Building Resilience and Recoverability of Electric Grid Communications

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Abstract

Industrialized society depends on continuously operating critical infrastructures, especially the electric grid and its associated telecommunications systems. A widespread, long-term outage of grid systems can result from natural disasters, accidents, or intentional actions. When such an outage occurs, outside assistance may be unavailable or impractical. Resulting societal impacts can be severe—even deadly. Therefore, infrastructures should be designed for resilience to prevent collapse and to facilitate rapid recovery.

The telecommunications system for the U.S. electric grid exemplifies a subsystem vulnerable to such a long-term outage. An electromagnetic pulse (EMP) can cause such an outage to telecommunication systems. To ensure resilience to an EMP event, the equipment can be shielded and collocated with protected on-site power and long-duration fuel storage.

Building resilience and facilitating reconstitution of the grid telecommunication system would have societal benefits far exceeding the investments required to obtain these capabilities. The cost estimation methodology we use in this analysis is broadly applicable for a variety of hazards and threats to complex critical infrastructures.

Keywords: Communications, Electric Grid, EMP, Costs, Estimate, Resilience, Recoverability

doi: 10.18278/jcip.1.2.8

Introduction

Ensuring the availability of reliable, resilient communications is fundamental to the operation of the electric grid and other components of the U.S. critical infrastructure. These, in turn, are vital to national security and economic prosperity. A catastrophic outage of the U.S. electric grid could seriously threaten critical, life-sustaining services, jeopardize the health of millions of people, and cost trillions of dollars in lost Gross Domestic Product (GDP).

Protecting utility communication systems and their power sources from EMP effects will increase electric grid resilience to a wide spectrum of hazards and facilitate rapid recovery, reducing the probability of extended outages. This study identifies proactive, cost-effective solutions that could be implemented promptly to protect utility communication and control systems from solar storms and EMP caused by nuclear detonations in the atmosphere or ground-based attacks. It also identifies possible sources of federal grants and methods of cost recovery to encourage utilities to invest in grid resilience.

In January 2010, Metatech Corporation, under contract to Oak Ridge National Laboratory, published Report Meta-R-320, "The-Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid" (Savage, Gilbert, & Radasky, 2010), along with three other reports on EMP. The executive summary for this series of reports states:

> *The nation's power grid is vulnerable to the effects of an electromagnetic pulse (EMP), a sudden burst of electromagnetic radiation resulting from a natural or man-made event. EMP events occur with little or no warning and can have catastrophic effects, including causing outages to major portions of the U.S. power grid possibly lasting for months or longer. (Oak Ridge National Laboratory, 2010)*

In May 2018, the National Security Council tasked the President's National Infrastructure Advisory Council (NIAC) to "examine the nation's ability to respond to and recover from a catastrophic power outage of a magnitude beyond the modern experience, exceeding prior events in severity, scale, duration, and consequences" (NIAC, 2018). The resulting report observes:

> *National plans, response resources, and coordination strategies would be outmatched by a catastrophic power outage. A catastrophic power outage could paralyze entire regions with grave consequences for national security, economic security, and public health and safety.*

The report further determined that restoration and recovery are almost impossible without functioning communications:

> *Survivable communications are the lynchpin for responding to this type of event and restoring electricity (e.g., ability for power companies to communicate with each other and the government).*

The NIAC report verifies that the nation's communication infrastructure is ill-equipped to respond to a catastrophic event:

- *All communication systems are vulnerable to damage or attack, necessitating a variety of possible communication methods.*
- *Current emergency communication systems are unlikely to provide the multi-sector connectivity and interoperability that will be essential in catastrophic power outages.*
- *Communication networks were designed for power outages that are infrequent or of short duration; backup generators and fuel storage are designed to support an outage of a few hours to a few days.*
- *Communications systems will require fuel for generators, but pipeline pumping stations, storage depots, and truck distribution could be affected by a catastrophic power outage, preventing necessary resupply needed for communication networks to continue to operate.*
- *Backup power generation is a commonly accepted emergency response standard, but backup communication capabilities are generally not standard.*
- *Existing plans and exercises rely on communications systems, which are likely to be unavailable or degraded during a catastrophic power outage. Cross-sector coordination and support require broader telecommunications hardening.*

The Electric Grid and Its Telecommunication System

The North American electric grid, consisting of the U.S. electric grid and the associated Canadian electric grid, is the world's largest machine. Electricity is produced at generating stations, stepped up to high voltage for transmission, and then stepped down for distribution to homes and businesses.

The North American electric grid is divided into three principal regions: Eastern Interconnection, spanning the East Coast to the Rocky Mountain Continental Divide; Western Interconnection; and the Electric Reliability Council of Texas (ERCOT), generally contiguous with the political boundaries of Texas. Each interconnection operates on a separate alternating current frequency of 60 cycles per second, with a few high voltage direct current ties between the interconnections.

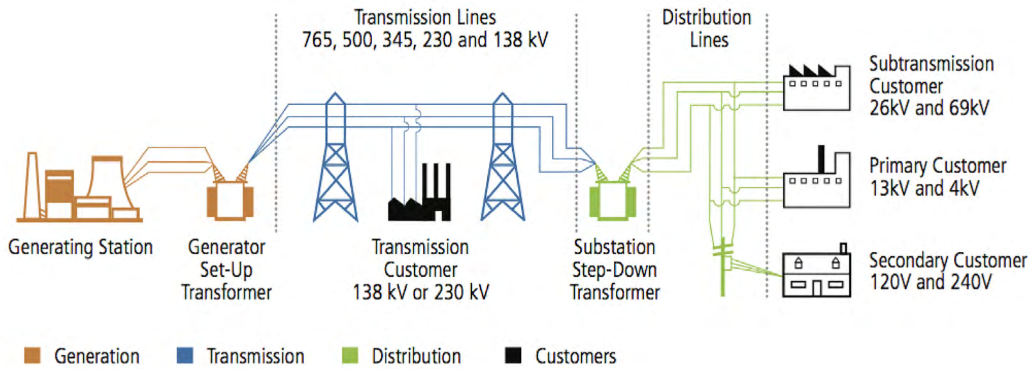

Figure 1. Electric Grid Generation, Transmission, Distribution, and Customers
Graphic credit: U.S. Department of Energy

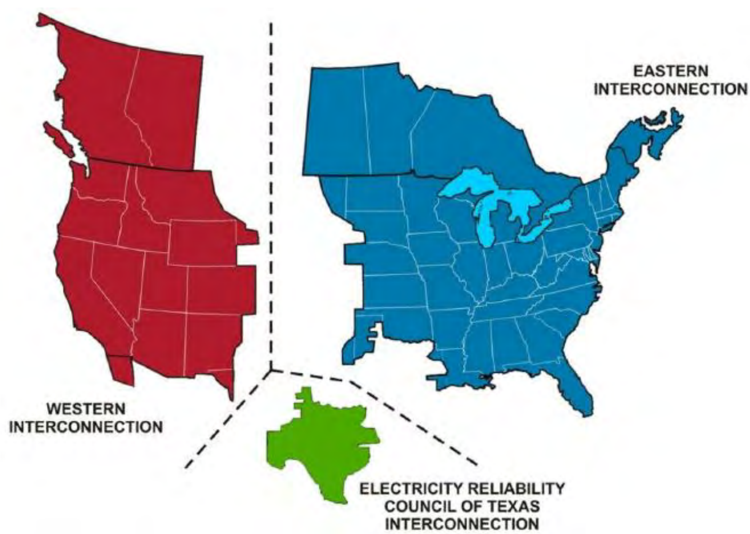

Figure 2. Interconnections of the North American Electric Grid
Graphic Credit: U.S Department of Energy

Within the U.S. portion of the interconnections, twelve master control rooms and several thousand subsidiary control facilities manage the operation of equipment at nearly 70,000 transmission and distribution substations. This far-flung control system is made possible by long-haul communications owned by both utilities and common carriers. The Canadian portion of the North American electric grid uses a similar system of control.

Communication technologies used in the U.S. electric grid principally include fiber optics, microwave radio, and copper conductor circuits. Utilities commonly rely on a mixture of company-owned circuits and circuits leased from common carriers. Communication systems of large, investor-owned utilities often consist of microwave and fiber optic networks. Smaller utilities, usually municipal or cooperative utilities, more often rely on leased circuits. When common carriers are used, the circuit reliability is designed for residential and commercial customers. That service level might not meet the needs of electric utilities during an emergency.

When generation reserves are switched in and ramped up during system recovery, it is important that the phase and frequency of the added power match the phase and frequency of the grid. Electric utilities have developed extensive communication networks to measure phase, frequency, voltage, current, and equipment temperature at points across the grid. Communication networks are vital to effectively synchronize the generation, transmission, and distribution of electricity with customer demand during normal operation and system recovery.

Electric grids and their telecommunications systems are interdependent. A long-term outage of the electric grid can cause a failure in the grid telecommunication subsystem because nearly all telecommunications ultimately depend on grid power. When communications from control rooms to substations fail, the lack of situational awareness and grid control can result in cascading grid collapse.

System Vulnerabilities and Failures

Because of the design of its protective equipment, the North American electric grid is susceptible to cascading collapse over wide geographic areas. A cascading collapse occurs when a disturbance propagates through the high voltage transmission lines of the grid, causing transformer protective devices called "relays" to interrupt the flow of energy between generation stations and consumers. Because high voltage transmission lines carry power hundreds or even thousands of miles, large geographic regions and millions of people can lose electricity when a cascading collapse occurs.

Causes for failure of electric grid communications include ordinary equipment malfunction; damage from natural disasters, human error, cyberattack, or physical attack; and loss of auxiliary electric power. A 2008 report from the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (EMP Commission) noted an additional cause of long-term grid outage—an EMP from the detonation of a nuclear weapon in the upper atmosphere (Congressional EMP Commission, 2008).

The telecommunications subsystem for the U.S. electric grid has been engineered for resilience against weather events, but not for resilience against EMP, severe solar storms, physical attack, and cyberattack. Of these events, atmospheric EMP detonation would likely have the highest consequence, because the effects would be continent-wide for a well-executed attack.

Adversaries can also launch ground based EMP attacks via radio frequency (RF) weapons activated from vehicles, drones, and even small suitcases. Unconventional forces (non-uniformed combatants) could use RF weapons to disrupt, damage, or destroy control circuitry at unshielded electric grid facilities. High-power microwave weapons are almost undetectable prior to use; they can be smuggled into target countries in pieces and assembled covertly.

Geomagnetic disturbances (GMD) (e.g., solar storms) are caused by coronal mass ejections from the Sun, which can be described as electromagnetic tsunamis. Solar storms cause strong, induced ground currents that can exceed several thousand amps of current over long distances with severe implications for the electric grid. For example, in July of 2012, a major solar storm missed the Earth by 7 to 9 days. Had the Earth been in the direct path of the solar storm, damage to the electrical grid could have been catastrophic (Washington Post, 2013).

The "Halloween Storms" erupted in 2003, affecting the Earth's magnetic field from October 19 through November 7. Comprised of an outbreak of 17 major flares, they remain some the most powerful solar storms ever recorded. The impacts were wide-ranging and significant. The violence of this "geomagnetic storm" caused spectacular "northern lights" that could be seen as far south as Florida and Cuba. The magnetic disturbance was incredibly intense. It actually created electrical currents in the ground beneath much of North America (NASA, 2009).

Other major cascading collapses of the electric grid in the 21st century include the Northeast Blackout in August 2003 and the Southwest Blackout in September 2011. The Northeast Blackout affected 55 million people in Michigan, Ohio, Pennsylvania, New York, New Jersey, Connecticut, and parts of Canada. The proximate cause was automatic tripping of a transmission line after contact with a tree branch. This initiating event was exacerbated by lack of situational awareness in a Midwest grid control room. The Southwest Blackout affected seven million people in California, Arizona, and parts of Mexico. This blackout was caused by an accidental disconnection of an Arizona-to-California transmission line by a substation technician.

Service was restored following both blackouts within 24 hours, although a few affected areas took longer to recover. Significantly, 24 to 72 hours is the accepted design basis for backup power of telecommunications systems. Had these blackouts lasted longer, energy for the grid's telecommunications systems could have been depleted, greatly complicating recovery.

Costing Methodology

The lack of well-supported, systemwide cost estimates has impeded progress in improving the resilience and recoverability of telecommunications for the U.S. electric grid, especially after an EMP event. Regulators and utility executives often understand the imperative of enhancing resilience. However, before actual improvements can be made, cost estimates are required for utility rate cases or, in the case of directly appropriated funds, fiscal notes prepared for state legislatures.

This study estimates the cost of building resilience and recoverability in electric grid telecommunications subsystem to an EMP attack and a cascading grid collapse. We also estimate the cost of providing long-term backup power for the grid's communications system. With minor adaptation, our methodology can be used to estimate protection costs for other electric grid subsystems.

We demonstrate how engineering analysis, vendor cost data, and publicly available information on facility counts can be combined to produce the requisite cost estimates. Detailed estimates such as these can be used to assess how resilience improvements apply for all hazards and threats. These include both natural and human-caused events that could produce a cascading collapse followed by the loss of auxiliary power for communications systems in large geographic areas.

To calculate the costs for grid resilience and recoverability, we first determined the vulnerabilities of individual pieces of equipment and estimated the cost to mitigate those weaknesses. We then determined the number of facilities to be protected and their associated equipment counts. With this information, we multiplied the per-unit protective costs by count of units to be protected. This procedure was repeated for each type of equipment and category of facility. Finally, we added the costs for each category of facility to determine the total cost for protection.

In the analysis, we estimate the cost of EMP shielding and long-duration backup power for grid telecommunications equipment. EMP shielding for communications equipment is a well-developed technology because the U.S. Department of Defense has protected its strategic systems for several decades. Protection commonly consists of shielded cabinets that act as Faraday Cages, filters for power and other conductors that penetrate cabinet walls, and low impedance grounding grids to absorb EMP.

Were an EMP attack to collapse portions of the U.S. electric grid, a functioning telecommunication system and long-duration backup power would be necessary for recovery. We examined several on-site power generation technologies and determined that Stirling engines powered by propane are the most cost-effective, long-duration backup power source, although other options could also be viable. These include hydrogen fuel cells and the post-event deployment of pre-positioned solar panels with battery storage.

Small Stirling engines are reliable and commercially available at moderate cost. They offer the advantage of using multiple types of fuel, which could be important following an EMP event. Propane distribution networks are well developed. Propane can be stored in steel tanks at low pressure, with a nearly indefinite shelf life. These characteristics make Stirling engines fueled by propane a good option for our study.

We researched costs by contacting vendors of protective devices, shielded cabinets, backup power sources, and fuel tanks; construction companies; and radio frequency test facilities. This study applies these costs to two principal methods of reliable grid communications: fiber optics and microwave radio for communications.

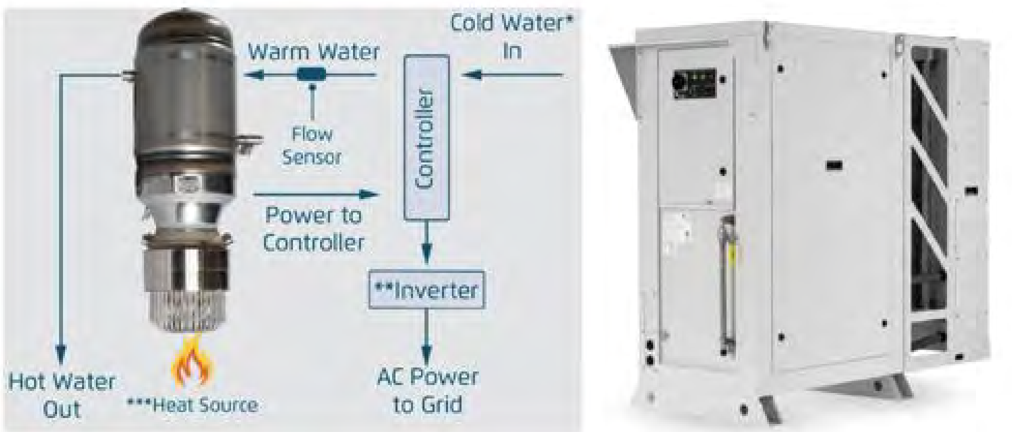

Figure 3. Stirling Engine Remote Power System
Photo Credit: Qnergy

Figure 4. Electric Grid Substation with Microwave Communications Dish on Tower
Photo credit: Creative Commons/vaxomatic

Results

The study presents these results: (1) estimated per-unit costs, including protection for fiber optic and microwave endpoints both at electricity control centers and substations; (2) replacement of leased circuits with fiber optics; and (3) protection of fiber optic amplification sites and microwave radio base stations. We estimate the number of facilities (and associated equipment counts) to be protected. Based on this information, we are able to determine systemwide costs for national protection (Winks, David, 2020).

The United States needs a mass-produced, easily deployed way to protect communication systems at 72,000 electric grid facilities across the country. As a general solution, we recommend communication equipment be placed in EMP-shielded cabinets. A key part of our proposed solution is backup power designed for six months of operation without refueling. Long-term backup power for electric grid communications will increase resilience to a wide variety of situations, not just EMP events.

The need for long-term backup power is supported by the electric grid experts. NIAC suggests in its report, "Surviving a Catastrophic Power Outage," that utilities:

> *Develop or support a flexible, adaptable emergency communications system that all sectors can interoperably use, that is self-powered, and is reasonably protected against all hazards to support critical service restoration and connect infrastructure owners and operators, emergency responders, and government leaders. (NIAC, 2018)*

The protected telecommunication subsystems examined in this study include those for control centers and substations—both common carrier circuits (including copper conductor circuits) and utility-owned circuits (such as microwave radio and fiber optic).

The proposed plan includes protecting between control centers and substations, including installation of long-duration backup power. The majority of these communications runs through microwave and fiber optic networks. Tables 1 and 2 below show examples of cost breakdowns for protection of communications equipment at control centers and substations.

Where copper conductor circuits are used—both by utilities and common carriers—we propose replacing these circuits with fiber optics. Installation of aerial fiber costs approximately $25,000 per mile. We estimate an average of 10 miles for each replaced copper conductor communications link.

Number of Facilities to Be Protected

Per the U.S. Department of Energy, approximately 3,200 electric utilities serve U.S. consumers (U.S. Department of Energy, 2015). Large utilities commonly consist of a primary control center and one or more backup centers. Smaller utilities may share control centers or contract out the control function. Our study assumes a total of 3,000 control centers to be protected. Of these, we estimate that 2,400 use fiber optics and 600 use microwave radio.

Table 1. Protection of Control Centers Using Fiber Optic Communications with Stirling Engines for Backup Power

Control Centers Using Fiber Optic Communications	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (44U)	$19,885		
Redundant 1 KW Stirling Engine	$46,451		
Propane Storage	$22,503		
Precise Timing Remote Unit	$1,130		
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$104,715	$83,837	$188,552

Table 2. Protection of Substations Using Microwave Communications with Stirling Engines for Backup Power

Substations Currently Using Microwave Communications	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (44U)	$19,885		
Redundant 1 KW Stirling Engine	$46,451		
Propane Storage	$22,503		
Precise Timing Remote Unit	$1,130		
EMP Shielded Waveguide Bandpass Filter	$4,661		
Heliax	$193	$906	
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$109,569	$84,743	$194,312

The Department of Homeland Security (DHS) indicates 68,992 electric grid substations operate in the United States (U.S. Department of Homeland Security, 2020). We estimate the number of substations by telecommunications technology and carrier as shown in Table 9 below. These numbers are derived by combining data from the Federal Communication Commission (FCC) (FCC Database, 2020), the United Technology Council (UTC) (UTC, 2019), the Smart Utilities report from Black & Veatch (Black & Veatch, 2020), and the DHS Homeland Infrastructure Foundation-Level Data (HIFLD) (U.S. Department of Homeland Security, 2020).

Table 3. Substation Communications by Technology and Carrier

Substation Communications by Technology and Carrier		
Communications Mode	Number of Substations	Percent of Substations
Utility Owned Fiber Optics	35,404	51%
Leased Circuit Fiber Optics	7,262	11%
Utility owned Copper Conductor Circuit	1,816	3%
Leased Circuit Copper Conductor	10,893	16%
Microwave Radio Link	13,617	20%
Total	68,992	100%

Fiber optic communication requires intermediate amplifiers, approximately one every 80 miles. We estimate 450,000 fiber miles for transmission and 250,000 fiber miles for distribution. By totaling transmission miles and allocating one amplifier per 80 miles, we estimate 8,750 fiber amplifiers.

Based on FCC data for radio licenses held by utilities, we estimate 4,570 radio base stations in the U.S. electric grid.

Systemwide Costs for Protection

We estimate total protection costs to be approximately $21 billion, subdivided by eight categories. For each category, we multiply the number of sites by the protection costs per site. We add the subtotals to determine the total cost of protection. This methodology is displayed in Table 4 below.

Table 4. EMP Protection for the U.S. Grid Using Stirling Engines

EMP Protection for the U.S. Grid Using Sterling Engines	Sites	Per Site	Total
Control Centers Using Fiber Optic Communications	2,400	$188,552	$452,525,630
Control Centers Using Microwave Communications	600	$194,312	$116,587,411
Substation Using Fiber Optic Communications	35,404	$188,552	$6,675,507,252
Substations Using Microwave Communications	13,617	$194,312	$2,645,951,292
Fiber Amplifier Sites	8,750	$178,610	$1,562,835,052
Mobile Radio Base Stations	4,570	$194,312	$888,007,447
Substations Upgraded from Copper to Fiber Optics	12,709	$444,088	$5,643,915,156
Substations Upgraded from Leased to Utility Fiber	7,262	$444,088	$3,224,967,493
Total			$21,210,296,732

An investment of $21 billion would significantly increase the resilience of the U.S. electric grid. It is important to observe that the grid's communications system is not its only vulnerable element. Therefore, we do not propose that this investment will provide comprehensive protection; instead, we assert this targeted investment would provide protection that has a low cost relative to the increase in resilience.

National Security Implications

Investing in EMP protection and long-term backup power for the electric grid's communication system is necessary to buttress national security. Military installations, law enforcement facilities, intelligence agencies, border control, and critical data processing facilities based in the continental United States depend on the commercial electric grid.

A robust, resilient communication system is also essential to expedite restoration of critical, lifeline services and diminish adverse health consequences for millions of Americans. Fuel, clean drinking water, wastewater services, food processing, emergency medical services, transportation, financial services—all lifeline services—and other sectors of the critical infrastructure rely on the electric grid. Lacking electricity, wastewater systems would shut down; sewers would backup into buildings and residences. Sewage contamination of rivers and drinking water could cause epidemics.

Electricity is required to manufacture medical supplies such as masks, gloves, protective clothing, syringes, catheters, and saline solutions. It is also required to produce and store vaccines and injectable medicines. Without electricity, existing inventories would spoil; production of new supplies would cease, precisely when most needed. Like vaccines, insulin also requires refrigeration. Lacking electricity, about six million Americans could die from the lack of this life-sustaining medicine (American Diabetes Association, 2015).

Medical facilities rely on electricity to refrigerate blood supplies and power diagnostic, purification, and sterilization equipment. Without these systems, life-saving surgeries would be difficult and dangerous to conduct. Without electricity, the lives of 468,000 Americans on dialysis would be at risk (NIH, 2016).

While the costs of investing in resilience and recoverability are generally borne by utilities and their ratepayers, benefits accrue to the entire society. A good, first-order method of estimating societal benefits—or avoided societal losses—is to assess the loss in GDP during an extended electric grid outage.

Annual GDP for the U.S. in 2020 was approximately $20 trillion or $1.7 trillion per month. We might assume that 90% of GDP is lost during a blackout or $1.5 trillion per month. By investing $21 billion to fortify the electric grid telecommunications system, it may be possible to accelerate the electric grid's recovery by several months. This investment should yield benefits that far outweighing the expenditure. A report issued by the National Institute of Building Sciences indicates that for every dollar invested in hazard mitigation, six dollars are saved during restoration (Center for Disaster Philanthropy, 2018).

It is also helpful to estimate the per capita cost of protection and place that figure in the context of other money that consumers spend on utilities. For example, the average monthly cable TV bill is approximately $217 (Consumer Reports, 2019) and the average monthly electricity bill is approximately $115 (Energy Information Administration, 2019). In comparison, our total estimate of $21.2 billion for protection spread out over 135 million electric utility ratepayers and ten years would be just $1.31 per month.

Paying for EMP Protection

Protecting against existential threats such as a prolonged outage of the national grid provides "an opportunity of convergence" in which multiple agencies can collaborate to respond to a common challenge. By taking a more comprehensive, all-hazards approach to risk mitigation, EMP protection could be incorporated as part of the cost for improving resilience related to severe weather. Technology that enhances resilience of utility infrastructures to lightning and transients caused by severe storms also serves in the events of solar storms, attacks from RF weapons, and atmospheric-based EMP attacks.

Many programs exist at the federal and state level to fund EMP protection for the communications infrastructure. Sources of funding include tax credits, loan guarantees, and grants. The FCC offers grants under its Federal Service Fund, a program established in 1997 to facilitate the deployment and adoption of fixed and mobile telecommunications and broadband services. Through its Rural Digital Opportunity Fund, the FCC also incentivizes utilities that bring 5G cellular capacity and high-speed broadband services to rural areas. FEMA offers grants for pre-disaster resilience. Grants are also available from the Department of Housing and Urban Development and the Department of Agriculture.

Conclusion

The U.S. electric grid is an immense machine operated by more than 3,000 utilities. Insufficient consideration has been given to assessing how targeted investments can boost its resilience and recoverability. While individual utilities may be able to estimate costs for protecting their respective parts of the grid and its equipment components, the task of assessing costs for systemwide protection can seem insurmountable. Lacking this data, it is difficult inform policymakers regarding societal benefits in relation to financial costs. Inaction results.

In this paper we demonstrate how a straightforward methodology of multiplying per-unit protection costs by the number of units to be protected can result in a transparent, supportable figure for systemwide investment. Publicly available information is sufficient for a first-order cost estimate.

Key findings:

1. Restoring critical functions of lifeline services following an EMP event hinges on real-time collaboration among network control centers and substations, generation plants, transmission systems, and distribution systems. Success depends on a functioning communication system at each of these installations.

2. A resilient communication system is the lynchpin to restore the electric grid, reconstitute the critical infrastructure, and reestablish lifeline services following a catastrophic EMP event—manmade or natural.

3. Functioning communication systems require EMP hardening for fiber transceivers, fiber amplifiers, microwave radios, and mobile radio base stations.

4. Investments in EMP protection will also protect against other grid threats, including physical and cyberattack, because communications with long-term backup power will aid in restoration after grid collapse from multiple causes.

It is important to consider this study in the overall context of cost and benefit. The estimated total cost of these proposed solutions is approximately \$21 billion or \$74 per person. Alternatively, failing to invest in EMP-hardened, resilient communications for the electric grid could result in a GDP loss in the order of \$20 trillion annually. The business case and the national security imperative for this investment are compelling.

Acknowledgements

We acknowledge the assistance of William Harris, Mary Lasky, and Henry Cooper in the research for this study. Research funding was provided by the Smith Richardson Foundation.

Acronyms and Abbreviations

DHS	Department of Homeland Security
DOE	Department of Energy
EMP	Electromagnetic Pulse
EIA	Energy Information Administration
ERCOT	Electric Reliability Council of Texas

FCC	Federal Communication Commission
GDP	Gross Domestic Product
HIFLD	Homeland Infrastructure Foundation-Level Data

Author Capsule Bios

Thomas Popik is Chairman, President, and co-founder of the Foundation for Resilient Societies. In addition to leading Resilient Societies, he serves as a principal investigator on critical infrastructures, specializing in resilience assessment, risk analysis, and economic modeling. Mr. Popik holds a Master of Business Administration from Harvard Business School and a Bachelor of Science degree in Mechanical Engineering from MIT. In his early career, Mr. Popik served as an officer in the U.S. Air Force.

David Winks' background includes Physics, Electrical, and Mechanical Engineering. This provides the foundation for his work as Chief Science Officer at Renewable Energy Aggregators. He is considered a subject matter expert on resilient power and communications to the U.S. Department of Defense's Electromagnetic Defense Task Force, InfraGard's National Disaster Resilience Council, the U.S. Department of Homeland Security, and the San Antonio (Texas) Electromagnetic Defense Initiative. His work focuses on resilience to all-hazards for critical infrastructure.

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