverable	Projected date for completion
	3.2 Understand the limits and benefits of islanding as an EMP protection strategy	3.2.1 Develop a study on the options available to island the grid and report on the effectiveness as a prevention and/or mitigation strategy including costs, benefits, and implementation feasibility of islanding in response to an EMP.	6/30/19
	3.3 Validate mitigation and protection strategies	3.3.1 Develop a report identifying and evaluating effective mitigation and protection measures for different components, equipment, and sub-systems.	12/31/20
	3.4 Analyze the need for a pilot program to harden substations to a range of EMP scenarios	3.4.1 Develop a report and project timeline to assess the feasibility of running field tests of different hardening techniques for a set of EMP scenarios.	9/30/21
Enhance response and recovery capabilities to an EMP attack	4.1 Familiarize the community to the unique challenges of recovering from EMP-induced damage	4.1.1 Develop an EMP training and exercise module to identify unique recovery challenges after an EMP based on hypothetical waveform information developed as a result of Goal 1 for use in national exercise scenarios.	12/31/19
		4.1.2 Adapt one or more DOE-hosted exercises to involve an EMP scenario.	6/30/20
	4.2 Explore the possibility of providing industry with warning and alert data regarding potential and actual EMP attacks on the United States	4.2.1 Meet with appropriate government departments and agencies to explore the possibility of timely notification(s) of impending EMP events to the emergency operations centers of electric power grid owners/operators and DOE.	6/30/18
	4.3 Understand the unique profile of EMP-induced damage	4.3.1 Conduct an analysis of the unique footprint of E1/E2/E3 damage at a level of detail that informs protection and mitigation strategies and the need to stockpile additional components to facilitate recovery.	12/31/20
	4.4 Understand the unique challenges of black starts after EMP-induced damage	4.4.1 Analyze the unique challenges facing utilities attempting a black start following EMP-induced damage.	6/30/20
		4.4.2 Work with industry and related organizations to encourage owners and operators to develop EMP annexes to their response and recovery plans that incorporate effective practices to mitigate damage and expedite restoration and recovery from an EMP event.	6/30/21
Share best practices across government and industry, nationally, and internationally	5.1 Share EMP information and best practices with other sectors	5.1.1 Share information with the Energy Government Coordinating Council (EGCC) and other sectors at EGCC meetings and other settings.	9/30/18

Department of Energy (DOE)-Industry joint strategy goal	DOE action item	Deliverable	Projected date for completion
	5.2 Share EMP information and best practices with other nations	5.2.1 Meet with foreign government officials and other organizations to share information on EMP resilience practices in unclassified and classified environments and to bring information back to other U.S. partners.	9/30/18

Source: DOE's 2017 EMP Action Plan. | GAO-18-67

Appendix VI: GAO Contacts and Staff Acknowledgments

GAO Contacts

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Staff Acknowledgments

In addition to the individuals named above, Jon Ludwigson (Acting Director), Ben Atwater (Assistant Director), and Barbara Guffy (Analyst-in-Charge) managed this assignment. Frederick K. Childers, Jonathan Felbinger, Daniel Friess, Alexandra D. Gebhard, Michael Harmond, Eric Hauswirth, Richard Hung, Miles Ingram, and Heidi Nielson made key contributions to this report.

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