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Ensuring Electricity Infrastructure Resilience Against Deliberate Electromagnetic Threats

December 14, 2022

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SUMMARY

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Ensuring Electricity Infrastructure Resilience Against Deliberate Electromagnetic Threats

Detonation of a nuclear weapon in the Earth's upper atmosphere or near-Earth space may generate a series of electromagnetic pulses—known as high-altitude electromagnetic pulse (HEMP)—that damage critical infrastructure on the Earth's surface. Observers are most concerned about potential HEMP effects on the electricity sector, given its specific vulnerabilities to electromagnetic threats and its role in maintaining the full range of essential infrastructure functions nationwide.

Scientists believe HEMP is generated by the interaction of the radiation and blast effects of an exploding nuclear device with the earth's upper atmosphere, magnetic field, and conductive geologic formations. HEMP has three main time components, usually labeled E1, E2, and E3, which occur in rapid sequence and create distinct and potentially hazardous effects over a broad geographic area. The E1 pulse may directly radiate sensitive electronics or couple with electrical equipment via control cables or other conductors. The E2 pulse has effects similar to lightning. The E3 pulse may induce currents in long-distance transmission lines that damage or disrupt large power transformers (LPTs) and other essential equipment.

While there is broad consensus in the electricity industry, the research community, and among policymakers that HEMP attacks may pose risk to electricity infrastructure, there is disagreement regarding specific HEMP hazard characteristics, the level of risk, and the need for—or feasibility of—expansive hardening initiatives. Although the basic theories underlying HEMP research are well-established, HEMP involves a range of complex physical phenomena—from sub-atomic processes to complex interactions of networked infrastructure systems under stress—which are not fully understood. The degree (and policy relevance) of scientific uncertainty is itself a significant source of disagreement among stakeholders.

In recent decades, Congress has pressed the research community and relevant federal agencies to advance scientific understanding of HEMP-related hazards to infrastructure, and to produce more authoritative risk assessments to inform both policy development and industry action. Congress has enacted a variety of mandates—primarily via national defense authorization acts—to spur basic research, applied research, and technology development, as well as risk management activities such as risk assessments, adoption of voluntary standards and best practices, and the expansion of public-private partnerships for coordination and information sharing with industry. A congressionally-chartered expert commission provided congressional testimony, reports, and recommendations between 2004 and 2017.

The 117th Congress has appropriated funds for new infrastructure investments through the Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58) and the Inflation Reduction Act (IRA; P.L. 117-169), even as implementation of previous mandates continued. Rapid introduction of solar and wind generation of electricity, microgrids, and utility-scale energy storage may offer potential resilience benefits, but could also introduce new vulnerabilities. Likewise, new operational control technologies to support integration of distributed energy resources with existing distribution networks may offer additional flexibility and resilience to the grid—assuming potentially sensitive electronic components are not damaged by HEMP. Research into the resilience of these technologies against HEMP is in its early stages. Research gaps complicate guidance to policymakers or industry stakeholders on near-term prioritization of critical systems and assets for hardening or other countermeasures. As a remedy, some IIJA provisions include HEMP research as an authorized activity. Other provisions may support HEMP research, but do not specifically authorize it. Actual support for HEMP resilience will largely depend upon how funds are apportioned to specific programs by implementing agencies.

Several other issues for Congress may also warrant attention. Gaps in data used to model HEMP hazards and their effects on infrastructure have long been identified as an obstacle to providing more authoritative risk assessments to key stakeholders. Improved coordination and information sharing between defense and civilian researchers may address some gaps. Additionally, resilience of new technologies to HEMP is an emerging concern. Congress may support additional research and development of resilience standards through its oversight and legislative authorities, while considering potential future technological advancements as appropriate. Emerging solid state technologies may enable introduction of standardized systems to replace older technologies, such as LPTs that require long lead times for manufacture, customization, and transport. Given the long service life of most electricity infrastructure assets, it may be appropriate to encourage investment in next-generation technologies, where possible, to avoid inefficient use of limited resources to harden obsolescent technologies against HEMP.

Contents

Figures

Tables

Appendixes

Contacts

Introduction

Detonation of a nuclear weapon in the upper atmosphere or in near-Earth space may generate a series of electromagnetic pulses—known collectively as high-altitude electromagnetic pulse (HEMP)—that damage the electric grid and other critical infrastructure on the earth's surface.[1] HEMP may directly radiate and damage sensitive electronics used to operate the grid, or couple with transmission lines and other conductors attached to essential equipment. This report focuses on HEMP-related risk to the electric grid, given its centrality to the operation of many other critical networked systems, such as water, transport, and communications. Other deliberate electromagnetic threats, such as battlefield electromagnetic pulse (EMP) weapons or improvised devices powered by conventional explosives, are outside the scope of this report. Likewise, this report does not provide an assessment of intent or capabilities of potential adversaries, or the likelihood of a HEMP attack.[2]

While there is broad consensus in the electricity industry, the research community, and among policymakers that high-altitude electromagnetic pulse attacks may pose risk to electricity infrastructure, there is disagreement regarding specific HEMP hazard characteristics, the level of risk, and the need for—or feasibility of—expansive HEMP-hardening initiatives.[3]

Congress has enacted a variety of mandates—primarily via national defense authorization acts—to spur basic research, applied research, and technology development, as well as risk management activities, risk assessments, adoption of voluntary standards and best practices, and the expansion of public-private partnerships for coordination and information sharing with industry. A congressionally chartered expert commission provided congressional testimony, reports, and recommendations between 2004 and 2017.

Most federal legislation has focused on the electricity sector, reflecting the broad consensus and priorities of government, industry, and the research community. Implementation of previous congressional mandates is ongoing, even as the 117th Congress has appropriated funds for new infrastructure investments through the Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58), the Inflation Reduction Act (IRA; P.L. 117-169), and other legislation. Prospective upgrades and buildout of electricity infrastructure may affect the sector's overall resilience to HEMP hazards,

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[1] The Cybersecurity and Infrastructure Security Agency (CISA), a Department of Homeland Security agency, designates electricity as a subsector of the Energy critical infrastructure sector, which includes generation, transmission, and distribution except for hydroelectric and commercial nuclear power facilities. See Department of Homeland Security and Department of Energy, *Energy Sector Specific Plan*, Washington, DC, 2015, p. 3, https://www.cisa.gov/sites/default/files/publications/nipp-ssp-energy-2015-508.pdf. As used in this report, "electricity sector" encompasses the entirety of the national generation, long distance transmission, and local distribution infrastructure.

[2] The congressionally-chartered Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (the EMP Commission) released several papers assessing foreign adversaries' intent and capabilities prior to its dissolution. See Peter Vincent Pry, *Foreign Views of Electromagnetic Pulse Attack*, the EMP Commission, Washington, DC, July 2017; ibid., *Political Military Motives for Electromagnetic Pulse Attack*, the EMP Commission, Washington, DC, July 2017; and ibid., *Nuclear EMP Attack Scenarios and Combined-Arms Cyber Warfare*, Washington, DC, July 2017. Available online at http://www.firstempcommission.org/.

[3] Some experts believe that certain of these hardening measures to protect essential grid equipment or maintain stockpiles of spare equipment may make the grid more resilient against more-frequently occurring electromagnetic threats from space weather, cyber, or physical attacks, providing additional potential benefits. See The 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 (the EMP Commission critical infrastructure report),Washington, DC, April 2008, p. 53, http://www.firstempcommission.org/uploads/1/1/9/5/119571849/emp_comm._rpt._crit._nat._infrastructures.pdf.

either by design or by chance. Congress may exercise oversight of related programs and activities to ensure that HEMP resilience is incorporated into electricity infrastructure at desired levels.

This report provides information on (1) the basic physics of HEMP; (2) existing risk management approaches and related legislation, policies, and directives; (3) the current state of scientific knowledge and related research programs; and (4) emerging science and technology policy issues. A concluding section summarizes potential issues for Congress.

High-Altitude Electromagnetic Pulse (HEMP) and Hazards to Electricity Infrastructure

U.S. and Soviet high-altitude weapons tests in the upper atmosphere in the late 1950s and early 1960s suggested that the electromagnetic effects of nuclear bombs detonated at high altitude (above 30 km) were potentially damaging to electrical grids, communications infrastructure, and other vital electronics-based systems many hundreds of miles away from the blast epicenter. Therefore, HEMP became a phenomenon of concern to military and civil defense planners.

The Partial Test Ban Treaty of 1963, signed by the United States, the United Kingdom, and the Soviet Union, precluded further scientific observations of HEMP effects on infrastructure in situ.[4] However, military and civilian scientists have continued theoretical work and laboratory testing on grid components and other electronics. In addition, naturally occurring space weather produces geomagnetic disturbances (GMD)—comparable in some aspects to the late-time (E3) magnetohydrodynamic pulse produced during HEMP events—that inform empirical research on large-scale electromagnetic hazards to infrastructure in natural settings.[5]

The HEMP Waveform

In general, scientists believe HEMP is generated by the interaction of the radiation and blast effects of an exploding nuclear device with the earth's upper atmosphere, magnetic field, and conductive geologic formations. HEMP has three main time components, usually labeled E1, E2, and E3, which occur in rapid sequence and create distinct and potentially hazardous effects over a broad geographic area.

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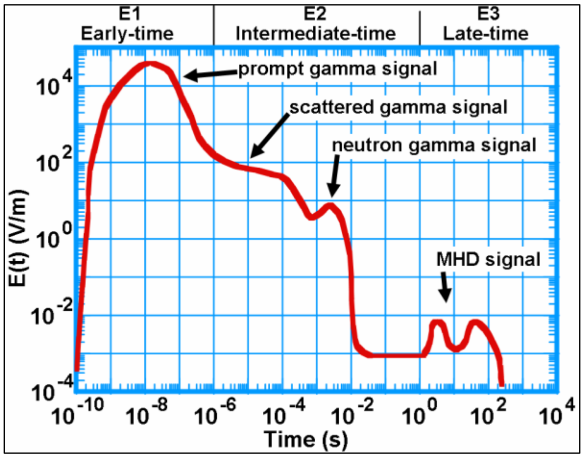
[4] See the National Archives, "Test Ban Treaty (1963)," https://www.archives.gov/milestone-documents/test-ban-treaty.

[5] Space weather refers to the dynamic conditions in Earth's outer space environment. This includes conditions on the Sun, in the solar wind, and in Earth's upper atmosphere. Both space weather-related geomagnetic disturbances and the late-time high-altitude magnetohydrodynamic pulse cause disturbances in the Earth's ambient magnetic field that may cause geologically induced currents, although there are significant differences in rise time, duration, geographic distribution, and amplitude. See Ross Guttromson, Craig Lawton, and Matthew Halligan, et al., *Electromagnetic Pulse—Resilient Electric Grid for National Security: Research Program Executive Summary*, Sandia National Laboratories, SAND2020-11227, Albuquerque, NM, October 2020, p. 15; and Maj. David Stuckenberg, "Electromagnetic Pulse Threats to America's Electric Grid: Counterpoints to Electric Power Research Institute Positions," *Over the Horizon: Multi-Domain Operations and Strategy*, pp. 17-18, August 27, 2019. For more information on space weather threats to infrastructure and federal risk management programs and activities, see CRS Report R46049, *Space Weather: An Overview of Policy and Select U.S. Government Roles and Responsibilities*, by Eva Lipiec and Brian E. Humphreys.

Figure 1. **Representation of HEMP Electric Field**



Source: Edward Savage, James Gilbert, and William Radasky, *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid*, Metatech, Meta-R-320, Goleta, CA, January 2010, p. 2-2.

Notes: E(t) (V/m) = electric field in Volts per meter. s = seconds. E1 is seen in the upper left quadrant of the graph as a rapid rise in electromagnetic energy. E2 is seen in a less pronounced peak in the middle of the graph. E3 is seen at the far right as two lower amplitude pulses. The graph is illustrative and provides only a generic representation of HEMP electric fields and timescales.

E1: Early Time Pulse

The fission component of a modern nuclear weapon (typically used to trigger a more powerful fusion reaction) releases an intense burst of gamma radiation within the first microsecond of detonation. When detonations occur at high altitude, the radiation ionizes air molecules in the gamma absorption layer roughly 30 kilometers (km) above the earth's surface. Electrons freed by this process scatter and interact with the earth's upper atmosphere and magnetic field before losing their energy and being reabsorbed a short time later. The brief, but high energy, movement of free electrons along the lines of the earth's ambient magnetic field generates a secondary electromagnetic pulse. Dependent on a number of conditions, part of this pulse may radiate downward towards Earth's surface as a high-amplitude radio signal.[6]

Although this E1 pulse may reach continental scale, the maximum strength of the electric field it generates—measured in kilovolts per meter (kV/m)—is concentrated within a smaller crescent-shaped area equatorward (i.e., southward in the Northern hemisphere) of the blast epicenter (see **Figure 2**) due to the influence of the Earth's magnetic field. The E1 pulse may damage electrical systems and electronic devices in two ways: (1) direct radiation of internal components, or (2) coupling with conductors, such as power transmission lines, power control lines, and certain

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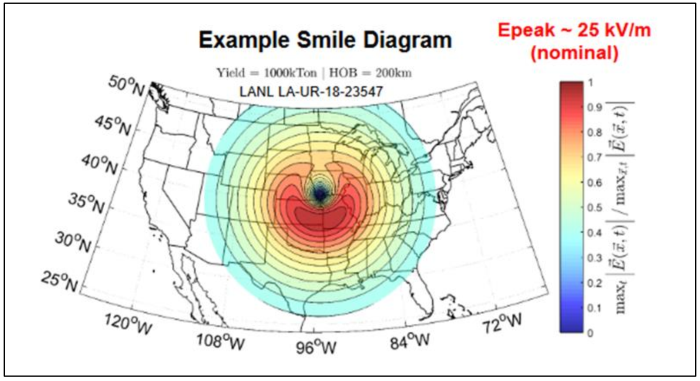
[6] For detailed description of HEMP physics, see Michael Kelly Rivera, Scott N. Backhaus, and Jesse Richard Woodroffe, et al., *EMP/GMD Phase 0 Report, A Review of EMP Hazard Environments and Impacts* (the LANL study), Los Alamos National Laboratory, LA-UR-16-28380, Los Alamos, NM, November 7, 2016, pp. 13-34, https://www.osti.gov/biblio/1330652. This section synthesizes descriptions of HEMP physics found in the LANL study and other studies cited in this report. According to the LANL study, most contemporary HEMP research is based on theories and insights from a series of research papers published between 1962 and 1986 by W.J. Karzas and Richard Latter, and Conrad Longmire et al. The authors provide the following disclaimer about their description of E1 physics: "To aid in the understanding of the phenomena, a number of [technically inaccurate] simplifications have been made. ... Although we have presented the above as if it was 'settled' science, by no means is this the case. Models of the E1 pulse incorporating more physical effects and more detail on the effects we described above are still being developed to this day" (p. 27).

communications lines, which act as antennae and may conduct damaging voltage surges into connected devices.

Figure 2. Potential HEMP E1 Effects of 1,000 Kiloton Weapon at 200 km Altitude over Central United States



Source: Los Alamos National Laboratory, in Electric Power Research Institute (EPRI), *High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies* (the EPRI study), Palo Alto, CA, April 2019, p. 2-3, https://www.roxtec.com/globalassets/03.-files/campaign-pages/emc/2019-epri-report.pdf.

The strength of the E1 pulse is only weakly correlated with increased weapon yield, because the same process that generates the radio signal described above also creates a powerful return current that builds throughout the E1 phase of the HEMP event. The return current partially attenuates the primary signal.[7] Height of burst also affects the strength of HEMP E1 hazard fields measured on the earth's surface. E1 effects are limited to line of sight from the epicenter to the earth's surface, so that detonations at higher altitudes affect a wider geographic area. As with any source of radiation, the intensity of illumination decreases with distance from the source. Any given weapon yield has an "optimal" height of burst wherein the strength of the hazard field created by the E1 pulse is maximized as shown in **Table 1**.

Table 1. HEMP E1 Maximum Waveforms as a Function of Weapon Yield and Altitude

Yield (kilotons)	Altitude (km)	E_{peak} (kV/m)
10	50	18
30	58	26
100	67	36
300	77	46
1,000	88	57

Source: Defense Threat Reduction Agency (DTRA), Department of Defense (DOD).

Notes: Adapted by CRS. For comparison, yield of the bombs used to destroy Hiroshima and Nagasaki were estimated by LANL in 1985 to be 15 kilotons and 21 kilotons respectively. Yield of modern Russian strategic weapons deployed on intercontinental ballistic missiles range between 100 and 800 kilotons, according to a 2022 Bulletin of the Atomic Scientists report.

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[7] LANL study, pp. 26-27.

The geographic area of maximum E1 electric field strength does not necessarily overlap with the geographic areas where infrastructure assets are most vulnerable to E1 hazards, according to a 2019 study by the Electric Power Research Institute (EPRI), an industry group. The report states that "maximum coupling generally occurs in areas to the east and west of ground zero and not south of ground zero where the area of maximum electric field amplitude is located."[8]

Peak field strength is therefore only one of several factors affecting overall risk to exposed electricity infrastructure. Other factors listed in the EPRI study include polarization of the E1 field, incidence angle between burst location and location of the asset on the ground, and azimuthal angle—the angle between the wave of electromagnetic energy and a wire or other conductor on or near the Earth's surface.[9]

E2: Intermediate Time Pulse

The E2 pulse (between 1 microsecond and 1 tenth of a second after detonation) is also generated by the fission component of a nuclear weapon.[10] The E2 pulse creates an electric discharge similar to lightning in its basic physics, but occurring over a much wider geographic area. Many scientists believe protective equipment that is already installed to prevent damage to the electric grid from lighting strikes is sufficient to mitigate E2 effects. However, some have cautioned that the earlier E1 pulse may damage this protective equipment, leaving grid infrastructure exposed to hazardous effects of the E2 pulse.[11] Despite this uncertainty, most EMP research focuses on the E1 and E3 pulses and their effects.

E3: Late Time Pulse

E3 is generated by the fusion component of a nuclear device. The physics and time scale of the E3 pulse differ from those of E1 and E2, because E3 is produced by the explosive effects of the device, not the initial release of gamma radiation from the fission reaction described above (see the "E1: Early Time Pulse" section). According to the LANL study, "The primary physical effect at work in the E3 phase involves the motion of plasma, ionized weapon debris, and ionized atmosphere within the Earth's magnetic field."[12] In general, E1 and E3 effects cannot be maximized simultaneously with a single weapon, because parameters such as optimal weapon yield and optimal detonation altitude are different for E1 and E3. Even so, significant E1 and E3 effects on the earth's surface may overlap in some cases.[13]

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[8] Electric Power Research Institute (EPRI), *High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies* (the EPRI study), Palo Alto, CA, April 2019, p. 2-9, https://www.roxtec.com/globalassets/03.-files/campaign-pages/emc/2019-epri-report.pdf.

[9] The EPRI study, pp. 2-7–2-8.

[10] The LANL study, p. 18.

[11] A.G. Tarditi, J.S. Besnoff, and R.C. Duckworth, et al., *High-Voltage Modeling and Testing of Transformer, Line Interface Devices, and Bulk System Components Under Electromagnetic Pulse, Geomagnetic Disturbance, and Other Abnormal Transients*, Oak Ridge National Laboratory (ORNL), ORNL/TM-2019/1143, Oak Ridge, TN, March 18, 2019, p. 4 and 8; and the EMP Commission critical infrastructure report, p. 33, http://www.firstempcommission.org/uploads/1/1/9/5/119571849/emp_comm._rpt._crit._nat._infrastructures.pdf.

[12] The LANL study, p. 27.

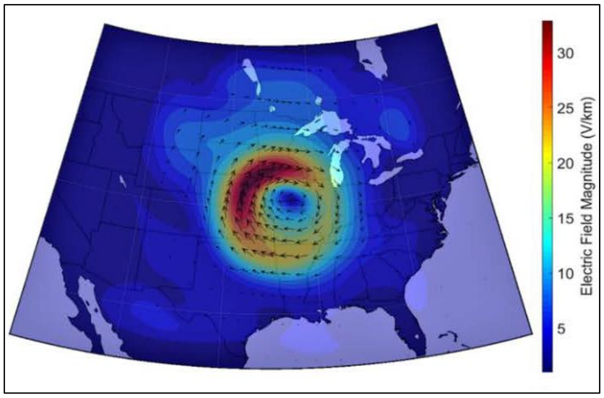
[13] Brian Pierre, Daniel Krofcheck, and Matthew Hoffman, et al., *EMP-Resilient Grid Grand Challenge: Task 3.1 Final Report*, Modeling Framework for Bulk Electric Grid Impacts from HEMP E1 and E3 Effects, SAND2021-0865, Albuquerque, NM, January 2021, p. 20, https://www.osti.gov/biblio/1764794.

The two primary components of the E3 pulse are the "blast" component (E3A) and the "heave" component (E3B). The E3A component is caused by the expansion of a large superheated conductive plasma ball produced by the detonation. The plasma ball pushes the earth's ambient geomagnetic field lines *outwards* as it expands and rises through the upper atmosphere. Much of the E3A component is attenuated by the effects of atmospheric absorption of the weapon's x-ray emissions below the blast epicenter, and so presents a lesser risk to infrastructure.

The E3B pulse is produced later as the plasma ball and associated effects dissipate, and the "ionized remnants of bomb debris and shock-heated atmospheric ions" settle in the upper atmosphere below the blast epicenter. This creates a conductive "hot ion patch," which heats and expands. This heated conductive patch becomes buoyant and rises through the upper atmosphere, producing an artificial geomagnetic disturbance as it pulls the geomagnetic field lines *inwards*.[14] According to a LANL model of an E3B environment, location of peak voltages changes over the course of the event.[15] **Figure 3** depicts the geoelectric hazard field 40 seconds after the blast.

Figure 3. Notional Geoelectric Field of "Heave" E3B Pulse at 40 Seconds

10,000 Kiloton Yield at 200 km (Magnitude in V/km)



Source: LANL diagram in EPRI Study.

Notes: The graphic does not depict predicted effects of a specific weapon.

As with E1, weapon yield and height of burst affect the strength of the resulting E3B hazard field. However, the magnitude of the E3B pulse does not increase much after weapon yield exceeds 10 kilotons—a yield typical of a small tactical warhead. However, the surface area of the hot ion patch increases with weapon yield and may disrupt Earth's magnetic field over a larger area.[16] A larger patch presents greater risk to electricity infrastructure, because the resulting E3B pulse causes geomagnetic induced currents (GIC) that build cumulatively as they flow through long conductors, such as long-distance transmission lines.[17]

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[14] See the LANL study, p. 35.

[15] See the EPRI study, p. 2-11.

[16] See the LANL study, pp. 38-39; and James Gilbert, John Kappenman, and William Radasky, et al., *The Late Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid*, Metatech, Meta-R-321, Goleta, CA, January 2010, p. 2-15, http://www.futurescience.com/emp/ferc_Meta-R-321.pdf.

[17] For detailed description of E3 physics, see Jeffrey J. Love, Greg M. Lucas, and Benjamin S. Murphy, et al., "Down to Earth with Nuclear Electromagnetic Pulse: Realistic Surface Impedance Affects Mapping of the E3 Geoelectric Hazard," *Earth and Space Science*, vol. 8 (2021).

GIC may saturate the magnetic cores of large power transformers (LPTs) that enable transmission and local distribution of alternating current at useable voltages. According to a Department of Energy (DOE) study on naturally-occurring geomagnetic disturbances, saturation of the magnetic cores of LPTs by GIC can cause several damaging effects:[18]

- harmonic currents that can cause relays to trip equipment;
- fringing magnetic fields (i.e., flux outside the core) that can create heating in the transformer, which, if sufficiently high and of long duration, can lead to overheating and reduction of a transformer's life;
- increased reactive power consumption that can cause the system to collapse due to voltage instability;[19] and
- damage and upset of customer equipment due to power quality disturbances.

In addition, GIC may cause harmonic damage to generator rotors and thermal damage to static VAR compensators that provide reactive power to the grid, according to industry sources.[20]

The CISR Framework and HEMP

The technical summary presented above is a simplification of complex phenomena that are the subjects of continuing scientific research programs across numerous disciplines and sub-disciplines. The degree (and policy relevance) of scientific uncertainty is itself a significant source of disagreement among stakeholders in the national critical infrastructure security and resilience (CISR) enterprise. Industry stakeholders generally wish to avoid what some see as costly mandates to invest in unproven technologies based on limited scientific research, while some policymakers and advocacy groups believe the existing knowledge and technological bases are sufficient to justify an expansive hardening program across vulnerable critical infrastructure sectors.[21]

Industry adoption of EMP-hardened equipment in the electricity sector is market-driven in the United States. Equipment manufacturers may choose from among available hardening standards or specify their own proprietary testing criteria if they wish to make EMP resilience part of their

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[18] For example, see DOE, Division of Infrastructure Security and Energy Restoration, *Geomagnetic Disturbance Monitoring Approach and Implementation Strategies*, Washington, DC, January 2019, p. 3.

[19] Apparent power of a given AC system is a function of reactive power measured in Volts-Amps Reactive (VAR) used for voltage support, and active power used for lighting, heating, operation of machinery, and other useful work. Consumers are typically billed for active power. For a summary description, see Federal Energy Regulatory Commission, *Reliability Primer*, Washington, DC, p. 18, https://www.ferc.gov/sites/default/files/2020-04/reliability-primer_1.pdf.

[20] See ABB Inc., *SolidGround Grid Stability and Harmonics Mitigation System*, Mount Pleasant, PA, 2015, p. 3, https://search.abb.com/library/Download.aspx?DocumentID=2GNM110098.

[21] For discussion of industry perspectives on costs, see Government Accountability Office (GAO), *Critical Infrastructure Protection: Electricity Suppliers Have Taken Actions to Address Electromagnetic Risks, and Additional Research Is Ongoing*, GAO-18-67, Washington, DC, February 7, 2018, pp. 47-50; and Maj. David Stuckenberg, op cit., p. 7. Stuckenberg suggests that EPRI focused its EMP research on areas of grid operations (transmission and sub-station components) with strongest chances for early cost recovery of any mitigation investments. The North American Electric Reliability Corporation (NERC), the industry-led electric reliability organization for the bulk power system, stated in testimony to Congress in 2012 that HEMP events were acts of war and therefore defense against them was a federal responsibility. See U.S. Congress, House Committee on Homeland Security, Subcommittee on Cybersecurity, Infrastructure Protection, and Security Technologies, *The EMP Threat: Examining the Consequences*, Statement of the North American Reliability Corporation, 112th Cong., 2nd sess., September 12, 2012.

product marketing.[22] In some cases, manufacturers have also advertised the successful use of their equipment in testing by federal agencies or federally-sanctioned industry reliability organizations.[23] Companies may self-certify or seek third-party certification from an accredited body to indicate compliance with specific standards. Electricity producers may then decide whether the cost premium for hardened equipment is justified, given their specific risk profiles and tolerances.

Because much of the nation's critical infrastructure is owned and operated by the private sector on a for-profit basis, implementation of federal initiatives to counter known threats to infrastructure, including HEMP, often depends on industry engagement in public-private partnerships for resilience. Such engagement may involve sharing potentially sensitive information with government and non-government stakeholders, investing in research, and making relevant resilience investments based on available risk assessments and protection standards. These investments may involve significant up-front business costs that must be absorbed or passed to customers.

Federal initiatives to increase infrastructure resilience to HEMP hazards—often in response to congressional mandates or executive branch directives—have generally assumed the voluntary public-private partnership model as the basis for programs and activities. There is no federal regulatory requirement for hardening of critical infrastructure against HEMP.[24] Likewise, there is no relevant reporting requirement or centralized database containing information about industry adoption of hardening measures. However, the Department of Homeland Security (DHS) administers voluntary protected disclosure programs.[25] According to some observers, private-sector investment in HEMP resilience has generally been uneven and limited.[26]

Under the current regulatory framework, the federal government oversees reliability for the generation and transmission systems of the electric power sector. These components comprise the

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[22] For an overview of standards and their application to EMP protection, see William A. Radasky, "Protecting Industry from HEMP and IEMI," *In Compliance: Electronic Design, Testing & Standards*, October 31, 2018, https://incompliancemag.com/article/protecting-industry-from-hemp-and-iemi/.

[23] ABB Inc., ibid., p. 6, https://search.abb.com/library/Download.aspx?DocumentID=2GNM110098.

[24] NERC has issued standards for transmission operators to have GMD operating plans in place, to counter effects of space weather events. Such plans rely upon space weather forecasting and advance warning of major GMD events. These standards do not apply to manmade events that may occur with little or no notice, such as HEMP E3, and do not mandate specific equipment hardening measures. See DOE, Division of Infrastructure Security and Energy Restoration, *Geomagnetic Disturbance Monitoring Approach and Implementation Strategies*, Washington, DC, January 2019, pp. 6-7.

[25] DHS administers the Protected Critical Infrastructure Information (PCII) program under authorities of the Critical Infrastructure Information Act of 2002 (Title II, Subtitle B, of P.L. 107-296) to encourage industry sharing of sensitive critical infrastructure information in exchange for confidentiality and limited immunities against regulatory action, involuntary disclosure to third parties, and litigation.

[26] For example Chris Beck, Eric Easton, and Carl Eng, et al., *Electric Infrastructure Protection Handbook IV: Electromagnetic Pulse Protection Best Practices* (the EIS study), the Electric Infrastructure Security (EIS) Council, Washington, DC, January 1, 2021, p. 18; also DOE, Division of Infrastructure Security and Energy Restoration, Geomagnetic Disturbance Monitoring Approach and Implementation Strategies, Washington, DC, January 2019, p. 12; and Government Accountability Office (GAO), *Critical Infrastructure Protection: Electricity Suppliers Have Taken Actions to Address Electromagnetic Risks, and Additional Research Is Ongoing*, GAO-18-67, Washington, DC: February 7, 2018. According to the GAO report, only 3 of 11 electricity suppliers who responded to GAO enquires about HEMP resilience activities reported having studied possible network impacts of HEMP events. See also the Commission to Assess the Threat to the United States From Electromagnetic (EMP) Pulse Attack, *Assessing the Threat From Electromagnetic Pulse*, Executive Report (EMP Commission Executive Report), Washington, DC, July 2017, pp. 6-8, http://www.firstempcommission.org/uploads/1/1/9/5/119571849/executive_report_on_assessing_the_threat_from_emp_-_final_april2018.pdf.

bulk power system. The Energy Policy Act of 2005 (EPACT05; P.L. 109-58) authorized the Federal Energy Regulatory Commission (FERC) and its certified electric reliability organization, the North American Electric Reliability Corporation (NERC), to develop and enforce mandatory reliability standards for the bulk power system.[27]

In most cases, state and local authorities regulate local distribution systems and retail sales to customers, and may also mandate relevant reliability standards or specific risk mitigation activities. Federal or state regulatory authorities may allow for cost-recovery—i.e., passing costs of regulatory compliance on to customers. Alternatively, Congress or state legislatures may provide grants or otherwise direct relevant regulatory agencies to force utilities to absorb these costs.

Strategies, Plans, Policies, and Legislation

A variety of strategies, plans, policies, and legislation have guided federal efforts to understand and manage HEMP-related risks in recent decades.

Agency Strategies and Action Plans

In 2015, the Secretary of Energy directed DOE to develop an EMP resilience strategy (the DOE Joint Strategy) in coordination with the electric power industry through EPRI. DOE described the Joint Strategy, released in 2016, as "a public-private collaborative effort, designed to establish a common framework with consistent goals and objectives that will guide both government and industry efforts to increase grid resilience to EMP threats."[28]

The DOE Joint Strategy identified five goals:

1. improve and share understanding of EMP threat, effects, and impacts;
2. identify priority infrastructure;
3. test and promote mitigation and protection approaches;
4. enhance response and recovery capabilities to an EMP attack; and
5. share best practices across government and industry, nationally and internationally. An action plan based on the strategy was released in 2017.[29]

In 2018, DHS released an EMP/GMD strategy (the DHS strategy) in fulfilment of a congressional mandate enacted by Section 1913 of the National Defense Authorization Act for 2017 (FY2017 NDAA; P.L. 114-328).[30] The strategy identified three main goals:

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[27] For an overview of federal reliability requirements and regulatory framework, see CRS Report R45764, *Maintaining Electric Reliability with Wind and Solar Sources: Background and Issues for Congress*, by Ashley J. Lawson, especially the section "Electric Reliability Regulatory Framework."

[28] DOE and EPRI, *Joint Electromagnetic Pulse Resilience Strategy: A Collaborative Effort of the U.S. Department of Energy and the Electric Power Research Institute*, Washington, DC, July 2016, https://www.energy.gov/sites/prod/files/2016/07/f33/DOE_EMPStrategy_July2016_0.pdf.

[29] DOE, *U.S. Department of Energy Electromagnetic Pulse Resilience Action Plan*, Washington, DC, January 2017, https://www.energy.gov/sites/prod/files/2017/01/f34/DOE%20EMP%20Resilience%20Action%20Plan%20January%202017.pdf.

[30] Department of Homeland Security, *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances*, Washington, DC, October 9, 2018, https://www.dhs.gov/sites/

1. improve risk awareness of electromagnetic threats and hazards;
2. enhance capabilities to protect critical infrastructure from the impact of an electromagnetic incident; and
3. promote effective electromagnetic-incident response and recovery efforts. DHS indicated that the strategy will remain in effect until 2026 and be updated every two years thereafter.[31]

The EMP Commission

Congress first established the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (EMP Commission) under Title XIV of the Floyd D. Spence National Defense Authorization Act (NDAA) for Fiscal Year 2001 (P.L. 106-398). It was reestablished under Section 1052 of FY2006 NDAA (P.L. 109-163). Section 1075 of the FY2008 NDAA (P.L. 110-181) modified the EMP Commission's authorities, extending the deadline for previous reporting requirements among other provisions. The EMP Commission was reestablished for a second time under Section 1089 of the FY2016 NDAA (P.L. 114-92). Section 1691 of the FY2018 NDAA (P.L. 115-91) established a new EMP Commission to complete another assessment and report due April 1, 2019, but the provision was subsequently repealed by Section 1695 of the FY2020 NDAA (P.L. 116-92).

The EMP Commission released several reports under these authorizations, with the final report being published in July 2017. EMP Commission members have generally presented HEMP risk to critical infrastructure as posing an existential threat to the United States—a position that appears to have informed policy in some instances. According to a former senior Commission staff member, the EMP Commission informed development of Executive Order (E.O.) 13865, "Coordinating National Resilience to Electromagnetic Pulses," which—he claimed—sought to implement the EMP Commission's core recommendations "on an accelerated basis."[32]

Executive Order (E.O.) 13865 and the FY2020 NDAA

Table 2 summarizes EMP resilience provisions in Section 1740 of the National Defense Authorization Act for Fiscal Year 2020 (FY2020 NDAA; P.L. 116-92) derived from E.O. 13865, and the current status of mandated programs and activities.[33] In 2020, DHS published an update on steps taken to comply with E.O. 13865, and indicated it would conduct additional vulnerability testing of "prioritized critical infrastructure components" and validation testing of mitigation options "as funding becomes available."[34]

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default/files/publications/18_1009_EMP_GMD_Strategy-Non-Embargoed.pdf.

[31] Ibid., p. 5.

[32] Peter Pry, "Finally, a Presidential EMP Order That May Save American Lives," *The Hill*, March 28, 2019, https://thehill.com/opinion/national-security/436224-finally-a-presidential-emp-order-that-may-save-american-lives/; and Executive Office of the President, "Coordinating National Resilience to Electromagnetic Pulses," 84 *Federal Register* 12041, March 26, 2019, https://www.federalregister.gov/d/2019-06325.

[33] The Cybersecurity and Information Security Agency, a DHS agency, maintains an EMP/GMD information page with an overview of departmental activities and program updates at https://www.cisa.gov/emp-gmd.

[34] Department of Homeland Security, *Electromagnetic Pulse (EMP) Program Status Report*, August 17, 2020, p. 3, https://www.cisa.gov/sites/default/files/publications/emp-program-status-report_508.pdf.

Table 2. EMP/GMD-Related Requirements in FY2020 NDAA

Department or Agency	Requirement	Deadline	Status
Agencies supporting National Essential Functions	Update operational plans to protect against and mitigate effects of EMP/GMD on critical infrastructure.	March 20, 2020	DOE stated that its updated "response plans, programs and procedures and operational plans all account for the effects of EMP and GMD."
DHS (with relevant sector risk management agencies)	Conduct R&D to improve EMP/GMD effects modeling and resilience-enhancing technologies. Submit R&D Action Plan to Congress to address shortfalls.	March 26, 2020	DHS developing EMP risk models, and protection and mitigation technologies for identified high-risk infrastructure categories.
DHS (with DOD, DOE, DOC)	Complete intelligence-based Quadrennial Risk EMP/GMD Assessment (QRA) and brief to Congress. Use results to increase critical infrastructure resilience, prioritizing assets at greatest risk.	March 26, 2020	DHS refining risk models to support completion of initial quadrennial assessment. Initial prioritization of "limited set of systems, networks, and assets" complete, focusing on Energy and Communications sectors.
DHS	Distribute information on EMP/GMD to federal, state, local, and private sector stakeholders. Brief to Congress.	June 19, 2020	Ongoing through existing programs and activities. DHS may create program office to guide public-private engagements.
FEMA (with CISA, DOE, FERC)	Coordinate EMP/GMD response and recovery plans and procedures.	June 19, 2020	Ongoing compliance via existing plans and procedures—e.g. FEMA Power Out Incident Annex, and DHS EMP resilience guidelines.
DHS (with S&T, CISA, FEMA, DOD, DOE)	Pilot test of engineering approaches to mitigate EMP/GMD effects on critical infrastructure.	September 22, 2020	Under contract with Los Alamos National Laboratory (LANL) for completion by July 2021. DHS S&T released report on EMP mitigation best practices in August 2022.
DOD (with DHS, DOE)	Pilot test of engineering approaches to harden defense installations and associated infrastructure.	September 22, 2020	Interagency pilot project in San Antonio, TX, ongoing. Additional work pending completion of LANL pilot test of engineering approaches.

Department or Agency	Requirement	Deadline	Status
DHS (with sector-specific agencies, DOD, DOE)	Review test data on EMP/GMD effects on critical infrastructure to identify gaps. Within 180 days of review, develop integrated cross-sector plan using public-private partnerships to address identified data gaps.	December 20, 2020	No information provided.
DHS (with DOD, DOE)	Report to Congress on technological options to increase critical infrastructure resilience to EMP/GMD events and identify gaps and opportunities, with updates on quadrennial basis.	December 21, 2020	DHS developed technology scouting report for confidential distribution to federal agencies and designated private sector partners. Draft of report to Congress on technological options in review.
FEMA (with CISA, DOE, FERC)	Conduct EMP/GMD national exercise.	December 21, 2020	Completed in December 2020
DHS (with FEMA, CISA, DOD, DOC, FCC, DOT)	Report to Congress on effects of EMP/GMD on communications infrastructure with recommendations for changes to operational response plans.	December 21, 2020	Vulnerability assessment of priority infrastructure ongoing (scheduled completion July 2021). Report was expected January 2022.
FEMA	Maintain relevant emergency alerting systems. Brief Congress on state of emergency notification systems.	December 21, 2020	Complied via briefing to House Energy and Commerce Committee on November 2, 2020. FEMA has hardened some key emergency communications facilities.

Source: FY2020 NDAA (P.L. 116-92), Section 1740; email correspondence on March 8, 2021, with James Platt, Strategic Defense Initiatives, EMP/PNT/GMD Space Weather/Space Risks, National Risk Management Center, CISA; Department of Homeland Security, Electromagnetic Pulse (EMP) Program Status Report, August 17, 2020, and CRS search of public sources, 2022.

Notes: The DHS strategy anticipated E.O. 13865, stating "will adjust etc." Parentheses in the first column denote a coordination requirement for the lead department or agency (in bold). CISA = Cybersecurity and Infrastructure Security Agency (a part of DHS); DHS = Department of Homeland Security; DOC = Department of Commerce; DOD = Department of Defense; DOE = Department of Energy; DOT = Department of Transportation; EMP = electromagnetic pulse; FCC = Federal Communications Commission; FEMA = Federal Emergency Management Agency (a part of DHS); FERC = Federal Energy Regulatory Commission (an independent regulatory commission within DOE); GMD = geomagnetic disturbance; R&D = research and development; S&T = Science and Technology Directorate (a part of DHS).

Not included in the FY2020 NDAA is the E.O. 13865 requirement for DHS and other federal agencies to "identify regulatory and non-regulatory mechanisms, including cost recovery measures" for private sector entities to address EMP risk.[35]

HEMP and Infrastructure Legislation in the 117th Congress

The IIJA contains several infrastructure resilience provisions that either explicitly include addressing HEMP as a program consideration or implicitly allow addressing HEMP as part of an all-hazards risk management approach. Other provisions confine funding to extreme weather, wildfire, and natural disasters, but nevertheless may still affect HEMP resilience incidentally. For general information on IIJA grid resilience provisions, see CRS Report R47034, *Energy and Minerals Provisions in the Infrastructure Investment and Jobs Act (P.L. 117-58)*, coordinated by Brent D. Yacobucci.

IRA does not contain HEMP-specific provisions. However, changes in grid technology and topology envisioned under the law—such as increased use of renewable energy sources—may affect HEMP resilience incidentally. For general information on relevant IRA programs, see CRS Report R47262, *Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change*, coordinated by Jane A. Leggett and Jonathan L. Ramseur.

HEMP-Specific Provisions in the IIJA

Section 40125(d), "Modeling and Assessing Energy Infrastructure Risk," authorized $50 million over five years for creation of an "advanced energy security program" within DOE to support modeling of risks to energy networks posed by natural and human-made threats and hazards, "including electromagnetic pulse and geomagnetic disturbance."[36] EMP and GMD are the only hazards specifically named under this provision. Examples of eligible activities include development of new capacities to identify vulnerable grid components, research on grid hardening solutions, research mitigation and recovery solutions, grid resilience exercises and assessments, and "technical assistance to States and other entities for standards and risk analysis."

Section 40103(d), "Energy Infrastructure Resilience Framework," directs the Secretary of Energy, in collaboration with the Secretary of Homeland Security, FERC, NERC, and "interested energy infrastructure stakeholders," to research options for building and stockpiling portable replacement LPTs. In 2017, DOE published a plan in compliance with a similar congressional mandate enacted under Section 61004 of the Fixing America's Transportation Act (P.L. 114-94) to establish a strategic transformer reserve in partnership with industry stakeholders.[37]

Section 40321, under Subtitle C, "Nuclear Energy Infrastructure," requires DOE to submit a report to Congress on micro and small nuclear reactors. The mandated report must describe how the department could enhance energy resilience of DOE facilities and remote communities using micro-reactors and small modular reactors, and include an assessment of how such installations

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[35] *Federal Register*, op cit., p. 12045.

[36] Division J of IIJA appropriated funds for this and certain other programs listed in this report. For appropriations information on IIJA energy sector programs, see CRS Report R47034, *Energy and Minerals Provisions in the Infrastructure Investment and Jobs Act (P.L. 117-58)*, coordinated by Brent D. Yacobucci.

[37] Department of Energy, *Strategic Transformer Reserve*, Report to Congress, Washington, DC, March 2017, https://www.energy.gov/sites/default/files/2017/04/f34/Strategic%20Transformer%20Reserve%20Report%20-%20FINAL.pdf.

might address the "need for protection against cyber threats and electromagnetic pulses," among other threats and hazards.

IIJA appropriated $157.5 million under the "Science and Technology Directorate, Research and Development" heading, available until September 30, 2026, to the DHS Science and Technology Directorate (S&T) for CISR-related "research, development, test, and evaluation." EMP and GMD resilience capabilities were one of five named eligible categories for use of funds.[38]

Other Potentially Relevant IIJA Grid Resilience Provisions

Section 40101, "Preventing Outages and Enhancing the Resilience of the Electric Grid," authorized $5 billion in grant programs for electricity infrastructure owners and operators to protect the grid against "disruptive events"—defined as extreme weather, wildfire, or natural disaster occurrences that result in preventive or accidental outages, or hazardous safety conditions. Eligible activities include construction of microgrids and battery storage equipment, installation of adaptive protection technologies, replacement of power lines and underground cables, and hardening of power lines, facilities, substations, and other systems.

Section 40102, "Hazard Mitigation Using Disaster Assistance," amended the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act; 42 U.S.C. 5170c (f)(12)) to make installation of fire-resistant wires and undergrounding of wires eligible for Stafford Act funding. (Undergrounding wires may provide some attenuation of HEMP hazards; see the "Undergrounding Electrical Equipment and Power Lines" section.)

Section 40103 authorized $5 billion to support a new DOE program, "Upgrading Our Electric Grid and Ensuring Reliability and Resilience," which would offer competitive grants for states, tribes, local governments, and public utility commissions. Grants would fund technology demonstration projects related to resilience and reliability of the electric grid. The provision does not name specific threats or hazards. As of this writing, DOE has issued a request for information seeking information from stakeholders and a draft funding opportunity announcement.[39]

Section 40106, "Transmission Facilitation Program," authorized programs to increase transmission capacity, connect isolated microgrids to infrastructure, and support adoption of advanced technologies to increase "capacity, efficiency, resiliency, or reliability of an electric power transmission system."

Section 40107, "Deployment of Technologies to Enhance Grid Flexibility" authorized $3 billion in funds for the DOE Smart Grid Investment Matching Grant Program. Authorized activities include buildout of fiber and wireless broadband communication networks, and advanced transmission technologies and sensors, to enable better coordination of grid operations and enhance grid flexibility. (This includes the ability to island sections of the grid to isolate against cascading grid failures in case of extreme weather and nature disasters.) Grid flexibility is a power system's capacity to dynamically balance power supply with demand across a wide area using networked systems of electricity generation, transmission, and distribution.

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[38] The other four categories were (1) special event risk assessments rating planning tools; (2) positioning, navigation, and timing capabilities; (3) public safety and violence prevention to evaluate soft target security, including countering improvised explosive device events and protection of U.S. critical infrastructure; and (4) research supporting security testing capabilities relating to telecommunications equipment, industrial control systems, and open source software.

[39] See DOE, "Program Upgrading Our Electric Grid and Ensuring Reliability and Resiliency," https://www.energy.gov/bil/program-upgrading-our-electric-grid-and-ensuring-reliability-and-resiliency.

Section 40108, "State Energy Security Plans" amends the Energy Policy and Conservation Act of 1975 (P.L. 94-163; EPCA) to modify requirements for state energy security plans. Plans must address all energy sources and providers, include a state energy profile, address cyber and physical vulnerabilities, provide a risk assessment, and provide a risk mitigation approach, among other requirements, in order to receive federal financial assistance under Part D of EPCA. The program provides grants to support implementation of state energy plans.[40] Congress appropriated $500 million for formula grants to be awarded under the State Energy Program between FY2022 and FY2026.[41]

Section 40125, "Enhanced Grid Security," authorizes $250 million over five years for cybersecurity-related projects, and to support all-hazards based risk assessments of communications, control systems, and power systems architectures used to operate the grid. Additionally, it supports pilot projects with energy sector stakeholders to gain experience using relevant emerging technologies.

Section 11105, "National Highway Performance Program," allows for undergrounding "public utility infrastructure" in conjunction with otherwise eligible transportation projects authorized under the National Highway Performance Program (23 U.S.C. 119).

Research Issues

Issues of scientific theory, method, and analysis continue to be debated within the broader research community in response to emerging HEMP research and related policy initiatives. To date, research programs—each with its own objectives, assumptions, resources, and limitations—have generally produced inconsistent or incomplete estimates of HEMP-related risks to infrastructure. As such, existing research has failed to elicit broad industry consensus on the methods, scale, and scope of any broad-based hazard mitigation program.

HEMP Environments and Benchmarks

Non-defense research generally relies upon a limited number of unclassified models of electromagnetic hazard fields generated by HEMP—usually referred to as HEMP environments—to assess the potential effects of high-altitude nuclear detonations. Unclassified HEMP environments, such as the one represented graphically in **Figure 2**, provide the predicted peak strength of hazard fields in a given location in relation to the blast epicenter based on a generic waveform, but do not provide the fidelity needed to inform comprehensive and authoritative risk assessments, according to researchers.

For example, the EPRI study states, "several unclassified E1 EMP environments exist, but in general, these environments have limited usability because they are comprised of a single waveform or ... provide a generic representation of the peak electric field on the ground," and do not include other important parameters, such as polarization of the electric field and angle of incidence.[42] Researchers must then make educated assumptions about these parameters in order to

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[40] See DOE, "State Energy Program Guidance," https://www.energy.gov/eere/wipo/state-energy-program-guidance#bipartisan; and National Association of State Energy Officials, *NASEO's State Energy Planning Guidelines: Guidance for States in Developing Comprehensive Energy Plans and Policy Recommendations*, Arlington, VA, 2018, p. 18, https://naseo.org/Data/Sites/1/sepguidelines_2018_final.pdf.

[41] DOE, *State Energy Program Notice 22-03*, Washington, DC, August 26, 2022, p. 2, https://www.energy.gov/sites/default/files/2022-08/SEP_IIJA_Application_Instructions.pdf.

[42] EPRI study, p. 2-1. See also Ross Guttromson, Craig Lawton, and Matthew Halligan, et al., *Electromagnetic Pulse—*

predict effects on exposed infrastructure systems. (See the "Obstacles to Improved Risk Management" section.) Detailed findings and data from classified EMP research are generally not available outside the defense research community. In its final report, the EMP Commission criticized Department of Defense (DOD) data classification policies and the "absence of technology transfer and other support" to other agencies and critical infrastructure stakeholders.[43]

In a January 2021 memorandum, the Secretary of Energy released benchmark waveforms to inform testing and predictive modeling by industry and government entities in fulfillment of E.O. 13865.[44] The memorandum did not provide specific hardening standards or "specify the level of risk critical infrastructure faces from HEMP."[45] As such, the Secretary presented it as "a first step in a long conversation with civilian stakeholders to begin to understand the threat, consequence, and risk associated with EMPs and how to address the risks."[46]

The benchmark waveforms published in the memorandum were based on available unclassified research from the International Electrotechnical Commission (IEC), Oak Ridge National Laboratory (ORNL), and the EMP Commission. The provided peak field strengths for E1 and E3 electric fields were as follows:

- E1: 50 kV/m (Source: IEC)
- E3A: 80 V/km (Source: EMP Commission)
- E3B: 50 V/km (Source: IEC)

The DOE memorandum indicated that the benchmark values it provides were provisional, and that testing against these benchmarks may "exceed DOE's currently assessed threat levels by a factor of 2 due to predictive modeling uncertainties and potential excursions in HEMP environment levels." Further, "The recommended E1, E2, and E3 HEMP environment benchmark waveforms will be updated as necessary, based on further developments in our understanding of HEMP generation and modeling and simulation phenomenology."[47]

Modeling and Simulation of Infrastructure Resilience

Modeling and simulation are used to estimate risk levels to infrastructure in a given HEMP environment. Although straightforward in principle, the integration of modeling, simulation, and experimental testing of system components to identify and measure relevant risk factors is complex in practice.

Resilient Electric Grid for National Security: Research Program Executive Summary, Sandia National Laboratories, SAND2020-11227, Albuquerque, NM, October 2020, p. 11, for discussion of waveform limitations and research implications. According to the study, available unclassified waveforms from IEC commonly used in non-military HEMP risk assessments "lack additional details that, if included in the analysis, would often result in a lesser consequence," p.13. The report provides an overview of a three-year internally-funded research program to investigate HEMP and the electric power grid that produced 23 reports and papers.

[43] EMP Commission Executive Report, pp. 8- 9.

[44] Dan Brouillette, *Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and Other Critical Infrastructure to HEMP Insults*, Department of Energy, National Security Council Records, Washington, DC, January 11, 2021, https://www.energy.gov/sites/default/files/2021/01/f82/FINAL%20HEMP%20MEMO_1.12.21_508.pdf.

[45] Ibid., p. 1.

[46] Ibid.

[47] Ibid., p. 2.

Modeling and simulation studies must account for one or more of the following:

- interaction of radiation and blast effects of the weapon with the natural environment to produce HEMP hazard fields,
- interaction of HEMP hazard fields with exposed infrastructure systems and assets, and
- secondary or cascading effects of such interactions on critical infrastructure functions.

Researchers have used modeling and simulation to create and test synthetic electrical grids against notional HEMP events, but—absent data on specific system topologies and other sources of uncertainty—such tests can produce only general insights on grid behavior and failure modes.[48] According to EPRI, "Interconnection scale modeling requires a high-fidelity E1 EMP environment (not publicly available) and ability to perform coupling calculations on 1000's of substations simultaneously."[49]

Studies using a variety of research designs and methods have produced scientific advancement and limited consensus in some areas. However, widely divergent results and assessments of HEMP risk to critical infrastructure has highlighted a need for further research and methodological advancement.

Summary of HEMP Research Results

Despite significant gaps, existing HEMP research has identified several issues of concern that E1 radiative and conductive threats both present hazards to unprotected DPR, DCS, and supervisory control and data acquisition (SCADA) systems in control houses or generation facilities, according to some studies.[50] (Older electromechanical relays, which have largely been supplanted by DPRs, have been found to be highly resistant to electromagnetic pulses.)[51] However, conductive threats generally present higher risk. Relatively simple (and inexpensive) mitigations, such as use of shielding, grounding, and insulation of control lines, as well as modification of control house design and materials, appear to significantly reduce—but not eliminate—vulnerability to E1 hazards.[52]

LPTs may suffer physical damage from both E1 and E3 hazards, although estimates of likely damage vary. The EMP Commission warned of LPT hotspot heating caused by E3 induced core saturation and system harmonics on sufficient scale to render major grid interconnections inoperable for months or longer. More recent studies by EPRI and ORNL predicted that such losses would occur on a lesser scale and would likely not present a systemic hazard to grid operations—assuming that control and communications systems remained operable, and other grid equipment was undamaged.[53]

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[48] Brian Pierre, Daniel Krofcheck, and Matthew Hoffman, et al., *Modeling Framework for Bulk Electric Grid Impacts from HEMP E1 and E3 Effects*, Sandia National Laboratories, EMP-Resilient Grid Grand Challenge: Task 3.1 Final Report, Albuquerque, NM, January 2021, p. 35, https://www.osti.gov/servlets/purl/1764794.

[49] Randy Horton, "EPRI Electromagnetic Pulse Research," Presentation to NERC EMP Task Force Meeting, Washington, DC, June 12, 2019, p. 8, https://www.nerc.com/pa/Stand/EMPTaskForceDL/EPRI%206-12-19.pdf.

[50] For example, EPRI study, EMP Commission critical infrastructure report, and EIS study.

[51] EMP Commission critical infrastructure report, p. 24.

[52] For example, EPRI study, EMP Commission critical infrastructure report, and EIS study.

[53] EPRI study, p. xi; and ORNL, op cit., p. 4.

Several studies identify voltage collapse caused by E3B as being of generally greater concern than heat damage to a large number of transformers.[54] Experts predict that in the case of an interconnection-scale voltage collapse, restoration would be a complex and lengthy process. Lack of availability of utility-scale power adjacent to affected areas and functioning communications between geographically dispersed system operators might pose significant challenges.[55]

The vulnerability of generation facilities to HEMP threats is a topic of concern. Preliminary field testing of a working generation facility by EIS found that E1 threats "will likely disrupt or damage typical power plants."[56] The EPRI report stated, "Additional research is needed to evaluate the potential impacts of HEMP on generation facilities themselves," and suggested extending the existing mitigation framework for the transmission system to develop hardening and mitigation options for generation facilities.[57] Additionally, the increasing prevalence of renewables may offer both additional resilience and potential vulnerabilities. These technologies are rapidly evolving, and research on potential HEMP vulnerabilities is in its preliminary stages (see the "Inverter-Based Resources" section).

The Foundation for Resilient Societies, a critical infrastructure resilience research and advocacy organization, published a report in 2020 that highlighted vulnerabilities of communications technologies used to control electricity generation, transmission, and distribution.[58] For example, non-conductive fiber optic lines used for communications between electricity grid substations rely upon amplifier points—placed at roughly 80 mile intervals—and fiber transceivers at substations and control rooms. Fiber optic amplifiers and transceivers are vulnerable to HEMP, according to the report.[59] Similar risk exists where grid operators use wireless communications to control grid assets—often in inaccessible areas where fiber optic technology is cost-prohibitive. Wireless communications assets, such as cell towers, are protected against routine electromagnetic interference, but may be vulnerable to HEMP.[60]

Appendix A provides a summary of selected research products.

Emerging Science and Technology Policy Issues

Major infrastructure legislation enacted during the 117th Congress funds buildout of infrastructure capacity, research and planning activities, risk management activities, and expanded use of emerging renewable energy technologies in the electricity sector. As of this writing, implementation of authorized programs is in its early stages, and any eventual impact on HEMP resilience is unknown. The following sections highlight certain technologies supported via congressional authorizations and appropriations enacted under IIJA and IRA (see "HEMP and

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[54] For example, Ross Guttromson, Craig Lawton, and Matthew Halligan, et al., op cit., p. 15.

[55] EMP Commission critical infrastructure report, p. 31.

[56] EIS study, p. 123.

[57] EPRI study, 8-1; in 2019, EPRI announced new project to evaluate E1 EMP impacts to generation facilities. See Edison Electric Institute, "EPRI EMP Report & Grid Security: Key Messages," press release, April 2019, https://www.eei.org/-/media/Project/EEI/Documents/Issues-and-Policy/EPRI-EMP-Report—Grid-Security—Key-Messages.pdf, p. 2.

[58] See David Winks, *Protecting U.S. Electric Grid Communications from Electromagnetic Pulse*, The Foundation For Resilient Societies, Exeter, NH, May 2020.

[59] Ibid., p. 4.

[60] Ibid.

Infrastructure Legislation in the 117th Congress" section) that may have implications for HEMP resilience depending upon implementation policies.

Inverter-Based Resources

Wind, solar, fuel cells, and batteries make up an increasing share of power generation and supply capacity. These power sources use inverters to convert the direct current electricity they produce to alternating current electricity used by most electricity consumers. Wind resources are usually implemented on utility-scale. Solar and battery resources may be implemented at utility-scale to provide power for the grid, or may be used for rooftop and residential applications as distributed energy resources (DERs). Hybrid approaches use digital control systems to combine DERs operating as virtual power plants with grid-scale generation assets. Development and deployment of such systems is in its early stages, as of this writing.[61]

The comparative advantages or disadvantages of distributed or hybrid generation using inverter-based resources to provide energy and grid services during a HEMP event have not yet been extensively researched.[62]

A 2022 National Renewable Energy Laboratory (NREL) study on hybrid power plants and grid resilience suggested that "hybridizing or spatially distributing renewable energy generation assets, the complementarity of the distinct resources can be leveraged to provide energy and grid services more reliably than any of the assets can on their own."[63] However, it did not examine potential effects of HEMP on inverter-based resources or associated electronic control systems necessary to administer and provide operational control of hybrid power plants. The 2019 EPRI report states that resilience of inverter-based generation against E1 hazards is unknown. Other preliminary research indicates that photovoltaic panels are highly resistant to E1, but more testing of connected inverters and associated electronic control systems is necessary.[64]

Inverter-based resources can provide ancillary services to the electricity grid such as voltage support to help maintain stability if designed and configured appropriately.[65] Electric vehicles—essentially batteries on wheels—equipped with vehicle-to-grid (V2G) technology may provide the same grid services, but the relevant technologies to automatically aggregate and coordinate charging and power dispatch are still in the development and planning stages.[66] Existing research and development largely focuses on the routine application of battery storage and V2G

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[61] For example, see Miranda Wilson, "Northeast Embraces First-of-a-Kind Virtual Power Plant," *E&E News*, October 12, 2022, https://www.eenews.net/articles/northeast-embraces-first-of-a-kind-virtual-power-plant/.

[62] EPRI study, p. 4-25; and DOE, Wind Energy Technologies Office, "Wind Turbines Can Stabilize the Grid," May 16, 20222, https://www.energy.gov/eere/wind/articles/wind-turbines-can-stabilize-grid.

[63] Caitlyn E. Clark, Aaron Baker, and Jennifer King, et al., *Wind and Solar Hybrid Power Plants for Energy Resilience*, National Renewable Energy Laboratory, NREL/TP-5R00-80415, Golden, CO, January 2022, p. 4, https://www.nrel.gov/docs/fy22osti/80415.pdf.

[64] See Tyler Bowman, Jack David Flicker, Ross Guttromson, et al., 2020, "High Altitude Electromagnetic Pulse Testing of Photovoltaic Modules," Sandia National Laboratory, Albuquerque, NM, https://doi.org/10.2172/1614961.

[65] Malcolm Abbott and Bruce Cohen, "Issues Associated with the Possible Contribution of Battery Energy Storage in Ensuring a Stable Electricity System," *The Electricity Journal*, vol. 33, no. 6 (July 2020), pp. 1-6, and CRS Report R45980, *Electricity Storage: Applications, Issues, and Technologies*, by Richard J. Campbell.

[66] IIJA Sec. 40414 provides for data collection on electric vehicle integration with the electricity grids to further research on V2G applications. For a technical discussion of relevant issues, see Jingyuan Wang, Guna R. Bharati, and Sumit Paudyal, et al., "Coordinated Electric Vehicle Charging with Reactive Power Support to Distribution Grids," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1 (January 2019).

technologies for maintaining grid stability. The utility of these technologies in a HEMP scenario is largely unknown.

Microgrids

Microgrids may operate independently of the bulk electricity system if they are configured with the appropriate hardware and software.[67] Microgrids may be powered by a variety of power sources and may offer some resilience to connected homes, businesses, and essential facilities against large-scale outages caused by HEMP. However, microgrids—especially those intended for civilian use—are not necessarily designed to withstand E1 pulses that may affect power control systems and other sensitive electronics.[68]

Nonetheless, hardening microgrids against HEMP through the use of protective enclosures and other measures may be more practical and less costly than for conventional grid assets.[69]

By definition, microgrids do not use long transmission lines and LPTs that form the backbone of the electric grid, and so they do not have direct vulnerability to GMD caused by E3 when operated independently of the grid. Some connected microgrids have the capability to disconnect from major distribution networks and operate in "island" mode during an emergency in order to avoid cascading effects of large-scale grid failures.

Transmission Facilitation and Grid Flexibility

For economic reasons, the existing electricity system operates with minimal redundancy and spare capacity—a condition enabled by increased adoption of (potentially vulnerable) electronic controls and other digital technologies in recent decades.[70] Power grids are more vulnerable to disruption when they operate with little spare capacity, according to experts.[71] Increased transmission capacity provides greater margins for grid operators to manage disruptions and provide additional reactive power to maintain system voltages if necessary. A 2019 study by the National Renewable Energy Laboratory predicted that considerable growth in electricity demand due to anticipated electrification of residential heating and transportation (electric vehicles) would "likely require grid capacity expansion and make grid operations and planning more challenging."[72]

Infrastructure programs to support increased transmission capacity and grid flexibility may remediate these deficiencies to some degree. However, IIJA and IRA infrastructure programs to

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[67] According to DOE, "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to enable it to operate in grid-connected or island-mode." See Dan Ton, *Microgrid R&D Program at the U.S. DOE*, Office of Electricity, Department of Energy, Washington, DC, November 2018, p. 3, https://www.energy.gov/sites/prod/files/2018/12/f58/remote-microgrids-dan-ton.pdf.

[68] See George H. Baker, "Microgrids—A Watershed Moment," *Insight*, vol. 23, no. 2 (2020).

[69] Barry Wilson, *EMP Hardening with Electric Power Microgrids*, Enviropower, Renewable Inc., Boca Raton, FL, 2019, p. 7, https://eprenewable.com/wp-content/uploads/2019/04/EMP_Hardening-with-Electric-Power-Microgrids.pdf.

[70] The EMP Commission, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, Critical National Infrastructures*, Washington, DC, April 2008, p. 23.

[71] Ibid., p. 17.

[72] Michael Blonsky, Adarsh Nagarajan, and Shibani Ghosh, et al., "Potential Impacts of Transportation and Building Electrification on the Grid: A Review of Electrification Projections and Their Effects on Grid Infrastructure, Operation, and Planning," *Electrification*, vol. 6, November 13, 2019, p. 169, https://link.springer.com/article/10.1007/s40518-019-00140-5.

facilitate integration of inverter-based resources and microgrids into the existing bulk electric system focus on environmental performance—i.e., lower carbon dioxide emissions—and resilience to extreme weather, wildfires, and natural disasters.

Future Grid Technologies and HEMP

New and emerging grid hardware technologies based on semiconductor-based, solid state power converters may offer a number of broad resilience benefits, according to DOE. The 2021 DOE technology roadmap for solid state power substations (SPSS) envisions replacement of existing analog grid substation equipment with solid state technology.[73]

Eventually, such systems might enable a grid that is "fully asynchronous, autonomous, and fractal"—i.e., able to operate without frequency synchronization at the interconnection level; less reliant on long-distance communications networks for operational control; and able to rapidly isolate grid components to prevent cascading failures.

Solid state technologies may also help emergency recovery by providing more portable and interchangeable designs for major electric substation components. Such grid technology features have long been of interest to the HEMP policy and research community, given the risks of system-level impacts from a HEMP event.

However, successful commercialization of relevant technologies may be decades away in some cases. Additionally, their resilience to HEMP threats is largely unknown.

According to the DOE technology roadmap, "The ability to withstand electromagnetic interference (EMI) and *electromagnetic pulses* [emphasis added] are ... areas of investigation that will need to span the entire converter architecture, including the controllers and communication subsystems."

Improvements in grid flexibility may enhance the power system's capacity to dynamically balance power supply with demand across a wide area using networked systems of electricity generation, transmission, and distribution during a HEMP event, if only incidentally. However, potential operational benefits and resilience of such prospective systems to HEMP—many of which are still in the research and development phase—are largely unknown.[74] Loss of grid flexibility during a HEMP event may complicate efforts to manage disruptions and maintain functioning power supply. Existing HEMP research has largely focused on hazards to conventional grid operations, rather than inverter-based resources, microgrids, and advanced transmission technologies (see the section "Modeling and Simulation of Infrastructure Resilience").

Undergrounding Electrical Equipment and Power Lines

IIJA funds for undergrounding electrical equipment and power lines are restricted to protection against extreme weather, wildfires, and natural disasters (see "Other Potentially Relevant IIJA Grid Resilience Provisions"). However, undergrounding certain assets to protect against these hazards may incidentally affect HEMP resilience. EPRI research showed that undergrounding control cables at substations connected to DPRs provided significant equipment protection against simulated E1 pulses.[75] In the case of buried long-distance transmission lines, conductive earth may attenuate early-time E1 pulses—lessening any coupling hazards to the grid. However, undergrounding long-distance transmission lines would not prevent GIC caused by E3 magnetohydrodynamic effects, which propagate through conductive geologic formations underground and enter the grid through transformer groundings.

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[73] See Department of Energy, Office of Electricity, *Solid State Power Substation Technology Roadmap*, Transformer Resilience and Advanced Components Program, Washington, DC, June 2020, p. 31, https://www.energy.gov/oe/downloads/solid-state-power-substation-technology-roadmap.

[74] Ibid., p. 31.

[75] EPRI study, p. 4-10.

Issues for Congress

As of this writing, DHS and other relevant federal agencies continue to implement legislative mandates contained in the FY2020 NDAA, which legislate many of the directives contained in E.O. 13865 (see the "Executive Order (E.O.) 13865 and the FY2020 NDAA" section). Major outstanding items include DHS risk models for critical infrastructure and associated risk assessments, engineering approaches for risk mitigation, and identification of emerging EMP protection technologies. Many mandated deadlines have already passed. Documents submitted by other agencies in compliance with E.O. 13865, such as the DOE memorandum on HEMP waveforms (see the "HEMP Environments and Benchmarks" section) present data from existing sources that are more than a decade old in some cases, and contain caveats indicating uncertainty.

It is not clear that existing HEMP research is sufficiently mature for DHS, or any other federal agency, to provide authoritative guidance to policymakers or industry stakeholders on prioritization of critical systems and assets for hardening or other countermeasures in the near future. DHS has indicated more funding would be necessary to support necessary research (see the "Executive Order (E.O.) 13865 and the FY2020 NDAA" section). IIJA appropriations to federal agencies may support further research, depending upon how funds are apportioned to specific research programs by implementing agencies (see the "HEMP-Specific Provisions in the IIJA" section).

In all these potential HEMP-related issues, the appropriate roles for federal agencies, states, and the private sector would be fundamental areas for congressional consideration.

Obstacles to Improved Risk Management

Researchers consistently identify issues with the underlying quality of data used to model HEMP risk to critical infrastructure (see the "HEMP Environments and Benchmarks" section) as an obstacle to providing more authoritative risk assessments to critical infrastructure stakeholders. The EMP Commission and others have suggested that improved access to DOD and DOE/National Nuclear Security Administration data and research on electromagnetic effects of nuclear weapons, and selective declassification of certain data and research, might reduce such obstacles, if only to a degree. Congress may consider legislating parameters and specific objectives of interagency cooperation between DOD, DHS, DOE, and other relevant federal agencies, and provide funding and oversight as appropriate.

Researchers also note the need for more detailed modeling of underground geologic formations that play a role in propagation of E3 related hazards, and more detailed knowledge of specific infrastructure topologies that affect system-level resilience to HEMP (see the "Modeling and Simulation of Infrastructure Resilience" section). The U.S. Geological Survey, an agency of the Department of the Interior, administers a geomagnetism program that supports the National Space Weather Strategy, which focuses on naturally occurring electromagnetic hazards similar to manmade E3. The program received increased funding under the FY2020 appropriations act to continue a national magnetotelluric survey started by other federal agencies.[76] Congress may consider exercising oversight and other authorities to ensure relevant findings are available to the HEMP research community.

Similarly, Congress may consider exercising oversight of existing DHS administered partnerships with critical infrastructure stakeholders for protected critical infrastructure information disclosure

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[76] See CRS In Focus IF11181, *The U.S. Geological Survey (USGS): FY2020 Appropriations Process and Background*, by Anna E. Normand.

and information sharing, such as the Protected Critical Infrastructure Information program, which may assist DHS in completing HEMP risk management activities mandated by the FY2020 NDAA (see the "The CISR Framework and HEMP" section).

Incentivizing and Facilitating Investment in HEMP Resilience

E.O. 13865 contemplates future introduction of cost-recovery mechanisms (such as increased consumer electricity rates) that certain electricity providers could use to fund HEMP resilience investments. In September 2022, FERC released a Notice of Proposed Rulemaking (NOPR) to provide "incentive-based rate treatment" for utilities that invest in "advanced cybersecurity technology" and participate in cybersecurity threat information sharing programs, pursuant to Congress's instructions in IIJA.[77] The NOPR suggests certain cost-recovery mechanisms that may be further elaborated during the rulemaking process. Congress may wish to direct FERC to develop a similar rule to incentivize investment in HEMP resilience. Development and implementation of such a rule might depend in part on availability of improved risk models, risk assessments, and mitigation technologies as described above.

Congress may consider exercising oversight of development and implementation of State Energy Security Plans described in Section 40108 of the IIJA (see the "Other Potentially Relevant IIJA Grid Resilience Provisions" section) to ensure that HEMP resilience considerations are included as deemed appropriate. DOE administers the program at the federal level and reviews and approves individual state plans based on compliance with IIJA statutory requirements.[78]

Any congressional action would take place in a rapidly changing technology environment as grid modernization and hardening initiatives authorized under IIJA, IRA, and other legislation proceed, offering both opportunities and risk to policymakers (see the "Emerging Science and Technology Policy Issues" section). Inverter-based energy resources and microgrids may contribute to grid resilience against HEMP threats if they are appropriately configured and located to provide grid services, such as voltage support, and are able to survive the HEMP environment. Congress may consider supporting relevant research and development activities through legislation, oversight, and appropriations.

Relevant (functionally identical) technologies may be more or less resilient to HEMP, depending on what technical standards are applied to their design and manufacture, and their system configuration. Existing legislation primarily contemplates resilience to extreme weather hazards, wildfire, and other natural disasters as design considerations (see the "HEMP and Infrastructure Legislation in the 117th Congress" section). Congress may consider explicit inclusion of HEMP resilience in future infrastructure or related grants legislation. Additionally, Congress may consider directing FERC to oversee development and implementation of infrastructure protection standards specific to HEMP if deemed necessary (see "The CISR Framework and HEMP" section).

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[77] See FERC, "FERC Proposes Incentives for Voluntary Cybersecurity Investments," https://www.ferc.gov/news-events/news/ferc-proposes-incentives-voluntary-cybersecurity-investments. For a summary of existing threat information sharing programs, see CRS In Focus IF12061, *Critical Infrastructure Security and Resilience: Countering Russian and Other Nation-State Cyber Threats*, by Brian E. Humphreys.

[78] Department of Energy, Energy Efficiency and Renewable Energy Golden Field Office, *Administrative and Legal Requirements Document*, Golden, CO, March 28, 2022, p. 11, https://www.energy.gov/sites/default/files/2022-03/sep-state-energy-security-plan_alrd.pdf.

Future Technological Advancements

Congress may consider future technological advancements when developing policies relevant to HEMP resilience. For example, LPT stockpiling programs considered in the IIJA and previous legislation assume existing transformer designs as the basis for operational control of electricity transmission and distribution, which require large lead times for manufacture, customization, and transport (see the "HEMP-Specific Provisions in the IIJA" section). Emerging solid state technologies may enable a more rapid and flexible use of standardized systems to support a building-block approach to construction and repair of grid infrastructure that would eliminate the need for vulnerable LPTs. Likewise, such technology might enhance efficiency without increasing risks to grid stability—an improvement over most existing technologies (see "Future Grid Technologies and HEMP" text box, p. 20). Congress may consider balancing the need to manage risks to existing infrastructure against the possibility of eliminating certain risks through adoption of new technologies. Given the long service life of most electricity infrastructure assets, it may be appropriate to encourage investment in next-generation technologies where possible to avoid inefficient use of limited resources to harden obsolescent technologies against HEMP.

Appendix A. Selected Studies by Year

Research (year)	Research Design and Methods	Results and Conclusions
SANL (2021)	Modeling and simulation of E1 and E3 HEMP hazards to notional bulk electric power grid. (Effects of E3 harmonics not studied.) Use of statistical methods and component testing results to quantify transient response of a modeled grid to a HEMP event (IEC waveform), including cascading effects of E1 and E3.	Significant additional modeling and simulation work on interaction of HEMP environment with grid infrastructure needed "to draw realistic conclusions" on HEMP risk to infrastructure.
SANL (10/2020)	Study of conductive threat effects of simulated E1 HEMP events (using IEC waveform) on transmission lines and grid equipment control lines. Modeling and simulation to predict the effects of location and orientation of conductors relative to HEMP source on induced current and voltage, and produce statistics on peak value, rise time, and pulse width at a given location.	Average maximum voltages on overhead transmission lines were lower than the "typical worst case." Induced voltage on these lines was, on average, about 55% of the anticipated maximum value for a worst-case scenario for a given line orientation.
SANL (9/2020)	Testing of electric power substation circuits and certain protective equipment against simulated E1 insult. Injection of simulated E1 pulse into three different types of circuits (breaker, potential transformer, and current transformer) connecting digital protective relays (DPRs) in a control house with substation yard equipment.	"No equipment damage or undesired operation occurred on the tested circuits for values below 180 kV, which is significantly higher than the anticipated [E1] coupling to a substation yard cable."
SANL (4/2020)	Testing of photovoltaic (PV) modules against simulated E1 insult to 100 kV/m benchmark. Does not include testing of inverter systems used to convert direct current (DC) to alternating current (AC).	"No direct failures" of PV modules and only "minor observable module degradation" following exposure. Testing of inverter systems against observed coupled currents planned for future research.
EIS/SARA (2020)	DPR and distributed control system (DCS) components subjected to pulsed electric fields and pulsed current injection to limits specified by military standard (MIL-STD) 188-125. Working generating station exposed to simulated HEMP hazard fields. Strength of subcomponents tested or evaluated based on vendor documentation.	Unprotected DPRs and DCS components were susceptible to simulated HEMP insults. Simple remediation significantly mitigated risk. Generation station DCS and generator exciter systems are potentially vulnerable. Generation facility easily penetrated by simulated E1 fields.
EPRI (2019)	Commonly used DPRs subjected to simulated E1 pulsed electric fields and pulsed current injection based on MIL-STD-188-125 (up to 50 kV/m). Shielding effectiveness tests of typical substation control houses and mitigation devices. Interconnection-level assessments of E1 effects based on LANL (25 kV/m) and IEC 61000-2-9 (50 kV/m) E1environments, and E3B effects based on LANL HEMP environment and predicted reactive power losses. Effects of harmonics not studied.	Conductive E1 threats pose significant threat to unprotected DPRs. Simple remediation significantly mitigates risk. E3B may produce regional blackouts due to voltage instability. Wide-scale LPT heat damage limited. Recoverable, assuming limited harmonic effects, and adequate E1 protection of DPRs, DCS, and communications.

Research (year)	Research Design and Methods	Results and Conclusions
ORNL (2019)	Assessment of system-wide impact to LPTs of voltage surges and harmonics caused by HEMP or GMD. Pulsed electric fields based on IEC E1 benchmark for stress test of voltage arresters and bushings to validate modeling. Computational analysis of E1 and E2 effects on transformer windings. E3 effects modeling based on actual grid topology to predict GIC impacts on LPT core saturation and harmonics generation. Impact of GIC-blocking devices on grid stability simulated.	E1 may cause rapid voltage surges on long power lines, bypassing arresters designed to protect LPTs. Risk mitigated in some cases by modification of system topology and use of updated LPT designs. E3 is a "reduced risk event." Voltage stability is maintained even with significant loss of reactive compensation units. GIC-blocking devices on LPTs are best risk-mitigation option.
EMPC (2017)	Analysis of E3 fields created by two Soviet tests in 1962. Infrastructure modeling and simulation from 2008 study. Protective relays, DCS, and supervisory control and data acquisition (SCADA) systems exposed to simulated E1insults via free-field illumination and cable current injection. Expert assessment of likely cascading effects of entire HEMP sequence, and restoration considerations.	Recommended E3 field strength benchmark of 85 V/km for testing purposes. SCADA and—to lesser degree—DCS most vulnerable. DPRs comparatively robust. Wide scale and long-lasting grid collapse likely in many scenarios.

Sources: Brian Pierre, Daniel Krofcheck, and Matthew Hoffman, et al., *Modeling Framework for Bulk Electric Grid Impacts from HEMP E1 and E3 Effects*, Sandia National Laboratories, EMP-Resilient Grid Grand Challenge: Task 3.1 Final Report, Albuquerque, NM, January 2021; Richard L. Schiek and Matthew Halligan, *Statistical Profiles of E1 EMP Coupling to Single Conductors*, Sandia National Laboratories, SAND2020-10738, Albuquerque, NM, October 2020; Alfred Baughman, Tyler Bowman, and Ross Guttromson, et al., *HEMP Testing of Substation Yard Circuit Breaker Control and Protective Relay Circuits*, Sandia National Laboratories, SAND2020-9872, Albuquerque, NM, September 2020; Tyler Bowman, Jack Flicker, and Ross Guttromson, et al., *High Altitude Electromagnetic Pulse Testing of Photovoltaic Modules*, Sandia National Laboratories, SAND2020-3824, Albuquerque, NM, April 2020; Chris Beck, Eric Easton, and Carl Eng, et al., *Electric Infrastructure Protection Handbook IV: Electromagnetic Pulse Protection Best Practices*, the Electric Infrastructure Security (EIS) Council, Washington, DC, 2020; Electric Power Research Institute (EPRI), *High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies*, Palo Alto, CA, April 2019; A.G. Tarditi, J.S. Besnoff, and R.C. Duckworth, et al., *High-Voltage Modeling and Testing of Transformer, Line Interface Devices, and Bulk System Components Under Electromagnetic Pulse, Geomagnetic Disturbance, and Other Abnormal Transients*, Oak Ridge National Laboratory, ORNL/TM-2019/1143, Oak Ridge, TN, March 18, 2019; The Commission to Assess the Threat to the United States from Electromagnetic (EMP) Pulse Attack, *Assessing the Threat from Electromagnetic Pulse*, Executive Report, Washington, DC, July 2017.

Notes: EIS = EIS Council; EMPC = EMP Commission; EPRI = Electric Power Research Institute; ORNL = Oak Ridge National Laboratory; SANL = Sandia National Laboratories; SARA = Scientific Applications and Research Associates.

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