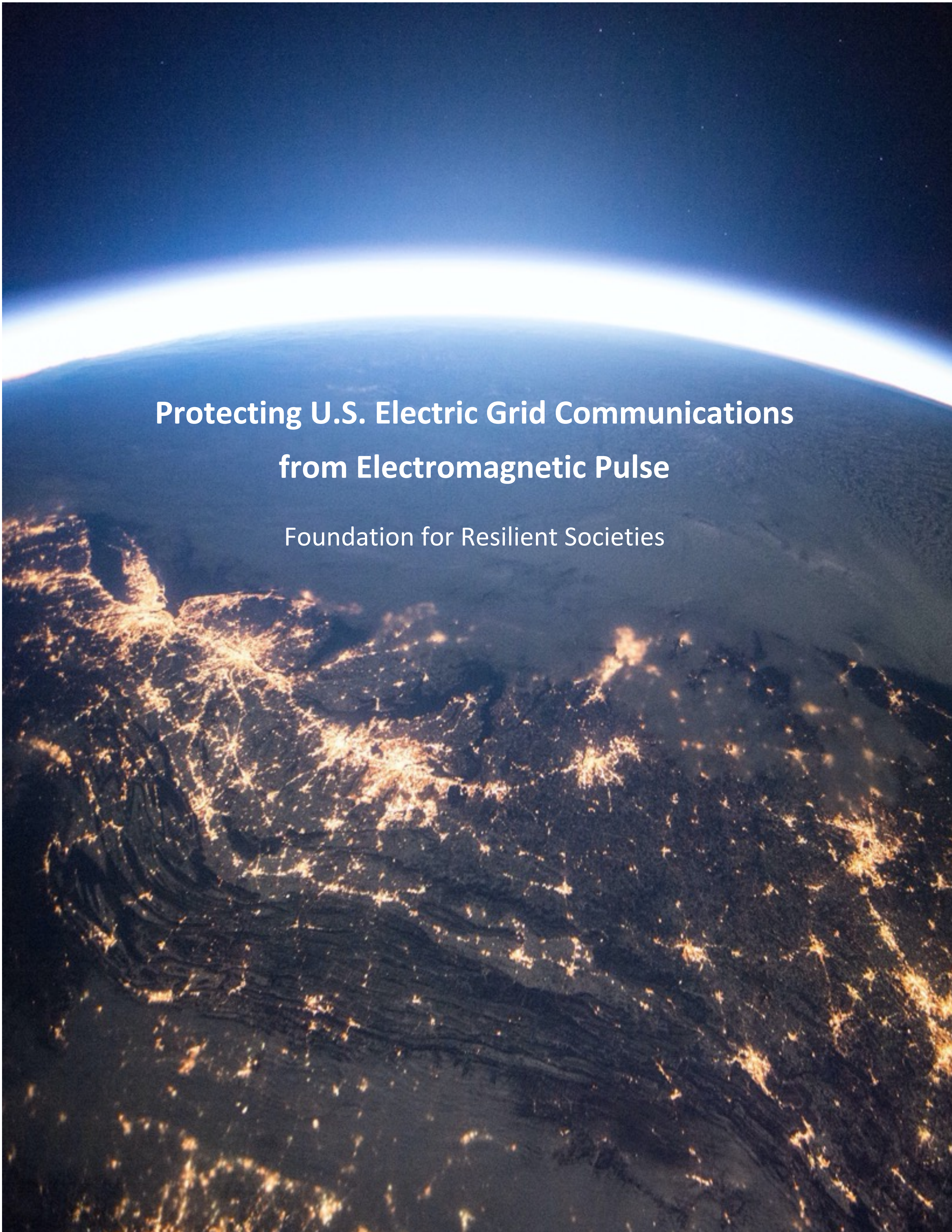

Protecting U.S. Electric Grid Communications from Electromagnetic Pulse

Foundation for Resilient Societies

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April 2020

Report prepared by David Winks (AcquSight, Inc.), under sponsorship of the Foundation for Resilient Societies

Cover Image: Observing Earth- ISS Expedition 46

“A photo taken by NASA astronaut Scott Kelly during his One Year Mission to the International Space Station clearly shows the snow-covered east coast of the United States. Taken in January 2016, the picture also shows the line separating the land from the Atlantic Ocean shortly before sunrise.” https://www.flickr.com/photos/nasamarshall/26116788633

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Abstract

A catastrophic outage of the U.S. electric grid could seriously jeopardize national security; threaten critical, life-sustaining services and, consequently, the health of millions of people; and cost trillions of dollars in lost revenue. This study identifies proactive, cost-effective solutions that could be implemented promptly to protect utility communication and control systems from solar storms and electromagnetic pulses caused by nuclear detonations in the atmosphere. It also identifies possible sources of federal grants and methods of cost recovery to encourage utilities to invest in grid resiliency. Protecting electric grid communications and its power sources could facilitate rapid recovery and prevent extended outages caused by natural or deliberate EMP events.

Acknowledgements

I would like to thank Tom Popik, Mary Lasky, and Bill Harris of the Foundation for Resilient Societies for their gracious and patient assistance with this report. Additionally, I would like to thank Curtis Birnbach and Dr. George Baker for their excellent technical insights and patient explanation of the rigorous scientific aspects of protecting against electromagnetic pulse. Special thanks to Carla Bass, Colonel, USAF (Ret), author of the award-winning book, "Write to Influence!", who tirelessly worked to improve the report.

1. Call to Action – Protect Utility Communications

Protecting utility communication systems from electromagnetic pulse (EMP) effects will increase electric grid resilience to a wide spectrum of hazards. Ensuring the availability of reliable, resilient communications is fundamental to 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.

National leadership, emergency planners, regulators, and utility owners increasingly recognize the risks of long-term blackout from EMP and other hazards. For example, 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).

NIAC's subsequent report characterized a "catastrophic event" as one that:

- Exhausts or exceeds mutual aid capabilities beyond modern experience
- Is likely to occur with little to no notice
- Lasts several weeks to months due to physical infrastructure damage
- Affects a broad geographic area and tens of millions of people
- Causes severe, cascading impacts that force critical sectors to operate in a degraded state

The 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.* (NIAC, 2018)

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.)* (NIAC, 2018)

According to NIAC, the United States needs a communication system (including IT) that is:

> *robust and capable of operating even in a degraded state to provide situational awareness and allow for coordination and information sharing among federal government authorities, SLTT government, owners and operations, and communities. Emergency communications should have backup power and be deployable to all infrastructure and critical supply chains.* (NIAC, 2018)

However, 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.* (NIAC, 2018)
- *Current emergency communication systems are unlikely to provide the multi-sector connectivity and interoperability that will be essential in catastrophic power outages.* (NIAC, 2018)
- *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.* (NIAC, 2018)
- *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.* (NIAC, 2018)
- *Backup power generation is a commonly accepted emergency response standard, but backup communication capabilities are generally not standard.* (NIAC, 2018)
- *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.* (NIAC, 2018)

Building on NIAC's observations, this study addresses hardening the utility communication infrastructure against EMP effects – including loss of alternating current (AC) power from the electric grid – and has three objectives. First, it identifies the various communication equipment needing greater resilience to EMP events (e.g., fiber optics, microwave radio, copper conductor lines, satellite, and mobile radio), the means to protect them, and approximate cost. Second, it provides policymakers a reference for societal benefits gained from protecting utility communications. Finally, it explores mechanisms to fund EMP protection.

We recommend a variety of EMP protections for utility communications, including installation of long-duration backup power, hardening of existing equipment, and replacement of equipment that cannot be cost-effectively hardened.

Our first-order and approximate cost estimate for EMP protection of key communications systems owned and operated by electric utilities is approximately \$20-30 billion.[1] The engineering and economic basis for estimating EMP protection costs can be further elucidated using the transparent framework that we propose in this study. Transparent and detailed cost estimates are a prerequisite for funding of EMP protections.

2. The EMP Threat Landscape

2.1 Emerging EMP Threats

The U.S. electric grid is vulnerable to a plethora of threats – manmade and natural – that were not considered by those who originally designed and constructed its components. This study addresses threats from EMP, including EMP from high-altitude detonation of nuclear weapons, naturally occurring EMP from solar storms, and localized EMP from radio frequency (RF) weapons.

Rogue nations increasingly realize that EMP is an asymmetric means of attacking industrialized societies.

> *North Korea says it's developed a "super explosive" hydrogen bomb that fits on an intercontinental ballistic missile, according to multiple media reports citing the country's state news agency. The North said in its statement Sunday that its H-bomb 'is a multi-functional thermonuclear nuke with great destructive power which can be detonated even at high altitudes for super-powerful EMP (electromagnetic pulse) attack according to strategic goals* (NPR, 2017).

In addition to pursuing its own nuclear program, North Korea may have transferred technology to Iran that increases the threat of an EMP attack (Foreign Affairs, 2018), including the means to launch missiles and satellites with EMP devices. On February 9, 2020, the Iranian Simorgh rocket with the Zafar 1 satellite reached an altitude of roughly 540 kilometers (Clark, 2020). While Iran's south polar launch did not achieve orbital velocity, it could have been practical training for a sub-orbital EMP attack.

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[1] Cost estimates for EMP protection have been developed using a transparent methodology that multiplies the per unit protection costs by the equipment and facility counts.

As the congressionally mandated EMP Commission reported in 2017 (EMP Commission Executive Report, declassified in 2018), Russia, China, North Korea and Iran all embed the use of high altitude nuclear EMP weapons in their military training and combined arms military doctrines. Moreover, Russia and China have test-flown airborne systems designed for regional electromagnetic spectrum operations, and Chinese media in March 2020 advocated readiness for Chinese use of EMP weapons against U.S. naval forces in the South China Sea to protect China's territorial claims. Other nations have developed both doctrine and electromagnetic spectrum weaponry. (EMP Commission Staff Report, 2017).

2.2 Impact of Nuclear EMP Events on Communications

When a nuclear weapon is detonated in the atmosphere, the resulting electromagnetic pulse can disrupt or damage electronic devices over a wide geographic area. Depending on the location and the height of the detonation, an EMP attack could interrupt communications in much of the United States. EMP-induced voltages in conductors attached to communications equipment, combined with surges from grid power, can damage circuitry in fiber optic networks and microwave radios commonly used by electric utilities for operational communications.

Fiber optic amplifiers are installed about every 80 miles along a fiber route and typically use AC power from the commercial electric grid. While the glass fibers connected to the amplifiers will not conduct EMP-induced currents and voltages, their power supplies are vulnerable.

EMP would likely damage unprotected microwave radios. Microwave and satellite transceivers use bandpass filters to operate in the presence of nearby radars, WIFI equipment, cell towers, and other transmitters. Standard bandpass filters may not be able to dissipate the level of power from EMP events, which generate electric fields approximately 250 times stronger than a nearby airport radar.

Fiber optic equipment, microwave radios, and satellite transceivers all rely on commercial grid power. Incoming power lines act as antennas during an EMP event. The electromagnetic pulse can induce several hundred amps of current in these cables. Following an EMP event, the long-term absence of AC power from the commercial electric grid will cause communications to fail when battery backups deplete, and backup generators run out of fuel.

2.3 Impact of Geomagnetic Disturbances on Communications

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)

The solar storm triggered disruptions to the Global Positioning System (GPS), affecting the Federal Aviation Administration's navigation system and causing aircraft to be rerouted.

> *On Friday March 10, 1989 astronomers witnessed a powerful explosion on the sun. Within minutes, tangled magnetic forces on the sun had released a billion-ton cloud of gas. It was like the energy of thousands of nuclear bombs exploding at the same time. The storm cloud rushed out from the sun, straight towards Earth, at a million miles an hour.* (NASA, 2009) (NASA, 2009)
>
> *The Quebec Blackout was by no means a local event. Some of the U.S. electrical utilities had their own cliffhanger problems to deal with. New York Power lost 150 megawatts the moment the Quebec power grid went down. The New England Power Pool lost 1,410 megawatts at about the same time. Service to 96 electrical utilities in New England was interrupted while other reserves of electrical power were brought online. Luckily, the U.S. had the power to spare at the time…but just barely. Across the United States from coast to coast, over 200 power grid problems erupted within minutes of the start of the March 13 storm. Fortunately, none of these caused a blackout.* (NASA, 2009)

The solar storm of August 4, 1972 caused an outage of the L4 coaxial cable system link from Plano, Illinois to Cascade, Iowa. It also had considerable effect on the U.S. Navy during the Vietnam War.

> *During the first few weeks of August, a series of extremely strong solar flares caused a fluctuation of the magnetic fields in and around South East Asia. The resulting chain of events caused the premature detonation of more than 4,000 magnetically sensitive DSTs (Destructor mines).* (Michael Gonzales, 2015)

> *For the U.S. Navy, dealing with the event was of utmost priority. Hartman and Truver (1991) note that "… the HaiPhong Destructor Field was actually swept by a solar magnetic storm in August of 1972."* (Delores J. Knipp1, 2018)

The "Railroad Storm" storm in 1921 caused a blackout of the railroad communication systems in New York and started fires in control facilities in New York and Sweden.

> *Telephone lines were disrupted in the U.K., New Zealand, Denmark, Japan, Brazil and Canada.* (Scientific American, 2019).

2.4 Impact of Radio Frequency Weapons on Communications

Radio frequency weapons can deliver localized EMP 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.

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Figure 1: Radio Frequency Weapon Mounted in a Van (Advanced Fusion Systems, 2019)

RF weapons, as shown in Figure 1 and Figure 2, can disable electric grid communications. The complete RF weapon system, comprised of an antenna, an RF source, a high voltage power supply, and a capacitor bank, can be mounted into a small, commercial van as shown in Figure 1. These weapons are designed to operate at specific frequencies and can transmit tens of pulses per second that couple to computer circuitry, creating currents that interrupt or destroy chips. Typical protection devices, such as metal oxide varistors (MOVs), may overheat and degrade. MOVs may not effectively defend against repeated RF weapon attacks.

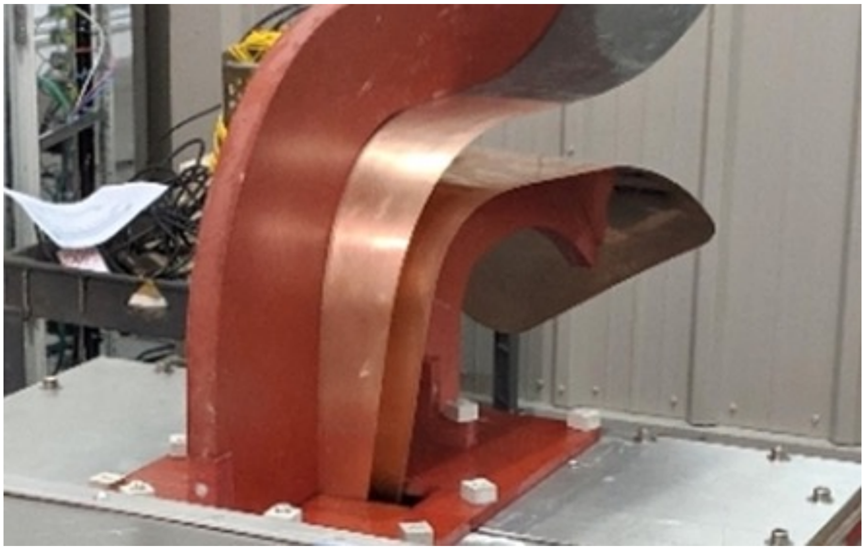

Figure 2: RF Weapon Antenna (Advanced Fusion Systems, 2019)

Figure 2 shows the rear view of the antenna mounted on the source assembly. The size and design of the antenna is specific to the operating frequencies of the weapon.

3. EMP Protections – Scoping the Challenge

To estimate the cost of EMP protections, it is first necessary to determine the types, characteristics, and counts of electric grid facilities. Key parameters in our study include the number of utility control centers, substations, and radio base stations. The statistic for transmission route miles is another key parameter. The precise number and characteristics of utility facilities are not definitively known because utilities restrict access to this sensitive information. The U.S. electric grid is considered one of the most complex "machines" ever created. For the purposes of this study, we estimate 3,000 control centers; 69,000 substations; 8,750 fiber amplification sites; and 4,750 radio base stations[2], totaling approximately 86,000 locations with communications equipment (see Appendix B). We give the basis for these estimates below.

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[2] FCC Database for Radio Base Stations, January 2020

3.1 Control Centers

There are more than 3,200 electric utilities in the United States (U.S. Department of Energy, 2015). Larger utilities may have multiple control centers, while smaller utilities may use shared services. This study assumes a total of 3,000 control centers will need EMP protection for their communications.

3.2 Substations by Communications Technology and Carrier

The DHS Homeland Infrastructure Foundation-Level Data (HIFLD) shows that the number of electric substations in the United States totals 68,992 (U.S. Department of Homeland Security, 2020). We used data from the Federal Communication Commission (FCC), the United Technology Council (UTC), the Smart Utilities report from Black & Veach, and the Department of Homeland Security (DHS) to estimate the number of substations by telecommunications technology and carrier. We arrived at these estimates:

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 Links	13,617	20%
Total	**68,992**	**100%**

Table 3. 1: Substation Communications by Technology and Carrier

3.3 Fiber Optic Amplification Sites

We estimated the number of intermediate nodes for fiber amplifiers using 450,000 fiber miles for transmission and 250,000 fiber miles for distribution with amplifiers every 80 miles. By totaling transmission miles for transmission and distribution and then dividing by the metric of one amplifier every 80 miles, we arrived at an estimate of 8,750 fiber amplifiers.

3.4 Radio Base Station Sites

We calculate the total of 4,570 radio base stations based on the FCC data on utility radio licenses below 1 GHz as of January2020. The FCC maintains a database of all radio transmitters in the United States, a majority of which are used by telecommunication carriers and broadcasters. The map in Figure 3 represents all licensed radio links in the United States in the 6 GHz frequency range.

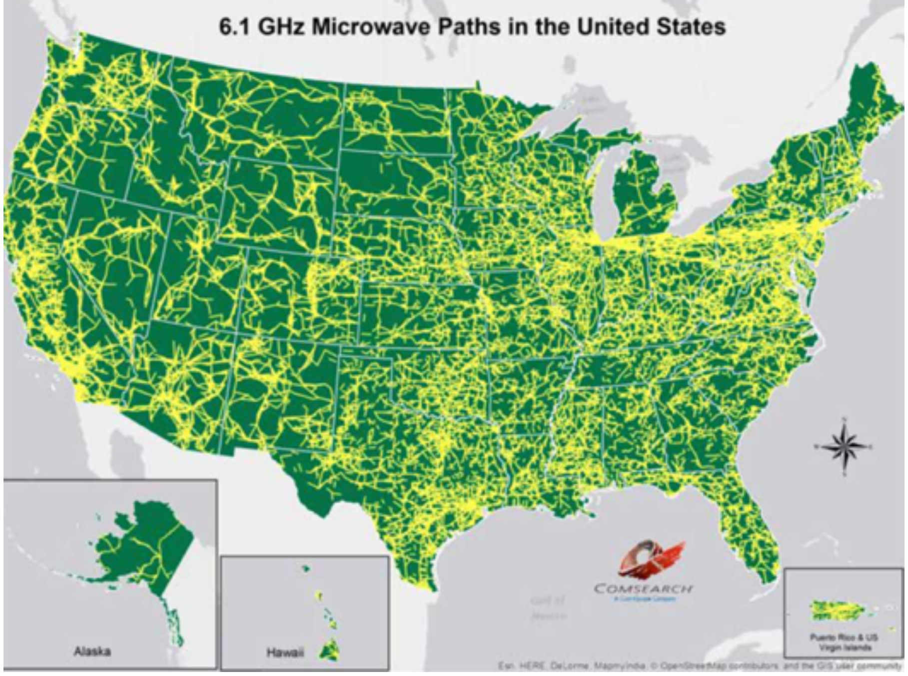

Figure 3: Microwave Link Paths in the United States (Commscope, 2017)

Electric utilities currently use 51,954 radios at all frequencies. The electric utility radios can be classified by operating frequency band. Table 3.2 shows the number of radios in each frequency band.

Frequency	Number of Radios
Less than 1 GHz	4,570
2.1 GHz	4
2.5 GHz	29
4 GHz	4
6 GHz	32,087
11 GHz	13,193
13 GHz	21
18 GHz	1,566
23 GHz	480
Total Radios	51,954

Table 3. 2: Number of Radios by Operating Frequency (FCC Database, 2020)

3.5 Substations Connected by Microwave Radios

For rural areas without telecommunications infrastructure, microwave radios can be the most cost-effective way for utilities to communicate between control centers and substations. Utilities generally use frequencies above 1 GHz for microwave connections from substations to control centers. Most utility radio connections use redundant microwave radios to prevent a communication outage. When redundant radios are used at each end of the link, a total of 4 radios is installed per link. Longer radio links require intermediate connections with an additional four radios. For greater reliability, utilities may deploy microwave radio systems in loops instead of point-to-point connections. All of these factors influence the estimates on the number of substations connected using microwave communications. Black & Veach in its report (Black & Veatch, 2020) indicates that number of substations connected by microwave could be 20 percent or more. This study estimates that 20 percent of the substations in the DHS HIFLD database are connected by microwave communications, which is 13,617 substations.

4. Benefits of EMP Protection

Investing in EMP protection for the electric grid’s communication system can buttress national security by minimizing the loss of gross domestic product (GDP) and expediting the restoration of lifeline services (e.g., water, wastewater, and hospitals). Military installations, law enforcement facilities, intelligence agencies, border control, and critical data processing facilities based in the continental United States also depend on the commercial electric grid.

- **A report issued by the National Institute of Building Sciences[3] indicates that for every dollar invested in hazard mitigation, six dollars are saved during restoration** (Center for Disaster Philanthropy, 2018).

4.1 Minimize Loss of GDP

To develop a value for protected communications, it is necessary to quantify the potential loss in GDP. A catastrophic loss of electricity over an extended area and time would cause a major or possibly complete cessation in manufacturing goods or providing services, resulting in lost wages, interruption in supply chains, and societal turmoil that would most likely intensify as the outage persists. If preparation allowed some lifeline services to function after an EMP event, we estimate that 10 percent of the nation's $22 trillion GDP (The Balance, 2020) could be preserved. As parts of the grid are restored, the value of lost GDP would lessen until the grid is fully restored.

- **If a functioning utility communication system accelerated the restoration of the grid, the value of that resilience investment, along with the value of other necessary resilience investments, could be $1.65 trillion per month.[4]**

4.2 Expedite Restoration of Lifeline Services

Protecting communication systems for the electric grid is essential to accelerate restoration of critical services and minimize 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, and sewers would backup into buildings and residences. Sewage contamination of rivers and drinking water could cause epidemics.

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[3] *How $1 Invested in Mitigation Saves $6 in Future Disaster Costs*, National Building Institute

[4] The societal benefit of protecting utility communications from EMP assumes other necessary investments in resilience.

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, it would be difficult and dangerous to conduct life-saving surgeries. Without electricity, the lives of 468,000 Americans on dialysis would be at risk (NIH, 2016).

5. Recommended EMP Protections

The United States needs a mass-produced, easily deployed way to protect communication systems at 86,000 electric grid locations 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)

5.1 Long-Duration Backup Power

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 reads:

> *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)*

Using the "months or longer" statement in the executive summary as a basis, we determined that six months of backup power would be prudent for utility communications.

We also assumed an operation plan whereby refueling could occur within the six-month timeframe. Refueling 68,992 substations as part of an operation plan, presumes that refineries remain operational. It also presumes availability of sufficient vehicles and more than 1,400 field service crews to conduct the refueling operation. This analysis postulates that each crew could refuel at least two substations per week. At a rate of at least 2,800 substations per week, all 68,992 substations would be refueled in about six months.

We considered multiple approaches for providing six months of backup power. The generation options included diesel, propane, and natural gas reciprocating engines; hydrogen, natural gas, and ammonia-based fuel cells; Stirling engines fueled by propane; and renewable sources such as photovoltaic (PV) solar, organic photovoltaic (OPV), solar thermal, and wind turbines. Appendix C examines each of these options.

We eliminated long-term power solutions that use reciprocating engines because they require maintenance more frequent than six months.

We provide cost estimates for Stirling engines using propane, hydrogen fuel cells, and solar PV energy systems for comparison.

The solar PV energy systems have several limitations. The arrays are not redundant and may degrade with the loss of some panels, depending on the wiring and the number of inverters. The solar PV arrays have been sized to account for low light in winter, inverter and battery charging system inefficiencies, and the need to store energy for up to five days of cloudy weather.

The batteries are the dominant cost in the solar power system. PV arrays generate most of the energy during four hours of daylight (in winter) to run the communications equipment for the remaining 20 hours. The sizing of the system takes into account that the batteries need to operate above 50 percent of their rated capacity.

Survivability of the solar panels is questionable in an EMP event. Sandia National Laboratory has just begun the first EMP testing on solar PV power systems. It's possible that the rate of change of voltage over time (dv/dt) from the EMP pulse could cause a strong piezoelectric stress in the crystals of the solar cells and damage them. For this reason, we recommend that the solar panels, batteries, and inverters be stored in EMP-shielded cases for post-EMP event deployment on pre-installed mounts. However, a second EMP event occurring after the solar arrays are deployed could cause a catastrophic loss of the PV arrays.

A possible mitigation strategy would be to shield the solar PV arrays using a fine metal mesh. The mesh would occlude about 20 percent of the light, but it could protect the cells enough to survive. The solar panel array would need to be increased in size by 20 percent to account for this loss of solar efficiency. The inverters and batteries would still need E1 protection. The effectiveness of this approach would need to be verified by testing (See Appendix A).

Given the concerns about the survivability of solar arrays after an EMP event, this study addresses hydrogen fuel cells and Stirling engines as other alternatives. The tradeoffs between hydrogen fuel cells and Stirling engines are difficult. The costs are roughly comparable. Both have been used for fiber amplification sites, remote cell sites, and railroad signaling sites. Due to their small size, hydrogen fuel cells can be placed in the shielded equipment racks. Stirling engines are larger and require additional space in the substation yard for installation. The larger size of Sterling engines adds costs for EMP shielding and requires shielded cabling to the equipment cabinet. Both solutions store fuel in above-ground, pressurized vessels. The propane is stored at lower pressure than hydrogen. Both the propane and hydrogen pressure vessels require ballistic protection.

Stirling engines and hydrogen fuel cells differ in fuel usage. Stirling engines have the advantage of operating with multiple types of fuel including propane, natural gas, alcohol, and hydrogen. They are “load-following,” using less fuel when the load is lower. Propane used by Sterling engines has a well-developed distribution network and can be safely stored almost indefinitely. For areas with high sunlight, such as the southwest part of the United States, Stirling engines can be paired with solar troughs to provide a long-duration, emission-free solution. Hydrogen fuel cells are fuel specific. They offer much higher efficiencies; zero emissions; and a low, external heat and visual signature.

The size of the power generation systems is determined based on the equipment power requirements. Communication systems for substations use about 425 W of power; fiber amplification sites use about 185 W. Each site uses a 1kW power source.

The fuel for each site was calculated to last for six months of operation after an EMP event. The EMP protection costs for fiber-connected substations are based on 425W of power consumption and 1,841 kWh of fuel.

The estimated costs per site are based on quotes from material suppliers, equipment manufacturers, excavators, and general contractors. The costs for site surveys, drawings, permits, and project management are typical for general contractors as they manage equipment installations across the country. The equipment costs use a 95 percent pricing curve where the price declines by 5 percent as the quantity doubles. This allows the study to estimate equipment pricing as volumes reach 4,000 sites per year.

Fiber amplification sites have less equipment and use less power (185 W); therefore, the equipment requires a half size cabinet (22U) and a smaller amount of stored fuel (818 kWh) for 180 days of operation.

Based on our cost estimates, we recommend Stirling engines as the solution for providing long-duration, EMP-protected backup power for utility communications. This selection is based on several factors including deployment history, physical size, effectiveness of long-duration fuel storage, efficiency, environmental impact, permitting, multi-fuel capability, cost, availability of fuel, and implementation schedules. We recognize that utility engineers may prefer other long-duration power sources that are also technically viable and cost-effective. Therefore, we are presenting the hydrogen fuel cell and PV solar cost estimates for comparison.

5.2 EMP Shielding for Communications Equipment

To protect the microwave radios, the precise timing system, and the fiber optic communications equipment at substations, these items will need to be mounted in EMP-shielded cabinets. The cabinets will need be connected to low impedance grounding grids.

In control centers, communications equipment can be placed in several shielded cabinets or in a shielded room. (See Appendix C).

5.3 Low Impedance Grounding Grids

One of the most important aspects of EMP protection is having an effective low impedance grounding grid for connection to the shielded enclosure and the shielded equipment cabinets. We recommend that a 16 ft. by 16 ft. grounding grid be installed at each site 6 ft. below the structure, extending at least 6 ft. beyond the structure in each direction. The vertical straps from the grounding grid can be welded to the structure every 2 ft. around the perimeter and every 2 ft. along the equipment cabinets inside the structure. Ground enhancement material can be added as needed, depending on the conductivity of the soil. (See Appendix C)

5.4 Precise Timing

Precise timing is used by substation communication systems and control systems for synchronization. It is likely that the GPS receivers in substations will be damaged by the pulse from an EMP event. Spare GPS units could be stored at each substation in EMP-shielded cases or the precise timing could be distributed over fiber and microwave communications from precision clocks in control centers. Timing distribution would require a module in each substation to receive the precise time information. To minimize cost, these modules could be slave units to master clocks in the control centers. We recommend that precise timing modules be deployed in the shielded cabinets to replace the GPS signals that would be lost when GPS ground receivers are damaged by an EMP.

5.5 Replacement of Copper Conductor Leased Lines

Utilities use copper conductor leased lines to provide command and control to about 12,907 substations throughout the United States. Copper lines commonly connect substations to telephone switching centers. Copper lines are also used to connect the terminals of fiber communications within switching centers.

While it is possible to protect equipment at both ends of a copper circuit from an EMP pulse, telecommunication carriers in most cases may not have installed EMP shielding for the copper-to-fiber transition equipment, the control systems, the backup power, or cooling systems in the telephone switching center. As a result, it would be cost prohibitive to protect leased copper lines from EMP.

Utilities should, instead, consider replacing leased copper conductor circuits with fiber installed in their powerline right-of-way or with microwave radio connections, depending on which is most technically feasible and cost-effective. For the purpose of this cost study, we recommend replacement of copper conductor circuits with fiber optic and microwave communications We assume that 80 percent of the replacement will use aerial fiber and 20 percent will use microwave communications.

6. Per-Site Costs of EMP Protection

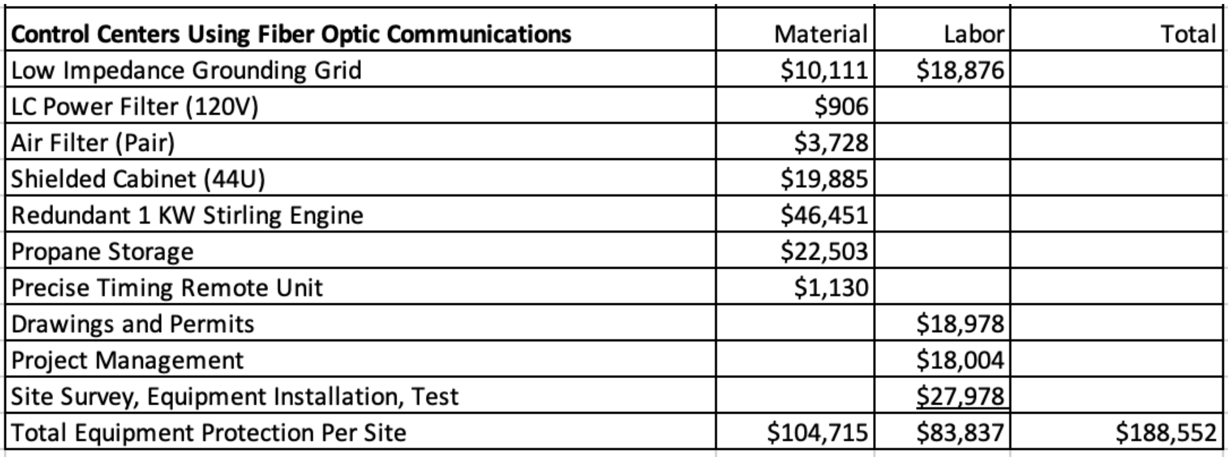
We determined the cost to protect each type of site having communication systems by evaluating the electrical power requirements, the volume of equipment, external waveguide or cables to be shielded, and the installation cost. The power requirements and the anticipated outage duration determined the amount of fuel storage. This study presents costs of shielded power sources in this sequence: 1) Stirling engines, 2) hydrogen fuel cells, and 3) PV solar arrays.

Option 1: EMP Protection with Stirling Engines

Our first option for EMP protection uses Stirling Engines as the backup power source. This option is separately calculated because the backup power source is a key cost driver.

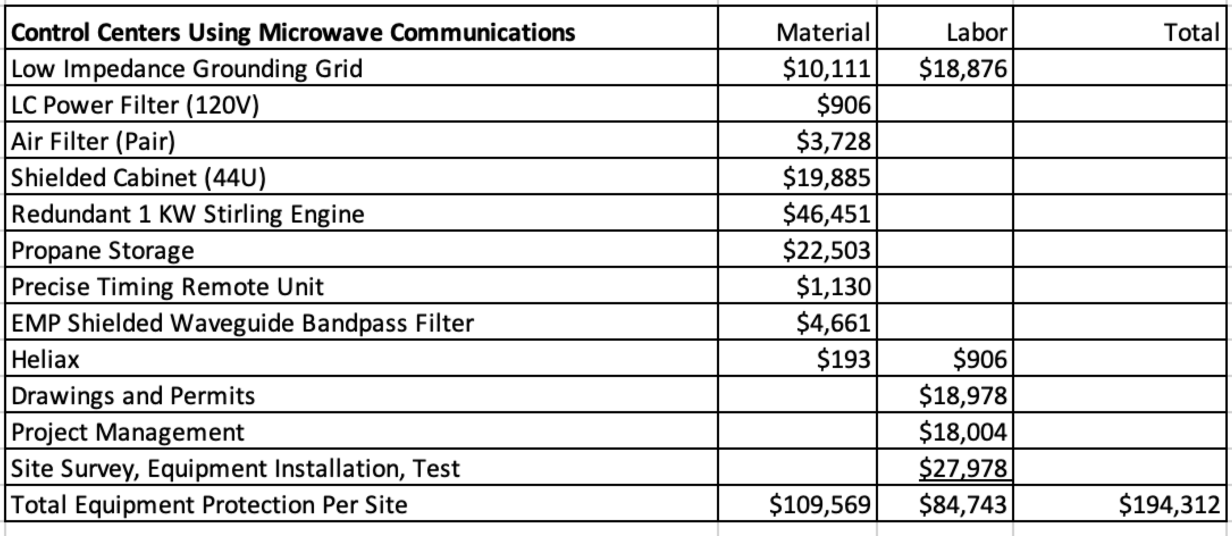
Control Centers

The EMP protection costs for control centers is enumerated below, subdivided by communications technology.



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 6. 1: Control Centers Using Fiber Optic Communications and Stirling Engines



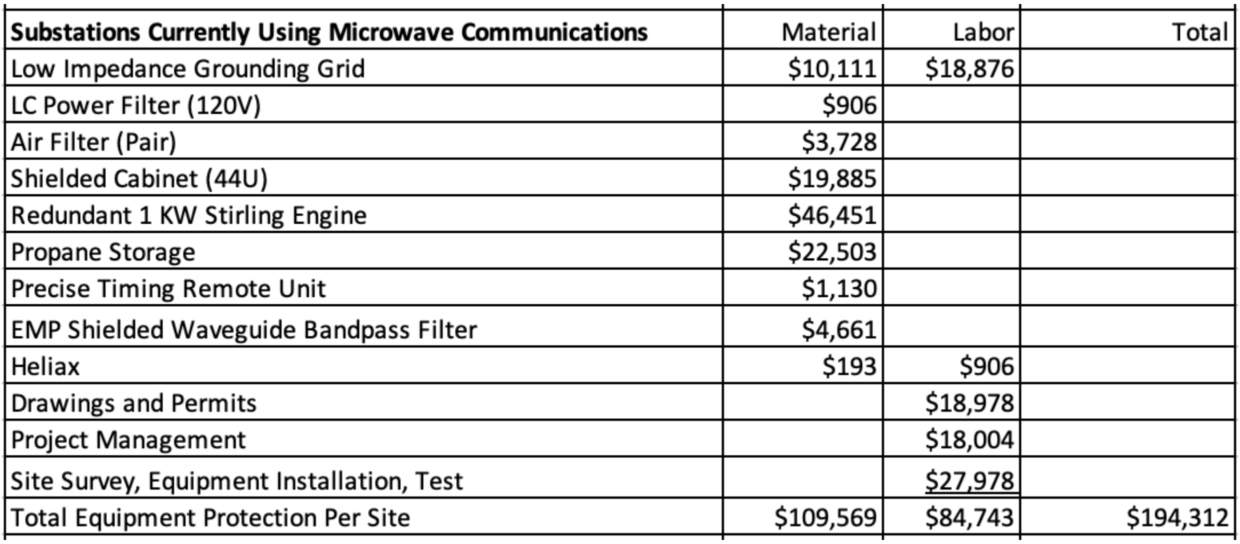
Control Centers Using Microwave Communications	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (44U)	$19,885		
Redundant 1 KW Stirling Engine	$46,451		
Propane Storage	$22,503		
Precise Timing Remote Unit	$1,130		
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

Table 6. 2: Control Centers Using Microwave Communications and Stirling Engines

Substations

The EMP protection costs for substations is enumerated below, subdivided by communications technology.

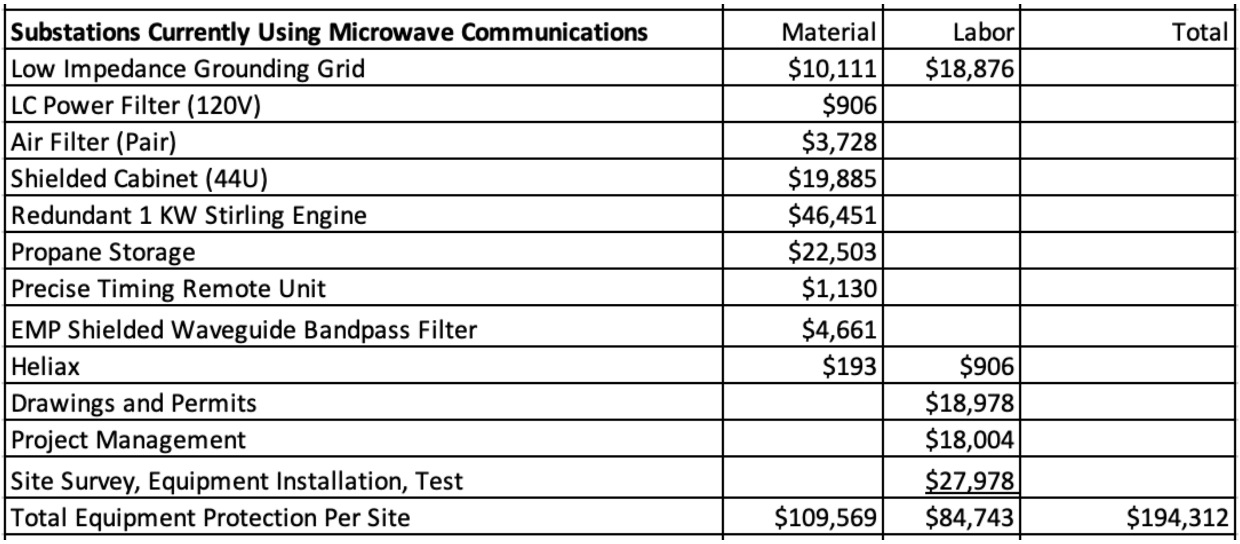
Fiber Optic Communications



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

Table 6. 3: Substations Currently Using Microwave Communications (Stirling Engines)

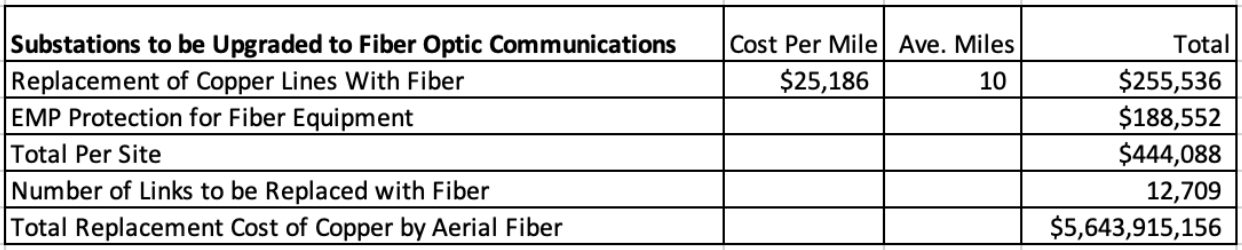
Microwave Communications



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

Table 6. 4: Substations Currently Using Microwave Communications (Stirling Engines)

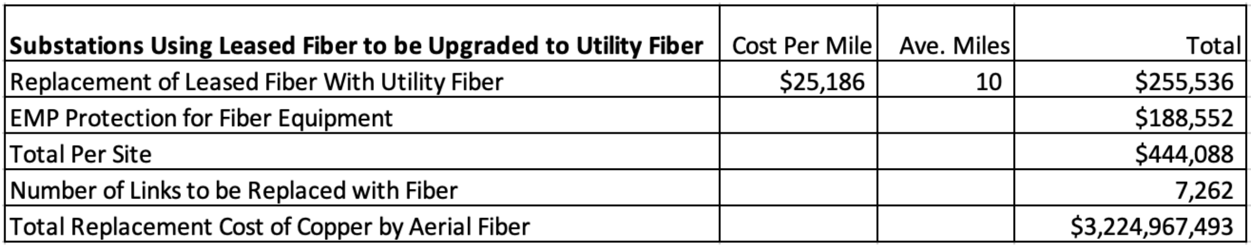
Leased Circuit Copper Conductor



Substations to be Upgraded to Fiber Optic Communications	Cost Per Mile	Ave. Miles	Total
Replacement of Copper Lines With Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$188,552
Total Per Site			$444,088
Number of Links to be Replaced with Fiber			12,709
Total Replacement Cost of Copper by Aerial Fiber			$5,643,915,156

Table 6. 5: Substations to be Upgraded to Fiber Optic Communications (Stirling Engines)

Leased Circuit Fiber Optics

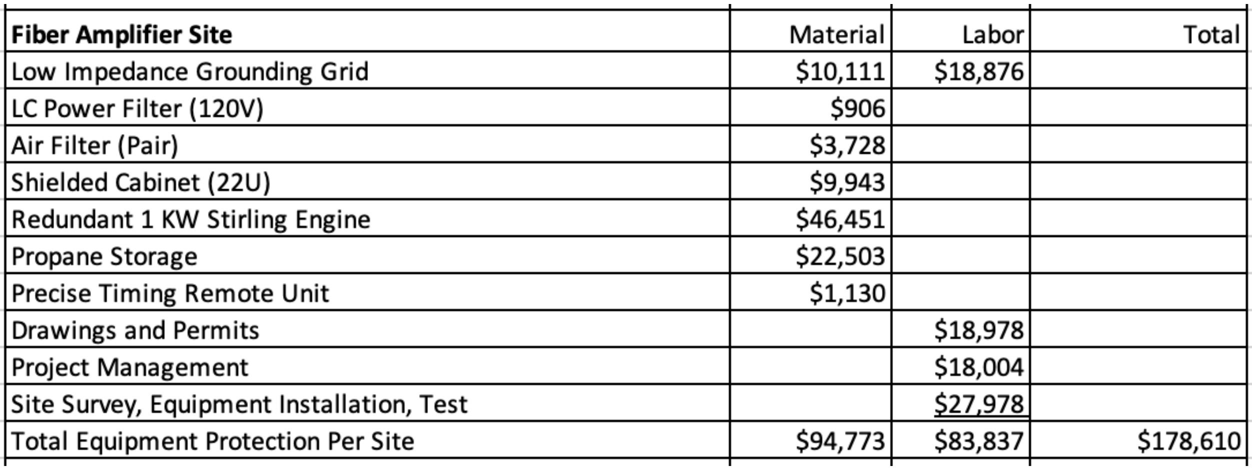


Substations Using Leased Fiber to be Upgraded to Utility Fiber	Cost Per Mile	Ave. Miles	Total
Replacement of Leased Fiber With Utility Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$188,552
Total Per Site			$444,088
Number of Links to be Replaced with Fiber			7,262
Total Replacement Cost of Copper by Aerial Fiber			$3,224,967,493

Table 6. 6: Substations Using Leased Fiber to be Upgraded to Utility Fiber (Stirling Engines)

Fiber Optic Amplification Sites

Where copper conductor circuits are to be upgraded with fiber options, we enumerate the EMP protection costs for the additional amplification sites below.

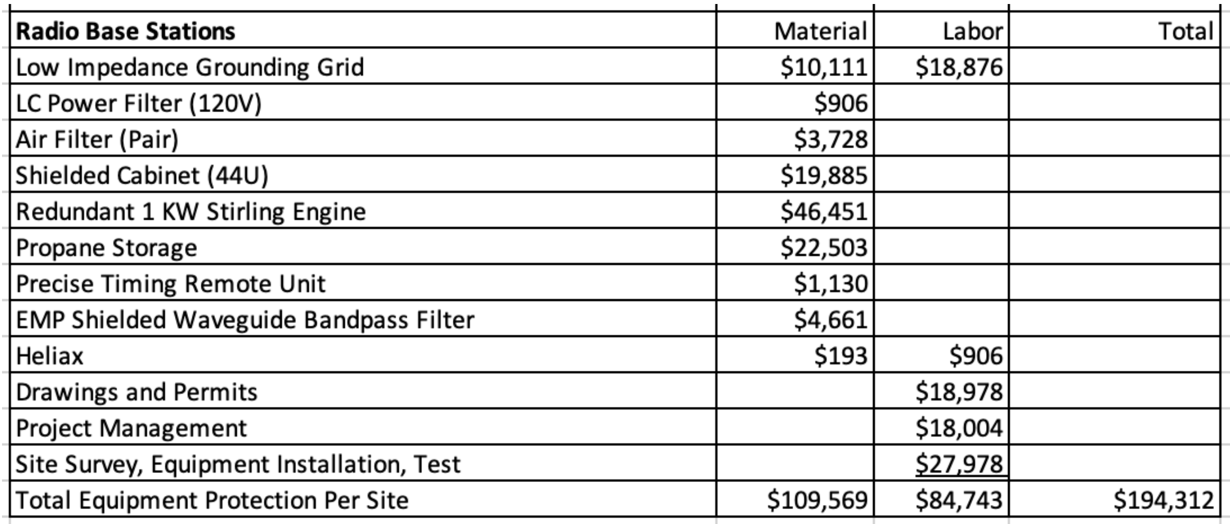


Fiber Amplifier Site	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (22U)	$9,943		
Redundant 1 KW Stirling Engine	$46,451		
Propane Storage	$22,503		
Precise Timing Remote Unit	$1,130		
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$94,773	$83,837	$178,610

Table 6. 7: Fiber Amplifier Sites (Stirling Engines)

Radio Base Stations

For EMP protection of radio base stations, we enumerate the costs below.



Radio Base Stations	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

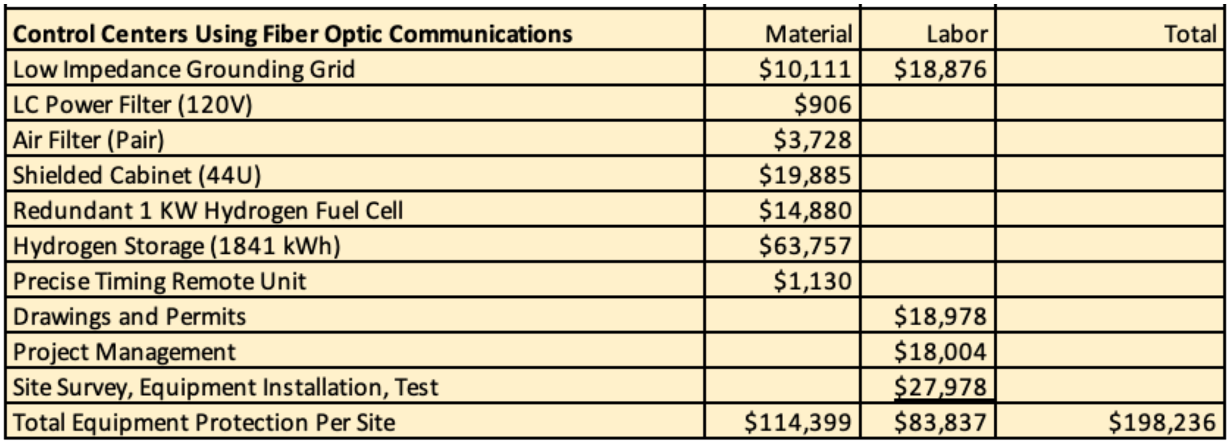
Table 6. 8: Radio Base Stations (Stirling Engines)

Option 2: EMP Protection with Hydrogen Fuel Cells

Our second option for EMP protection uses hydrogen fuel cells as the backup power source. This option is separately calculated because the backup power source is a key cost driver.

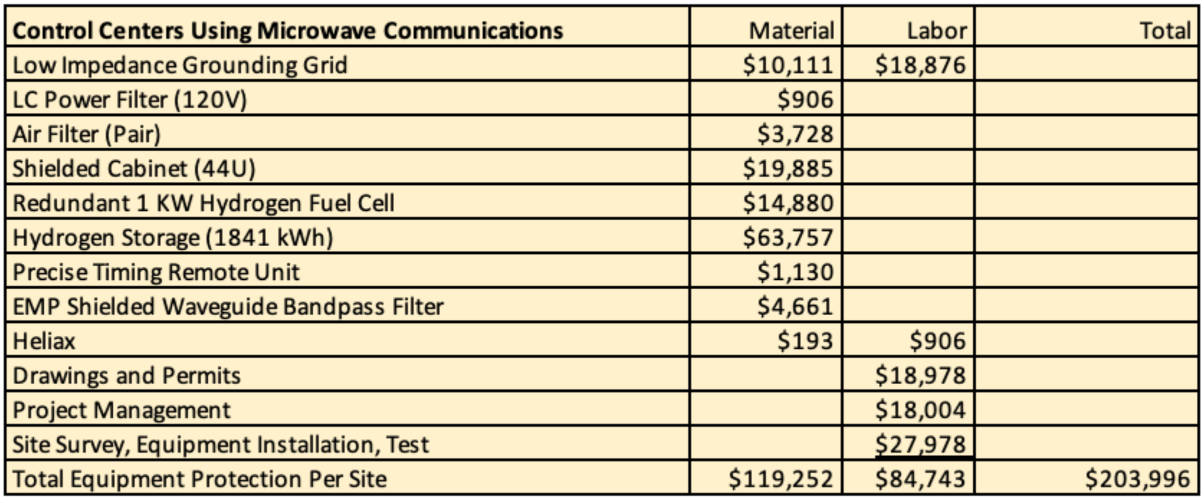
Control Centers

The EMP protection costs for control centers with hydrogen fuel cell backup power are enumerated below, subdivided by communications technology.



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 Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
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	$114,399	$83,837	$198,236

Table 6. 9: Control Centers Using Fiber Optic Communications (Fuel Cells)



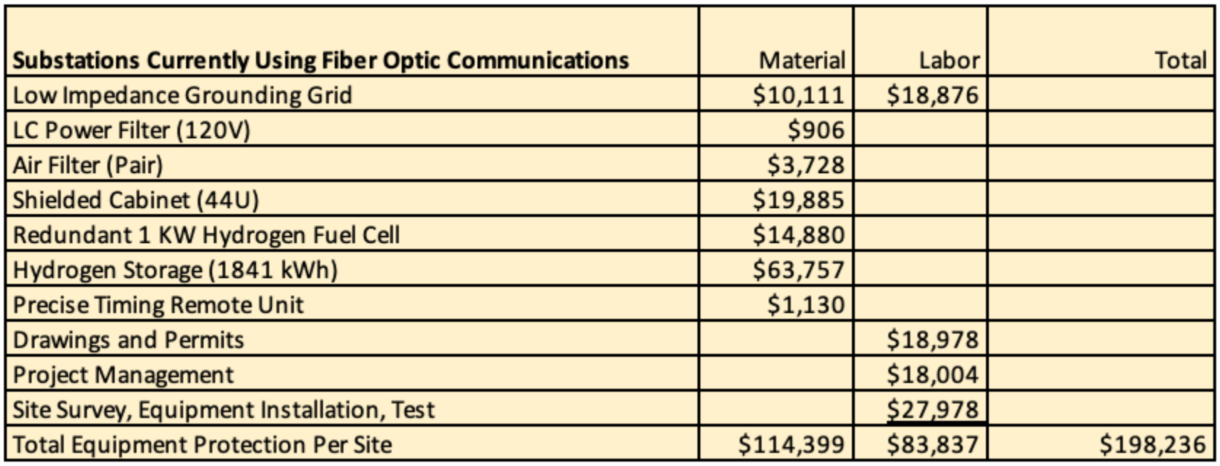
Control Centers Using Microwave Communications	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (44U)	$19,885		
Redundant 1 KW Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
Precise Timing 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	$119,252	$84,743	$203,996

Table 6. 10: Control Centers Using Microwave Communications (Fuel Cells)

Substations

The EMP protection costs for substations with hydrogen fuel cell backup power is enumerated below, subdivided by communications technology.

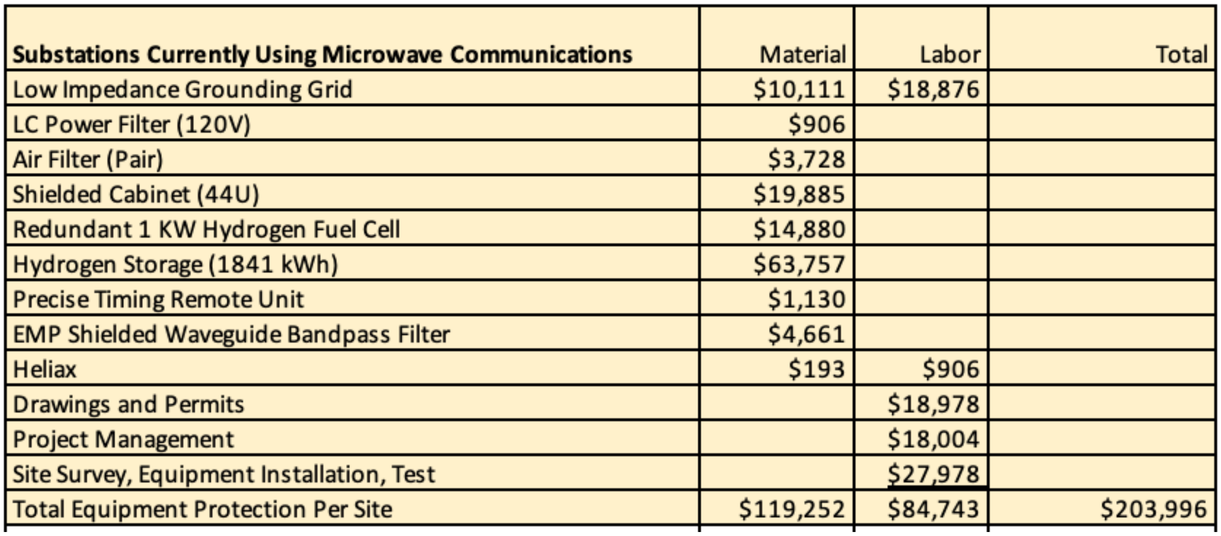
Fiber Optic Communications:



Substations Currently 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 Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
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	$114,399	$83,837	$198,236

Table 6. 11: Substations Currently Using Fiber Optic Communications (Fuel Cells)

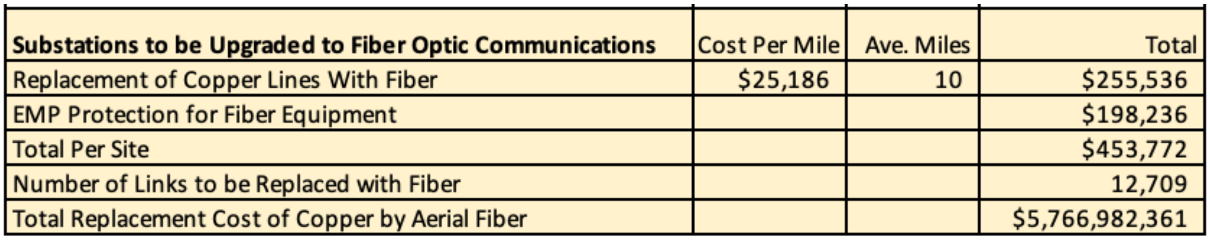
Microwave Communications



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 Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
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	$119,252	$84,743	$203,996

Table 6. 12: Substations Currently Using Microwave Communications (Fuel Cells)

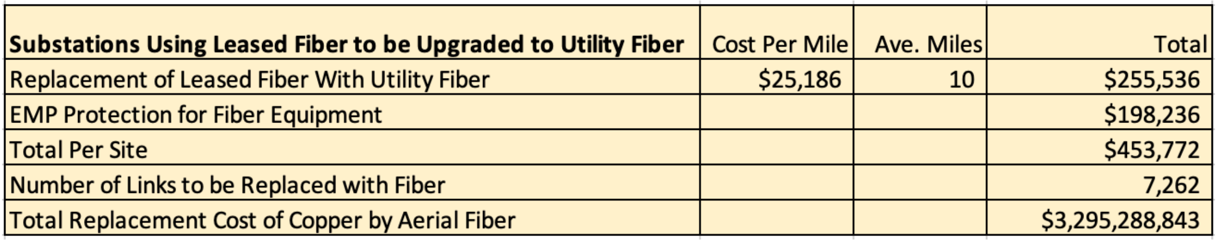
Leased Circuit Copper Conductor



Substations to be Upgraded to Fiber Optic Communications	Cost Per Mile	Ave. Miles	Total
Replacement of Copper Lines With Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$198,236
Total Per Site			$453,772
Number of Links to be Replaced with Fiber			12,709
Total Replacement Cost of Copper by Aerial Fiber			$5,766,982,361

Table 6. 13: Substations to be Upgraded to Fiber Optic Communications (Fuel Cells)

Leased Circuit Fiber Optics

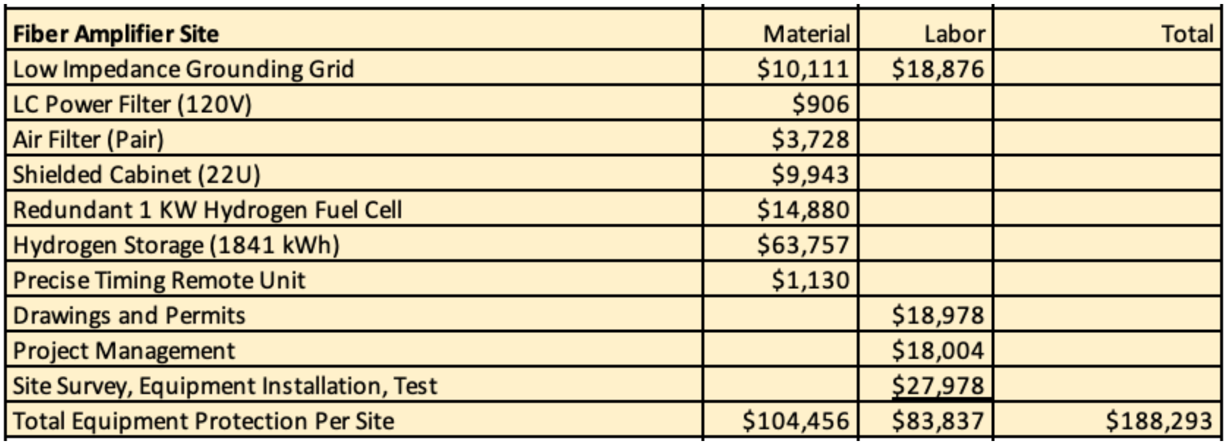


Substations Using Leased Fiber to be Upgraded to Utility Fiber	Cost Per Mile	Ave. Miles	Total
Replacement of Leased Fiber With Utility Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$198,236
Total Per Site			$453,772
Number of Links to be Replaced with Fiber			7,262
Total Replacement Cost of Copper by Aerial Fiber			$3,295,288,843

Table 6. 14: Substations Using Leased Fiber Upgraded to Utility Fiber (Fuel Cells)

Fiber Optic Amplification Sites

Where copper conductor circuits are to be upgraded with fiber optics, we enumerate the EMP protection costs for the additional amplification sites with hydrogen fuel cells as backup power below.

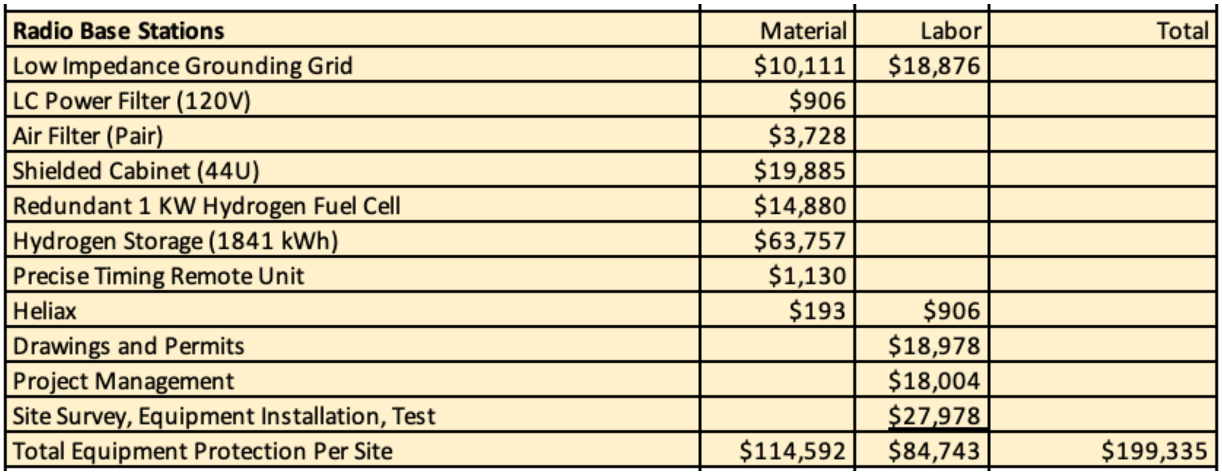


Fiber Amplifier Site	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (22U)	$9,943		
Redundant 1 KW Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
Precise Timing Remote Unit	$1,130		
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$104,456	$83,837	$188,293

Table 6. 15*: Fiber Amplifier Site (Fuel Cells)*

Radio Base Stations

For EMP protection of radio base stations using hydrogen fuel cells as backup power, we enumerate the costs below.



Radio Base Stations	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 Hydrogen Fuel Cell	$14,880		
Hydrogen Storage (1841 kWh)	$63,757		
Precise Timing Remote Unit	$1,130		
Heliax	$193	$906	
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$114,592	$84,743	$199,335

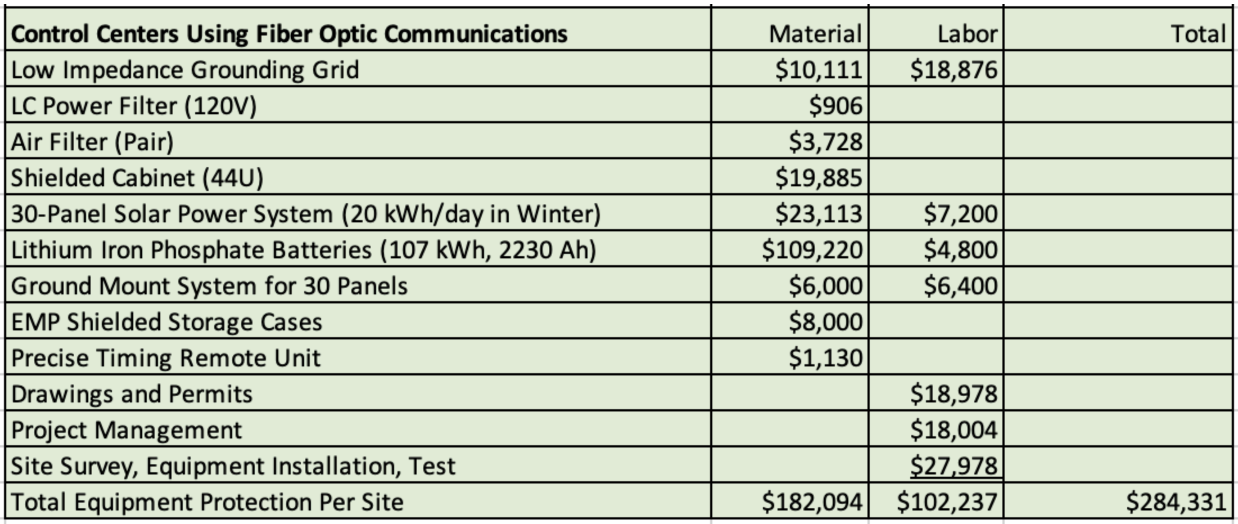
Table 6. 16: Radio Base Stations (Fuel Cells)

Option 3: EMP Protection with PV Solar Power Systems

Our third option for EMP protection uses solar PVs as the backup power source. This option is separately calculated because the backup power source is a key cost driver.

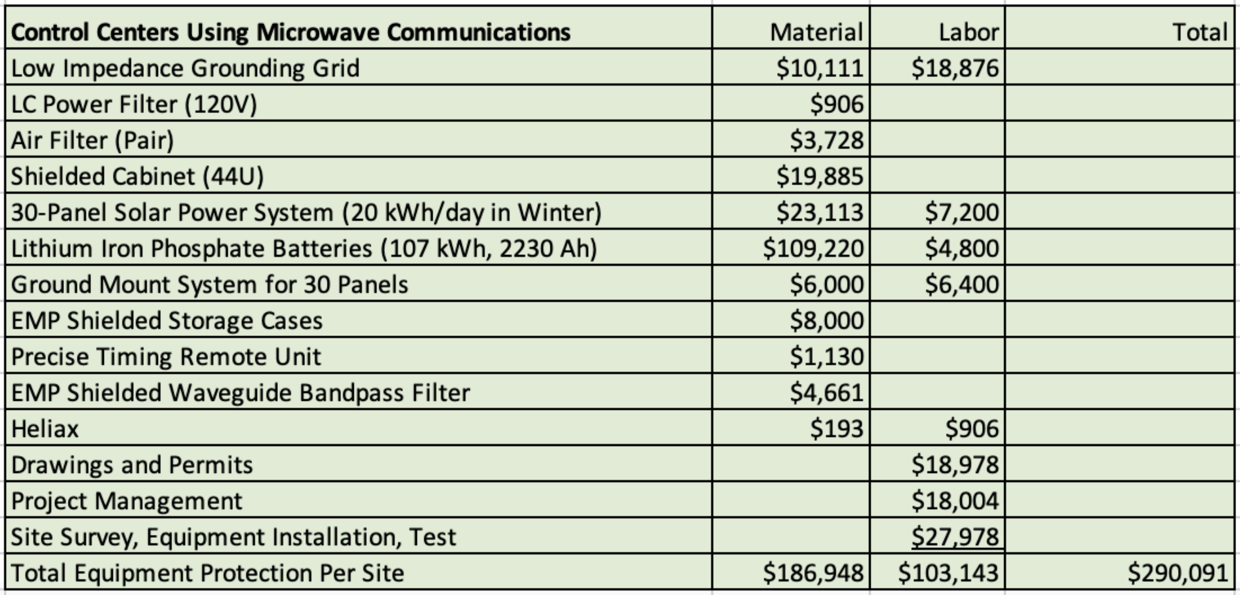
Control Centers

The EMP protection costs for control centers with solar PV backup power is enumerated below, subdivided by communications technology.



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		
30-Panel Solar Power System (20 kWh/day in Winter)	$23,113	$7,200	
Lithium Iron Phosphate Batteries (107 kWh, 2230 Ah)	$109,220	$4,800	
Ground Mount System for 30 Panels	$6,000	$6,400	
EMP Shielded Storage Cases	$8,000		
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	$182,094	$102,237	$284,331

Table 6. 17: Control Centers Using Fiber Optic Communications (PV Solar Power)



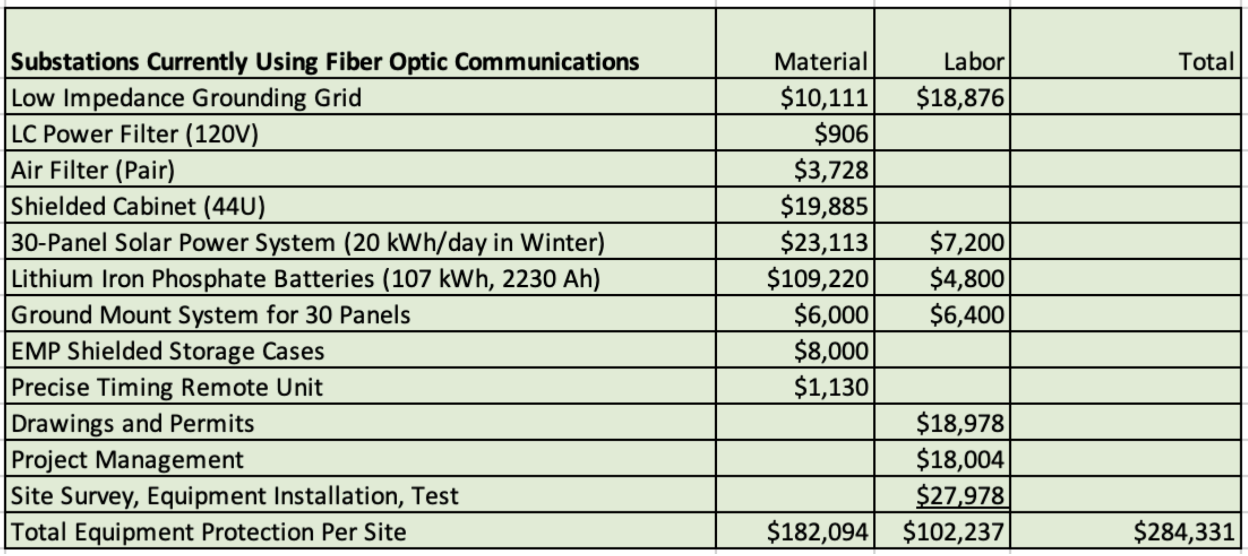
Control Centers Using Microwave Communications	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (44U)	$19,885		
30-Panel Solar Power System (20 kWh/day in Winter)	$23,113	$7,200	
Lithium Iron Phosphate Batteries (107 kWh, 2230 Ah)	$109,220	$4,800	
Ground Mount System for 30 Panels	$6,000	$6,400	
EMP Shielded Storage Cases	$8,000		
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	$186,948	$103,143	$290,091

Table 6. 18: Control Centers Using Microwave Communications (PV Solar Power)

Substations

The EMP protection costs for substations with solar PV backup power is enumerated below, subdivided by communications technology.

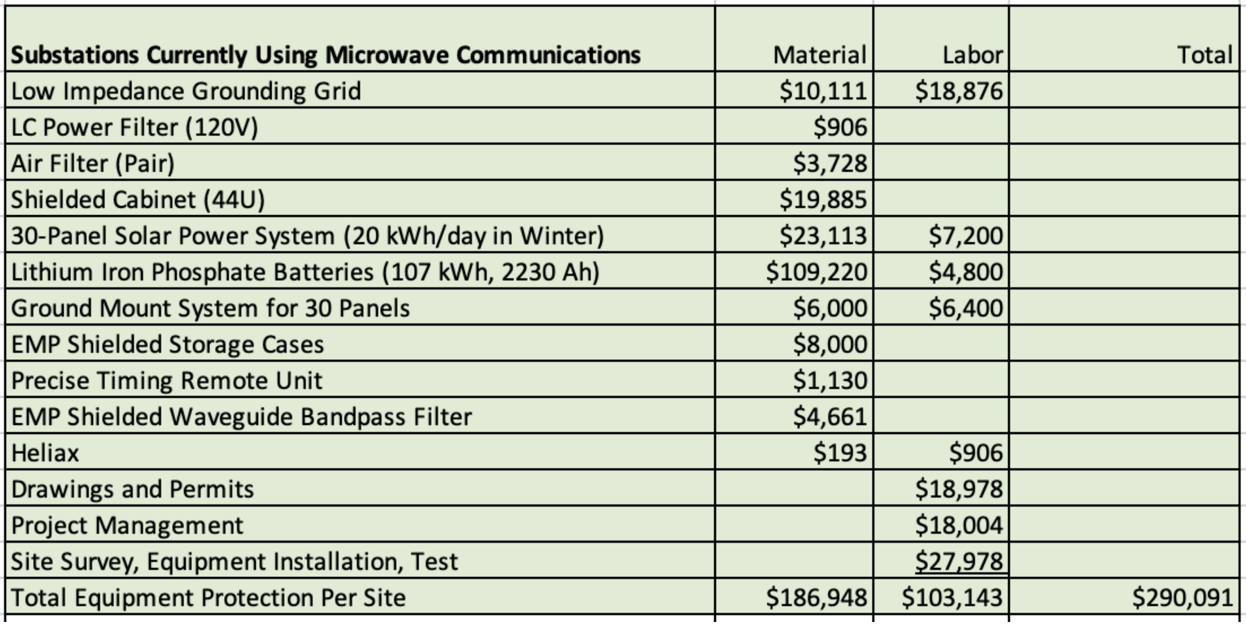
Fiber Optic Communications:



Substations Currently 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		
30-Panel Solar Power System (20 kWh/day in Winter)	$23,113	$7,200	
Lithium Iron Phosphate Batteries (107 kWh, 2230 Ah)	$109,220	$4,800	
Ground Mount System for 30 Panels	$6,000	$6,400	
EMP Shielded Storage Cases	$8,000		
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	$182,094	$102,237	$284,331

Table 6. 19: Substations Currently Using Fiber Optic Communications (PV Solar Power)

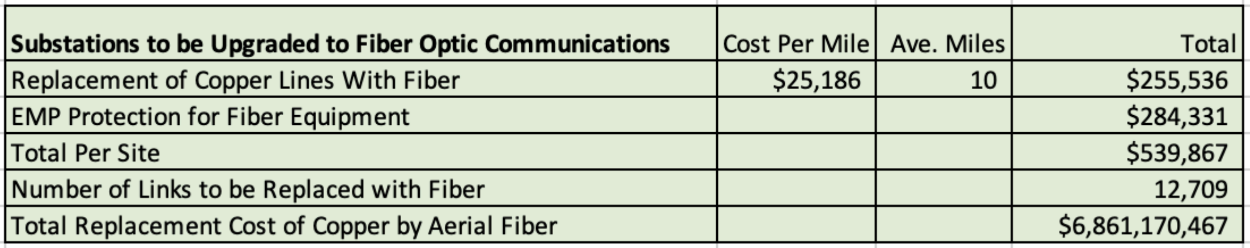
Microwave Communications



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		
30-Panel Solar Power System (20 kWh/day in Winter)	$23,113	$7,200	
Lithium Iron Phosphate Batteries (107 kWh, 2230 Ah)	$109,220	$4,800	
Ground Mount System for 30 Panels	$6,000	$6,400	
EMP Shielded Storage Cases	$8,000		
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	$186,948	$103,143	$290,091

Table 6. 20: Substations Currently Using Microwave Communications (PV Solar Power)

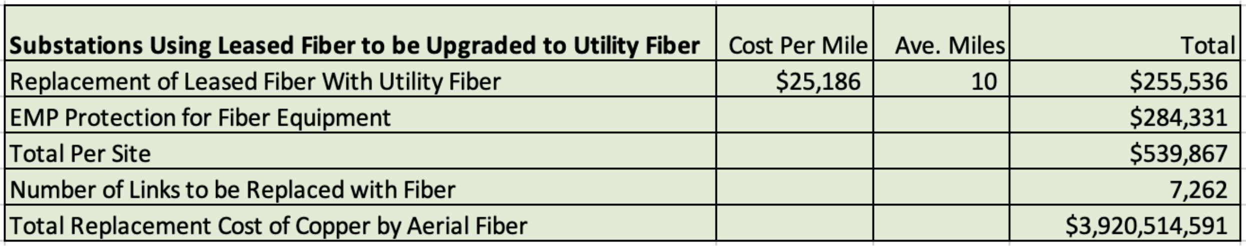
Leased Circuit Copper Conductor



Substations to be Upgraded to Fiber Optic Communications	Cost Per Mile	Ave. Miles	Total
Replacement of Copper Lines With Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$284,331
Total Per Site			$539,867
Number of Links to be Replaced with Fiber			12,709
Total Replacement Cost of Copper by Aerial Fiber			$6,861,170,467

Table 6. 21: Substations to be Upgraded to Fiber Optic Communications (PV Solar Power)

Leased Circuit Fiber Optics

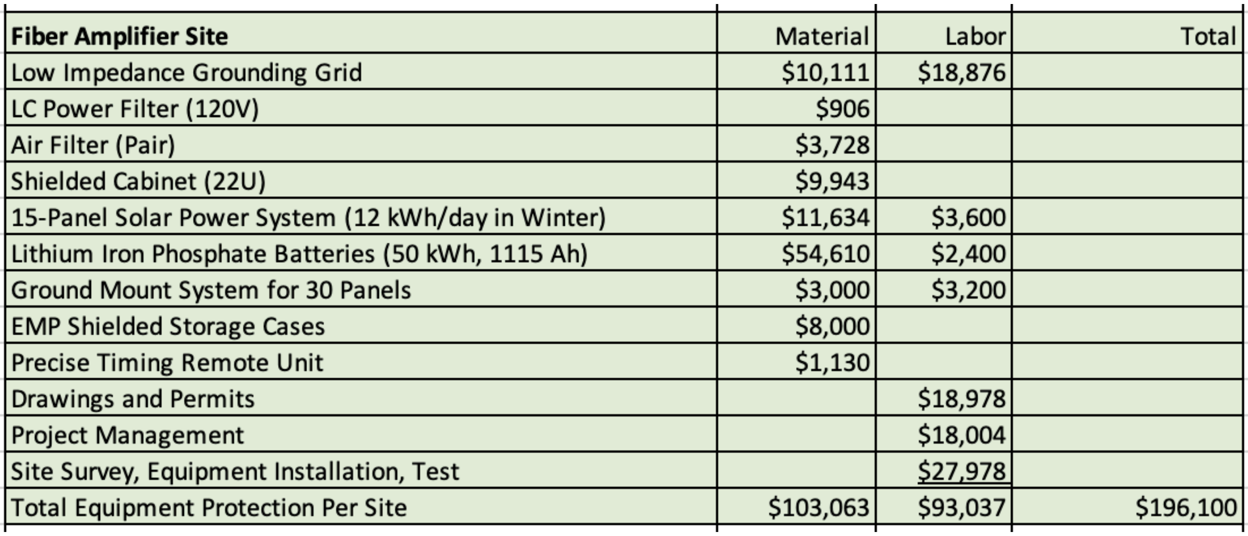


Substations Using Leased Fiber to be Upgraded to Utility Fiber	Cost Per Mile	Ave. Miles	Total
Replacement of Leased Fiber With Utility Fiber	$25,186	10	$255,536
EMP Protection for Fiber Equipment			$284,331
Total Per Site			$539,867
Number of Links to be Replaced with Fiber			7,262
Total Replacement Cost of Copper by Aerial Fiber			$3,920,514,591

Table 6. 22: Substations Using Leased Fiber to be Upgraded to Utility Fiber (PV Solar Power)

Fiber Optic Amplification Sites

Where copper conductor circuits are to be upgraded with fiber optics, we enumerate the EMP protection costs for the additional amplification sites with solar PV as backup power below.

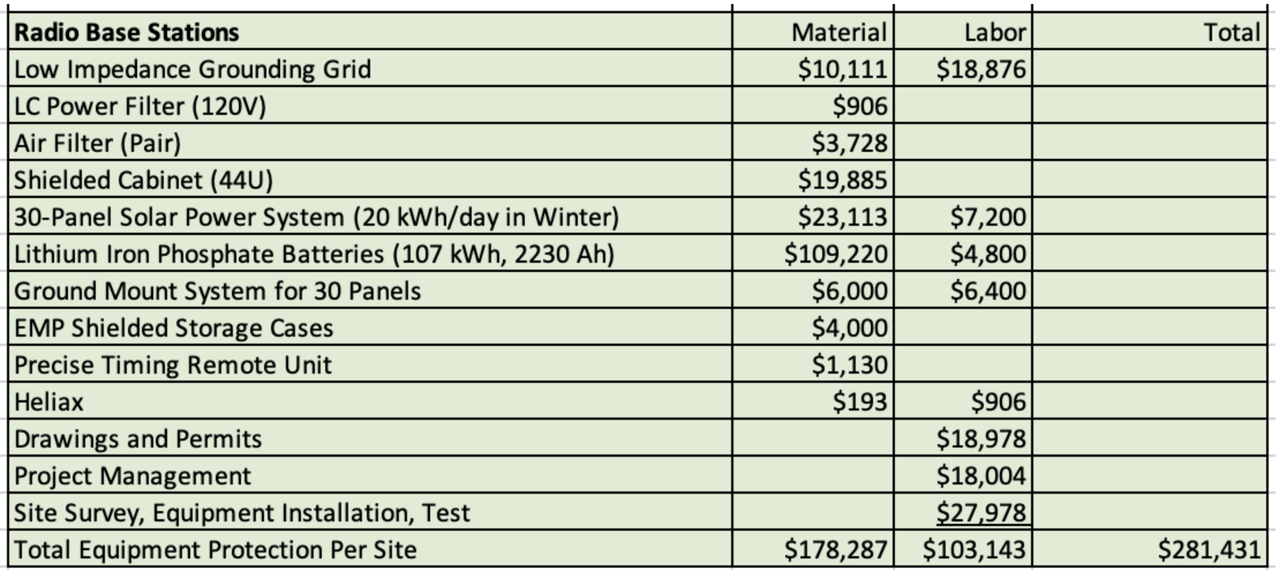


Fiber Amplifier Site	Material	Labor	Total
Low Impedance Grounding Grid	$10,111	$18,876	
LC Power Filter (120V)	$906		
Air Filter (Pair)	$3,728		
Shielded Cabinet (22U)	$9,943		
15-Panel Solar Power System (12 kWh/day in Winter)	$11,634	$3,600	
Lithium Iron Phosphate Batteries (50 kWh, 1115 Ah)	$54,610	$2,400	
Ground Mount System for 30 Panels	$3,000	$3,200	
EMP Shielded Storage Cases	$8,000		
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	$103,063	$93,037	$196,100

Table 6. 23: Fiber Amplifier Sites (PV Solar Power)

Radio Base Stations

For EMP protection of radio base stations using solar PV as backup power, we enumerate the costs below.



Radio Base Stations	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		
30-Panel Solar Power System (20 kWh/day in Winter)	$23,113	$7,200	
Lithium Iron Phosphate Batteries (107 kWh, 2230 Ah)	$109,220	$4,800	
Ground Mount System for 30 Panels	$6,000	$6,400	
EMP Shielded Storage Cases	$4,000		
Precise Timing Remote Unit	$1,130		
Heliax	$193	$906	
Drawings and Permits		$18,978	
Project Management		$18,004	
Site Survey, Equipment Installation, Test		$27,978	
Total Equipment Protection Per Site	$178,287	$103,143	$281,431

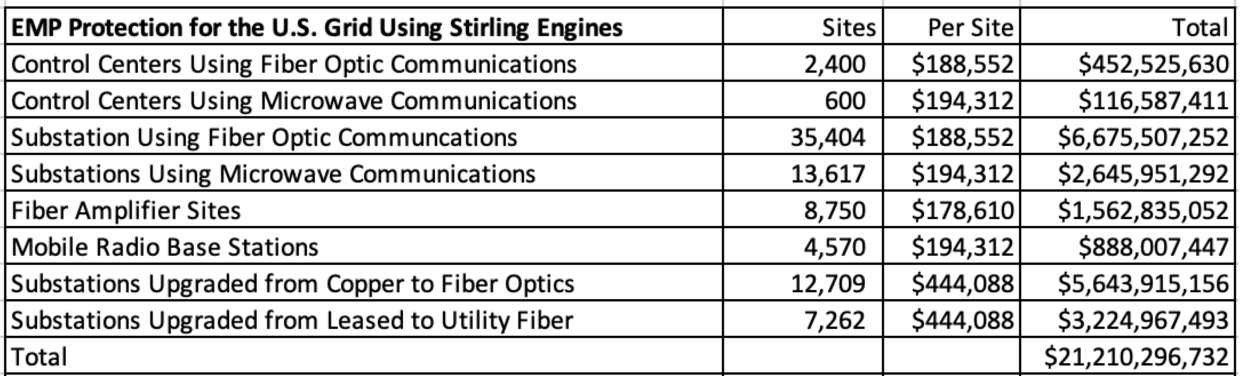
Table 6. 24: Radio Base Stations (PV Solar Power)

7. Total Costs for EMP Protection

To calculate the total EMP protection costs for installed equipment, we multiplied the per-site costs for each type of site by the corresponding number of sites. We also estimated annual cost to maintain the equipment based on 20 percent of the installed equipment cost per year.

7.1 Installed Equipment Costs

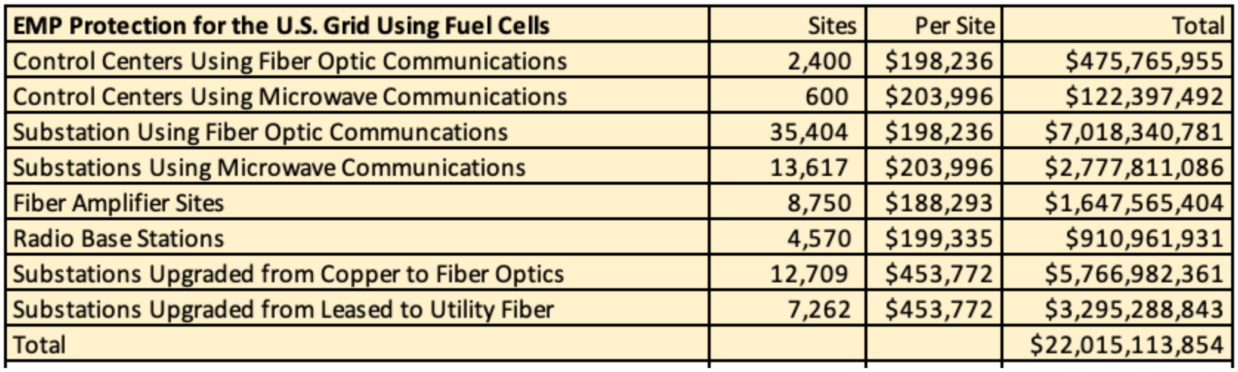
We estimated the total EMP protection cost using Stirling engines as a power source is as follows:



EMP Protection for the U.S. Grid Using Stirling 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 Communcations	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

Table 7. 1: EMP Protection for the U.S. Grid Using Stirling Engines

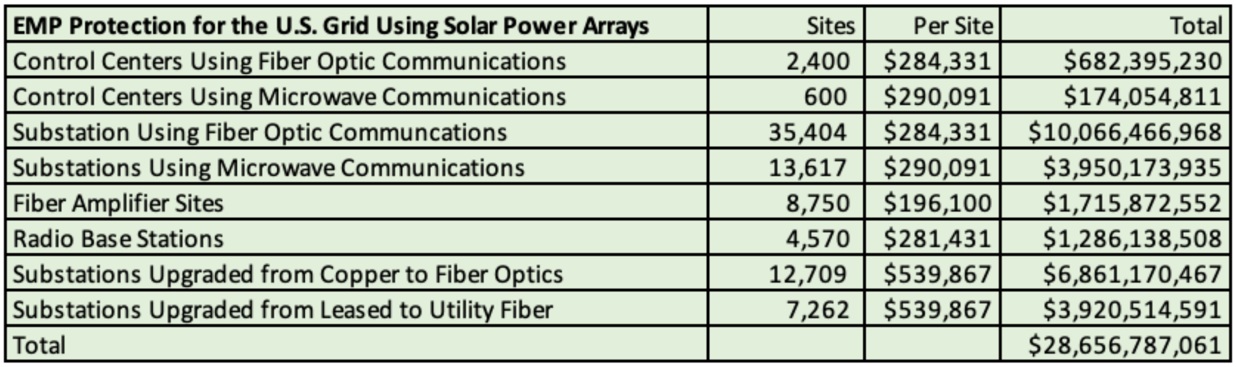
We estimated the total installed cost for EMP protection using hydrogen fuel cells as a power source is as follows:



EMP Protection for the U.S. Grid Using Fuel Cells	Sites	Per Site	Total
Control Centers Using Fiber Optic Communications	2,400	$198,236	$475,765,955
Control Centers Using Microwave Communications	600	$203,996	$122,397,492
Substation Using Fiber Optic Communcations	35,404	$198,236	$7,018,340,781
Substations Using Microwave Communications	13,617	$203,996	$2,777,811,086
Fiber Amplifier Sites	8,750	$188,293	$1,647,565,404
Radio Base Stations	4,570	$199,335	$910,961,931
Substations Upgraded from Copper to Fiber Optics	12,709	$453,772	$5,766,982,361
Substations Upgraded from Leased to Utility Fiber	7,262	$453,772	$3,295,288,843
Total			$22,015,113,854

Table 7. 2: EMP Protection for the U.S. Grid Using Fuel Cells

We estimated the total installed cost for EMP protection using PV solar power as a power source is as follows:



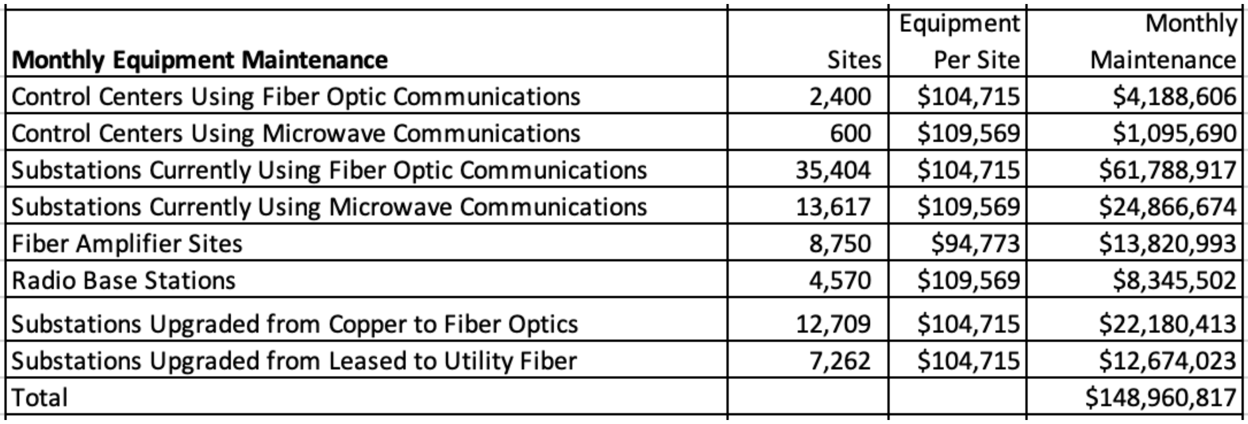
EMP Protection for the U.S. Grid Using Solar Power Arrays	Sites	Per Site	Total
Control Centers Using Fiber Optic Communications	2,400	$284,331	$682,395,230
Control Centers Using Microwave Communications	600	$290,091	$174,054,811
Substation Using Fiber Optic Communcations	35,404	$284,331	$10,066,466,968
Substations Using Microwave Communications	13,617	$290,091	$3,950,173,935
Fiber Amplifier Sites	8,750	$196,100	$1,715,872,552
Radio Base Stations	4,570	$281,431	$1,286,138,508
Substations Upgraded from Copper to Fiber Optics	12,709	$539,867	$6,861,170,467
Substations Upgraded from Leased to Utility Fiber	7,262	$539,867	$3,920,514,591
Total			$28,656,787,061

Table 7. 3: EMP Protection for the U.S. Grid Using PV Solar Power

7.2 Monthly Maintenance Costs

Sustained EMP protection requires periodic inspection and testing to ensure changes to the equipment have not inadvertently degraded effectiveness of the shielding and grounding. To inspect, maintain, and repair the sites as items wear out, it would be prudent to budget 20 percent of the equipment capital cost per year.

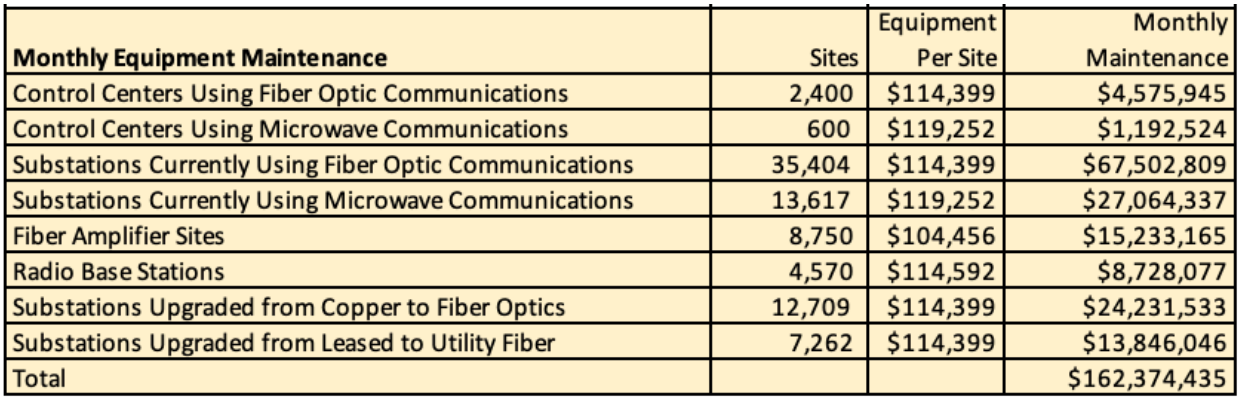
We estimated the monthly maintenance cost using Stirling engines is as follows:



Monthly Equipment Maintenance	Sites	Equipment Per Site	Monthly Maintenance
Control Centers Using Fiber Optic Communications	2,400	$104,715	$4,188,606
Control Centers Using Microwave Communications	600	$109,569	$1,095,690
Substations Currently Using Fiber Optic Communications	35,404	$104,715	$61,788,917
Substations Currently Using Microwave Communications	13,617	$109,569	$24,866,674
Fiber Amplifier Sites	8,750	$94,773	$13,820,993
Radio Base Stations	4,570	$109,569	$8,345,502
Substations Upgraded from Copper to Fiber Optics	12,709	$104,715	$22,180,413
Substations Upgraded from Leased to Utility Fiber	7,262	$104,715	$12,674,023
Total			$148,960,817

Table 7. 4: Monthly Equipment Maintenance (Stirling Engines)

We estimated the monthly maintenance cost using hydrogen fuel cells is as follows:



Monthly Equipment Maintenance	Sites	Equipment Per Site	Monthly Maintenance
Control Centers Using Fiber Optic Communications	2,400	$114,399	$4,575,945
Control Centers Using Microwave Communications	600	$119,252	$1,192,524
Substations Currently Using Fiber Optic Communications	35,404	$114,399	$67,502,809
Substations Currently Using Microwave Communications	13,617	$119,252	$27,064,337
Fiber Amplifier Sites	8,750	$104,456	$15,233,165
Radio Base Stations	4,570	$114,592	$8,728,077
Substations Upgraded from Copper to Fiber Optics	12,709	$114,399	$24,231,533
Substations Upgraded from Leased to Utility Fiber	7,262	$114,399	$13,846,046
Total			$162,374,435

Table 7. 5: Monthly Equipment Maintenance (Fuel Cells)

We estimated the monthly maintenance cost using PV solar power is as follows:

Monthly Equipment Maintenance	Sites	Equipment Per Site	Monthly Maintenance
Control Centers Using Fiber Optic Communications	2,400	$182,094	$7,283,766
Control Centers Using Microwave Communications	600	$186,948	$1,869,480
Substations Currently Using Fiber Optic Communications	35,404	$103,063	$60,813,758
Substations Currently Using Microwave Communications	13,617	$186,948	$42,427,838
Fiber Amplifier Sites	8,750	$103,063	$15,029,951
Radio Base Stations	4,570	$178,287	$13,579,553
Substations Upgraded from Copper to Fiber Optics	12,709	$182,094	$38,570,575
Substations Upgraded from Leased to Utility Fiber	7,262	$182,094	$22,039,461
Total			$201,614,381

Table 7. 6: Monthly Equipment Maintenance (PV Solar Power)

8. Price Per Consumer for EMP Protection

We added amortized monthly equipment cost and monthly maintenance cost together to find the total monthly cost. This cost was divided by the total monthly electrical power distributed through the grid in megawatt-hours (MWh) to determine the cost per MWh for EMP protection.

We divided the 348,000 megawatt hours of electricity transiting the grid each month (U.S. Department of Energy, 2018) by the 153 million electricity ratepayers (U.S. Energy Information Administration, 2020) to reach an average use of 2,275 kilowatt-hours per customer (0.002275 MWh).

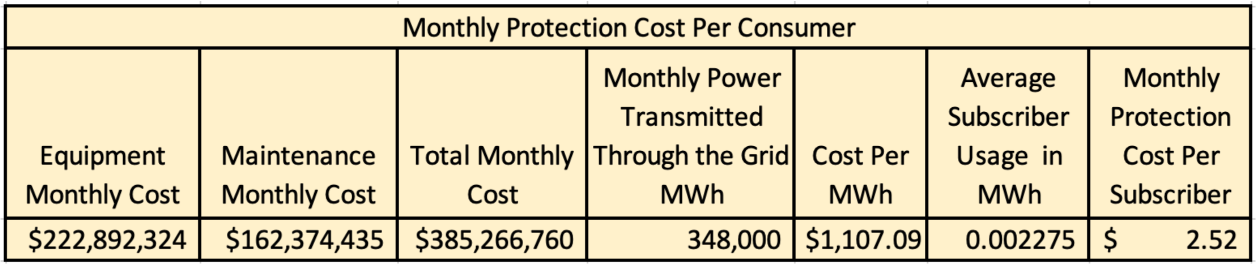
We then multiplied the cost per MWH for the EMP protection by the average customer use in MWh to determine the impact on the average customer's bill.

The incremental cost to the average customer's bill for EMP protection using the Stirling engines option is:

Monthly Protection Cost Per Consumer						
Equipment Monthly Cost	Maintenance Monthly Cost	Total Monthly Cost	Monthly Power Transmitted Through the Grid MWh	Cost Per MWh	Average Subscriber Usage in MWh	Monthly Protection Cost Per Subscriber
$214,743,942	$148,960,817	$363,704,759	348,000	$1,045.13	0.002275	$ 2.38

Table 8. 1: Monthly Protection Cost Per Consumer (Stirling Engines)

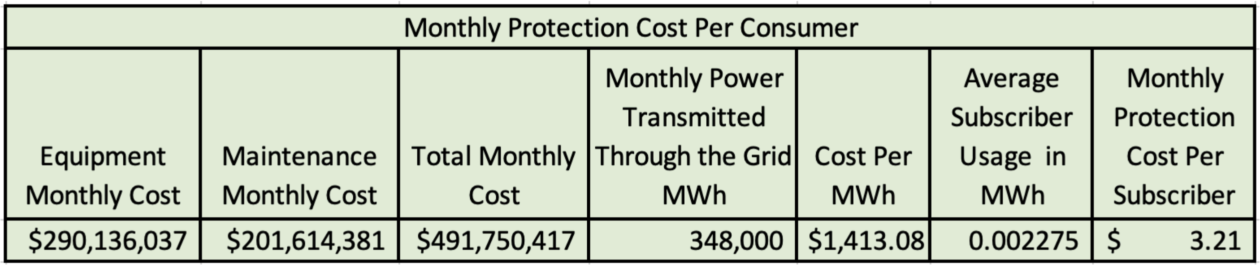
The incremental cost to the average customer's bill for EMP protection using the hydrogen fuel cell option is:



Monthly Protection Cost Per Consumer						
Equipment Monthly Cost	Maintenance Monthly Cost	Total Monthly Cost	Monthly Power Transmitted Through the Grid MWh	Cost Per MWh	Average Subscriber Usage in MWh	Monthly Protection Cost Per Subscriber
$222,892,324	$162,374,435	$385,266,760	348,000	$1,107.09	0.002275	$ 2.52

Table 8. 2: Monthly Protection Cost Per Consumer (Fuel Cells)

The incremental cost to the average consumer's bill for EMP protection using PV solar power option is:



Monthly Protection Cost Per Consumer						
Equipment Monthly Cost	Maintenance Monthly Cost	Total Monthly Cost	Monthly Power Transmitted Through the Grid MWh	Cost Per MWh	Average Subscriber Usage in MWh	Monthly Protection Cost Per Subscriber
$290,136,037	$201,614,381	$491,750,417	348,000	$1,413.08	0.002275	$ 3.21

Table 8. 3: Monthly Protection Cost Per Consumer (PV Solar Power)

The average electric bill in 2018 was $117 per month (US. EIA, 2018). By dividing the incremental cost by the average monthly bill, the investment in EMP resiliency for grid communications ranged from about 2 percent of the monthly bill for Stirling engines for backup power to about 3 percent using PV solar for backup power.

9. Implementing EMP Protection

Critical sites could be protected as the initial phase of a multi-year project. Within the power grid, a small percentage of generators is considered "black start" assets to restart other generation plants. Several substations can lie between black start generators and critical facilities. The substation at the end of the black start transmission system is a distribution substation, which can serve several critical customers.

Protecting critical sites across the country will require dedicated teams. A Program Manager for the entire program could assemble teams aligned with the seven regions of the Federal Emergency Management Agency (FEMA). Within each region, a Project Manager and Team Leads could manage the installation crews. With 70 installation crews per region averaging one installation per week, 490 sites would be protected each week. At this rate, installation teams could protect about 20,000 sites a year. The communication system for the entire grid would be protected in four years.

Each installation team would need an operator for the backhoe, the soil processor, and tamper for soil compaction. An electrician would be needed to weld the sections of the grounding grid and install the cabling and cabinet. An RF tester and an inspector would be needed to verify the installation of the power and protection systems. An installation manager would be needed to coordinate the logistics and supplies.

10. Paying for EMP Protection

Many programs exist at the federal and state level to fund EMP protection for the communications infrastructure. Examples include tax credits, loan guarantees, and grants. 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.

10.1 Federal Legislation

Congress can help advance EMP protection for grid communications by legislating tax policy. Tax credits are effective tools for encouraging capital investment. For example, the 30 percent tax credit for renewable energy systems prompted growth of an entire industry. A similar tax credit for EMP resilience could incent investment in electromagnetic shielding and other, related EMP technologies.

Since power and the location of cell sites will become increasingly important with the rollout of 5G cell networks, Congress could incent the sharing of shielded power sources for both utility telecom and public telecom systems. To help smaller utilities, the federal government could provide loan guarantees to reduce the cost of loans.

Other incentives could include expensing protection costs in the year incurred instead depreciating the cost over multiple years.

10.2 State Legislation

Investment decisions in distribution infrastructure often depend on the approval of cost recovery by state Public Utility Commissions (PUCs). To encourage investments in resiliency for the distribution grid, the National Association of Regulatory Utility Commissioners (NARUC) might develop model legislation to recover costs for EMP protection that states could adopt or amend.

Decisions to invest in transmission resiliency are influenced by the approval of regional transmission organizations (RTOs). RTO decisions are subject to review by the Federal Energy Regulatory Commission (FERC) under Sections 205 and 206 of the Federal Power Act. With FERC approval, RTOs could include EMP resiliency improvements for grid communication systems in the rate base for cost recovery.

10.3 Electricity Rates

State public utility commissions determine the rates charged to customers for electricity. To recover infrastructure investments, utilities must present a compelling case to public utility commissions that justifies including the expense in the customers' rate. Since all customers benefit from protected communications to a substation, it is reasonable that the expense of protection and resiliency be included in the base rate for electricity.

Public utility commissions may approve rate increases for resilience if EMP protection is part of an all-hazards approach to addressing risk. The proposed solutions will need to benefit all rate payers and have a value in excess of the recovered capital outlay. CenterPoint Energy, in its presentation to the NERC EMP task force, indicated that it successfully included EMP protection with other threat mitigation and received cost recovery for all-hazards resilience (NERC, 2019).

10.4 Department of Agriculture Grants

The Department of Agriculture has been actively involved in helping rural communities with electrification and broadband communications. It's reasonable to consider that USDA grants could include incentives to protect both rural electric and communication systems from electromagnetic threats. A recent initiative by the USDA is:

> *On March 23, 2018, Congress passed the Consolidated Appropriations Act which established a new broadband loan and grant pilot program, called the Rural eConnectivity Pilot Program (ReConnect Program). The Act appropriated a budget authority of $600 million to be used on an expedited basis.* (USDA, 2020)

One essential goal of the ReConnect Program is to expand broadband service to rural areas with insufficient broadband access, defined as 10 megabits per second (Mbps) downstream and 1 Mbps upstream. To be eligible, power utilities must partner with wireless service providers to offer broadband service to electric company clients in addition to their own use (USDA, 2020).

10.5 Universal Service Grants for Telecom

The FCC promotes universal access to telecommunications through the Universal Service Fund.

> *The Communications Act of 1934 stated that all people in the United States shall have access to rapid, efficient, nationwide communications service with adequate facilities at reasonable charges. The Telecommunications Act of 1996 expanded the traditional definition of universal service: affordable, nationwide telephone service to include, among other things, rural health care providers and eligible schools and libraries. Today, FCC provides universal service support through four mechanisms:*
>
> - *High-Cost Support Mechanism provides support to certain qualifying telephone companies that serve high-cost areas, thereby making phone service affordable for the residents of these regions.*
> - *Low-Income Support Mechanism assists low-income customers by helping to pay for monthly telephone charges as well as connection charges to initiate telephone service.*
> - *Rural Health Care Support Mechanism allows rural health care providers to pay rates for telecommunications services similar to those of their urban counterparts, making telehealth services affordable.*
> - *Schools and Libraries Support Mechanism, popularly known as the "E-Rate," provides telecommunication services (e.g., local and long-distance calling, high-speed lines), Internet access, and internal connections (the equipment to deliver these services) to eligible schools and libraries.* (FCC, 2020)

Many paths for telecommunication services use the utility power line right-of-way and rely on electricity from the power utility. Therefore, some universal service funds might be applied to electromagnetically protect communications, especially as telecommunication carriers deploy aerial fiber.

10.6 FCC Rural Digital Opportunity Fund

To bring 5G cellular capacity and high-speed broadband services to rural areas, the FCC is providing incentives to utilities serving these communities through the Rural Digital Opportunity Fund.

> *In 2020, FCC Chairman Ajit Pai announced his intent to create the Rural Digital Opportunity Fund, which will inject $20.4 billion into high-speed broadband networks in rural America over the next decade. Funding will be dispersed through a reverse auction to*

> *service providers. Funding will be used to deploy infrastructure to provide gigabit-speed broadband in the parts of the country most in need of connectivity. The Rural Digital Opportunity Fund represents the FCC's single biggest step yet to close the digital divide and will connect up to four million rural homes and small businesses to high-speed broadband networks. These networks will bring economic opportunity to rural America and help support future 5G technologies.* (FCC, 2020).

This fund could help provide EMP shielding for rural utility communication networks.

10.7 FEMA Grants for Pre-Disaster Resilience

FEMA is shifting its focus to provide funds for pre-disaster resilience rather than post-disaster reconstruction.

> *FEMA is developing a grant program as directed by the DRRA Section 1234: National Public Infrastructure Pre-Disaster Hazard Mitigation Grant Program. This Building Resilient Infrastructure and Communities (BRIC) program will be funded through the Disaster Relief Fund as a six percent set aside from estimated disaster grant expenditures.*
>
> *FEMA has a second program through the Federal Insurance and Mitigation Administration for FY 2019, called the Pre-Disaster Mitigation (PDM) Grant Program. The Fiscal Year (FY) 2019 Pre-Disaster Mitigation (PDM) grant program provides resources to assist states, tribal governments, territories and local communities in their efforts to implement a sustained pre-disaster natural hazard mitigation program, as authorized by the Robert T. Stafford Disaster Relief and Emergency Assistance Act, Public Law 93-288, as amended (42 U.S.C. 5133). The total amount of funds that will be distributed under the FY 2019 PDM grant program will be $250 million.* (Vaughan, 2019)

Some projects may qualify for EMP protection as part of an all-hazards resilience for utility communications. Power utilities could qualify for pre-disaster mitigation funds that could be applied to protect from EMP and GMD from solar storms as part of an all-hazards approach.

10.8 Housing and Urban Development (HUD) Grants

To assist urban areas in improving their resilience to disasters, HUD is providing pre-disaster resiliency grants.

> *The Further Additional Supplemental Appropriations for Disaster Relief Requirements Act, 2018 (Division B, Subdivision 1 of the Bipartisan Budget Act of 2018, Pub. L. 115-123,*

> *approved February 9, 2018) (the "Appropriations Act"), made available $28 billion in Community Development Block Grant disaster recovery (CDBG-DR) funds, and directed HUD to allocate not less than $12 billion for mitigation activities proportional to the amounts that CDBG-DR grantees received for qualifying disasters in 2015, 2016, and 2017.*
>
> *Over $6 billion in allocations have been made to states and territories affected by severe storms, but $9 billion remain unallocated* (Federal Register, 2019).

By taking an all-hazards approach to risk mitigation, it may be possible to include EMP protection as part of the cost for improving resiliency related to severe weather. The technology used to address solar storms, RF weapons, and EMP events makes utility infrastructure more resilient to lightning and transients caused by severe storms. Investments in communication systems for utilities could enable real-time adjustments and reconfigurations of the grid to route power around downed lines.

11. Key Findings

Our key findings are:

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 restore 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.
5. 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 $20-30 billion. Alternatively, failing to invest in resilient electric grid communications protections could result in the annual GDP loss of $20 trillion.
6. The business case and the national imperative for investments in EMP-hardened, resilient communications for the electric grid are compelling.

Appendix A: Additional Areas of Study

Several promising technologies might reduce cost for EMP protection. Additional studies could include testing these new technologies to determine potential cost savings and performance benefits.

Energy Storage

- Lithium Sulphur batteries using graphene and carbon nanotubes (CNT)
- Graphene-based supercapacitors for high energy storage
- Advances in hydrogen storage manufacturing

New EMP-Shielded Power Sources

- EMP-shielded Stirling engines
- Organic solar cells using Fullerenes
- Small solar thermal trough and Fresnel lens systems using hydraulic or pneumatic sun-tracking actuators and shielded electronics
- High-efficiency, graphene-enhanced thermal transfer fluids for solar thermal systems
- Photochemical solar panels for hydrogen generation
- Microturbines for control centers

New Shielding Technologies

- EMP pulse reflection and attenuation on powerlines using impedance altering disk sets
- Conductive ferrocement structures with nickel-coated carbon fibers
- Conductive composite coatings with polyurea for RF and ballistic protection
- Conductive graphene polymer matrix composites for RF shielding
- 3” thick shielding concrete panels with conductive composite wallpaper and Polyurea

Road-Mobile EMP Protected Control & Communication Centers

- Road-mobile control and communication centers that can be deployed before EMP protection is deployed at fiber and microwave communication sites
- Road-mobile control and communication centers as mid-crisis deployable spares (EPRI, 2019)

Appendix B: Electric Utility Communication Technologies

B.1 Introduction to Electric Utility Communications

The U.S. electric grid consists of more than 22,000 generation plants; 68,992 substations; 100 Balancing Authorities; 2,500 Phasor measurement points; 3,300 utilities; 450,000 miles of high voltage transmission; 2.5 million miles of distribution lines; and 151 million customers (Wang, 2019). Electric utilities collaborate to match the generation of electricity with the customer demand (load).

To transmit power from generators to distribution networks, transmission companies predominately use high voltage alternating current (AC) systems with some high voltage direct current (HVDC) connections. The alternating current systems require precise regulation of the transmission frequency (60 Hz). When generation suddenly decreases, the frequency of the grid also decreases. Unless the grid is "balanced" by immediately employing generation reserves, it can become unstable and possibly collapse.

When generation reserves are switched in and ramped up, it is important that the phase and frequency of the added power matches 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. Measurement points include generation plants, substations, and 76 million residential and 9.9 million commercial smart meters. The smart meters measure demand and are used to anticipate demand changes (U.S. Energy Information Administration, 2020). Communication networks are vital to effectively synchronize the generation, transmission, and distribution of electricity with customer demand.

Uses of Utility Communications:

Managing customer loads

Monitoring system performance

Reading smart meters several times per hour

Detecting misdirected or stolen energy

Controlling voltage in the power system

Detecting outages

Reconfiguring the system following a fault

Balancing loads for optimal system operation

Collecting load data for system planning

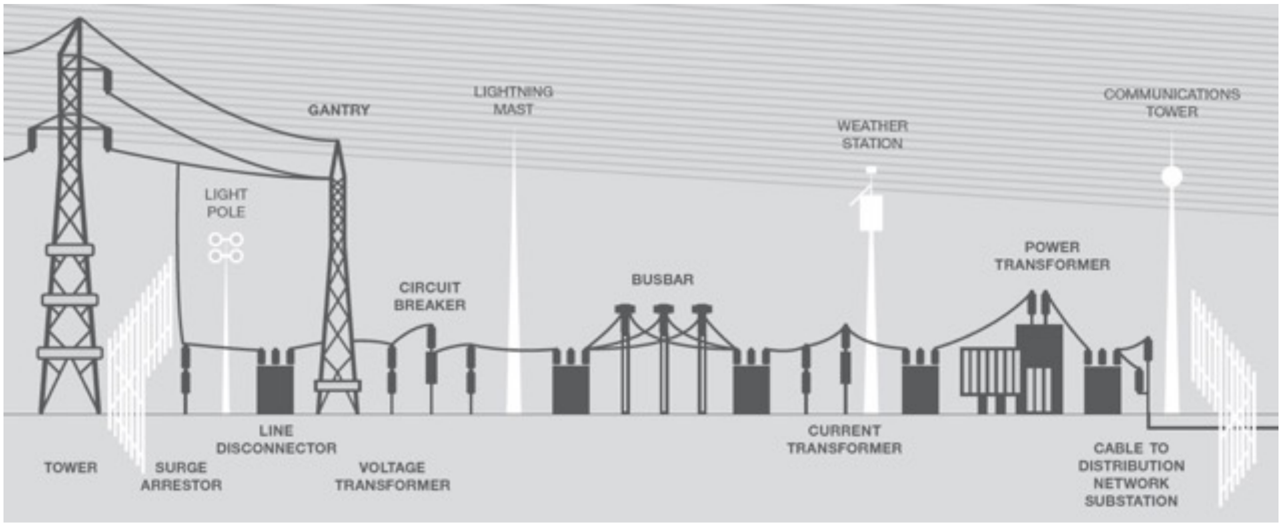


Figure 4: Monitoring and Controlling Power (ElectraNet, 2020)

The data collection and control functions for each utility have unique communication requirements. Distribution utilities collect data from smart meters at residences, commercial facilities, and medium voltage substations. Transmission utilities collect data and control electricity flow at substations in geographically disbursed networks. Generation utilities collect performance data on the generation plants that, in turn, rely on Balancing Authorities to dispatch generation. As distributed generation assets (renewables) are added to the grid, monitoring and controlling these distributed assets can involve long distances as illustrated in Figure 4.

B.2 Uses for Utility Communication Networks

A partial list of uses for utility communications networks includes:

- Monitoring system frequency
- Dispatch generation
- Control of electricity flow at switchyards and substations
- Monitoring equipment condition and health (e.g., transformer temperature, oil level, arc flash, ballistic impact, and acoustics)
- Monitoring security at generation plants and substations (e.g., access control, surveillance, time lapse, thermal cameras, motion detectors, radar-based intrusion detection, and video-verified alarms)

Devices connected to utility communications include:

- Digital Protective Relays (DPRs) to protect equipment against transients
- Digital Fault Recorders (DFRs) to record waveforms for analysis with high accuracy
- Sequence of Event Recorders (SERs) to record the status of switching elements in a time sequence for analysis
- Remote Terminal Units (RTUs) for SCADA communications with control centers
- Fault Locators (FLs) to accurately determine fault locations
- Other Intelligent Electronic Devices (IEDs) including "Programmable Logic Controllers (PLCs), power equipment controllers, position monitors, and interposing relays for surveying load, indicating operational status, and measuring revenue" (Jokovlievic, 2003)

B.3 Trends in Communication Requirements

Operational demands are increasing on utility communication networks. Distributed generation from renewable sources, grid scale energy storage, electric vehicle recharging, HVDC circuits, microgrids, and hydrogen production for fuel cells all require timely grid communications.

Renewable energy, while attractive to any society, introduces substantial variations in the production of electricity, since the generation can rapidly increase or decrease depending on the amount of sunlight or wind. To effectively integrate renewable energy sources, utilities are incorporating grid scale energy storage, HVDC circuits, and synchrophasors to convert the direct current (DC) to AC that is in phase with the grid. Regarding demand, rapid recharging of large numbers of electric vehicles at customer-selected times and locations can destabilize the grid. Increased real-time communications will be critical to integrate electric vehicles and other green-energy innovations.

Substation security will need to address the threat of radio frequency (RF) weapons, electromagnetic pulse (EMP) attack, and solar storms. To counter drones, substations may need to incorporate small high frequency radar systems, optical camera systems, and artificial intelligence to detect the threat. The requirements for radar and video image analysis will dramatically increase the communication data rate between substations and the control centers. With increasing rifle attacks on transformers, there will be an increasing need for monitoring, recording, and alerting on the acoustic signatures of rifle fire. The processing associated with this analysis will increase communication requirements. Similarly, recording and analyzing EMP characteristics from RF weapons, EMP events, and solar storms will also increase processing, storage, and communication requirements for substation control systems.

B.4 Utility Communication Technologies

Technologies used by utilities to communicate among control rooms, generation plants, and substations commonly include fiber optics, microwave radios, and both private and leased copper circuits.

Several factors influence how utility engineers choose communication technologies, such as the amount of data to be sent, the urgency of the data, the number of places sending and receiving data, the availability of commercial communications infrastructure, and the cost of implementing and maintaining the communications system. A utility company must consider its staff's expertise and training cost to implement new technologies.

While some substations still use copper lines for communications, most utilities are moving to direct fiber optic connections and line-of-sight microwave radios. Less commonly, utilities use satellite communications for operational communications.

B.4.1 Copper Lines

In the first stages of electric grid automation, substations were connected to control centers using copper, analog telephone lines. As digital technologies were introduced, substations used modems that would transmit data via in-band acoustic tones to convey information to a modem at the distant end. The data transmission rate was limited by the number of distinguishable tones and pulse rate. Advances in technology increased the initial data rates from 4.8 kilobits per second (kbps) to 44 kbps.

Digital signal processing enabled higher data rate transmission over copper lines. This advancement allowed telephone companies to offer High Speed Digital Subscriber Line (HDSL) and then Asymmetric Digital Subscriber Line (ADSL) technology with data rates up to six megabits per second. While the increased data rates have been beneficial, shielding of the ADSL equipment at both ends of the circuit would be required since copper wires act as antennas. Consequently, the induced voltage and current surges from an EMP event can damage electronic equipment at each end of the circuit.

Figure 5: Digital Subscriber Line Access Multiplexer (DSLAM) (Versa Technology, 2020)

Lines leased from commercial telecommunications carriers are the most common mode of copper wire communications. These leased lines may have to connect through multiple switch centers to reach the utility control centers. Shielding all these telecom switch centers along the path may be prohibitively expensive. The copper lines may also be inadequate for communications, command, and control of substations after an EMP event. It is also likely that the Global Positioning System (GPS) satellite receivers for the substations will be damaged by an EMP event. As a backup, utilities may want to distribute precise timing signals over fiber or line-of-sight microwave to substations. However, copper lines may not support this capability. Therefore, it is proposed that utilities replace the copper lines with fiber optic or microwave communications.

B.4.2 Fiber Optic Communications

Figure 6: 6500 Packet-Optical Platform (Ciena, 2020)

Utilities often use fiber optic cables to connect control centers with substations. The fiber optic cables are deployed in rings to prevent a single fiber cut from taking down the network. Fiber amplifiers are placed approximately every 80 miles around the fiber rings to ensure the signal is not degraded. Ciena, ADVA, Infinera, Nokia (Alcatel-Lucent), Cisco, SEL, and Fujitsu are some of the most widely deployed brands of fiber amplifiers and Dense Wave Division Multiplexing equipment. These fiber amplifiers are rack-mounted in equipment shelters or communication vaults. Each amplifier module consumes about 35 watts of power. The fiber amplifiers range from about $3,000 to $10,000 per unit, depending on features, brand, and capacity. A redundant fiber amplifier system uses about 70 W of power. Each amplifier is generally installed with a small uninterruptable power supply (UPS) and a grid power connection in a communications vault or hut. Some systems are protected with backup fuel cells or small propane generators.

To extend their fiber networks, utilities are installing aerial fiber cables close to power lines, such as on mixed use poles that also carry electricity:

> *These fiber cables need to be resistant to electricity, which can be difficult as many aerial cables contain high tensile steel (HTS) for tensile strength or aluminum barriers*

> *to protect the optical fiber from crushing forces. All-Dielectric Self Supporting (ADSS) cables have been specially designed to meet this need. Rather than metal, they contain glass reinforced plastic (GRP) or other supporting members, giving them dielectric, non-conducting properties. ADSS cables are lightweight (PPC's version weighs just 51lb (23kg) per kilometer), they do not add dramatically to strain on existing poles. This removes the need for expensive remedial works to strengthen them. (Trezise, 2020)*

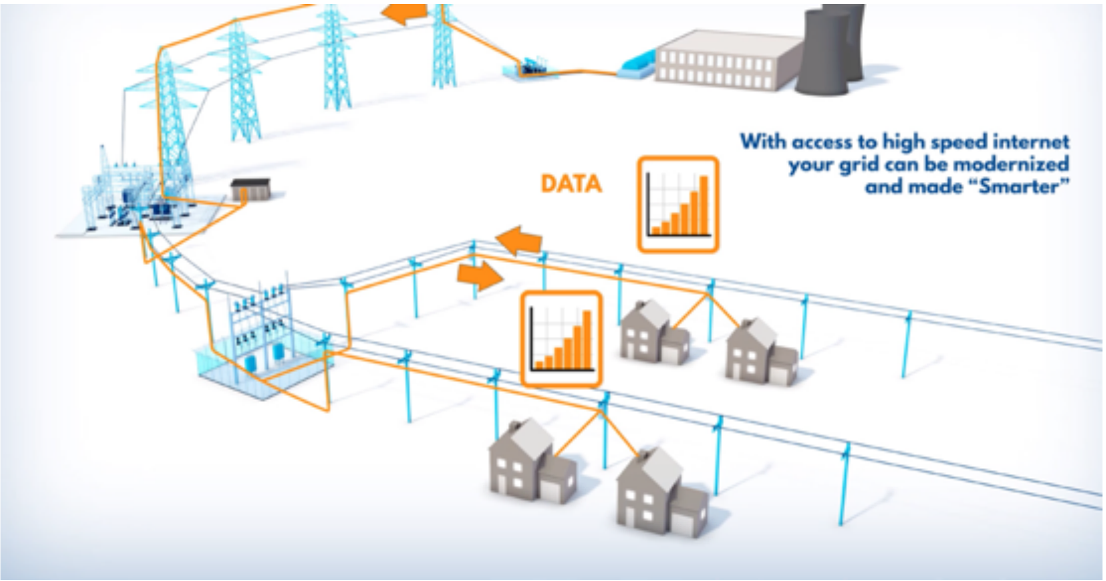


Figure 7: Aerial Fiber Network Illustration (AFL, 2019)

One trend driving the expansion of utility fiber networks is the move to smart grids:

> *Advanced metering infrastructure (AMI) is one example of a headlining technology for smart grid applications in the last decade. This enhancement for meter reading has provided significant operations and maintenance savings for electric utilities. Distribution automation is also being utilized today by monitoring and controlling devices in reclosers, switches, and capacitor banks to improve the efficiency and reliability of the grid. AMI and distribution automation are just two examples of many current smart grid applications with which increased data requirement has led many electric utilities to build or expand a fiber backhaul. (AFL, 2019)*

Fiber network switches and routers are used to connect the physical fibers into networks. The topology example below shows how these devices are deployed in the network.

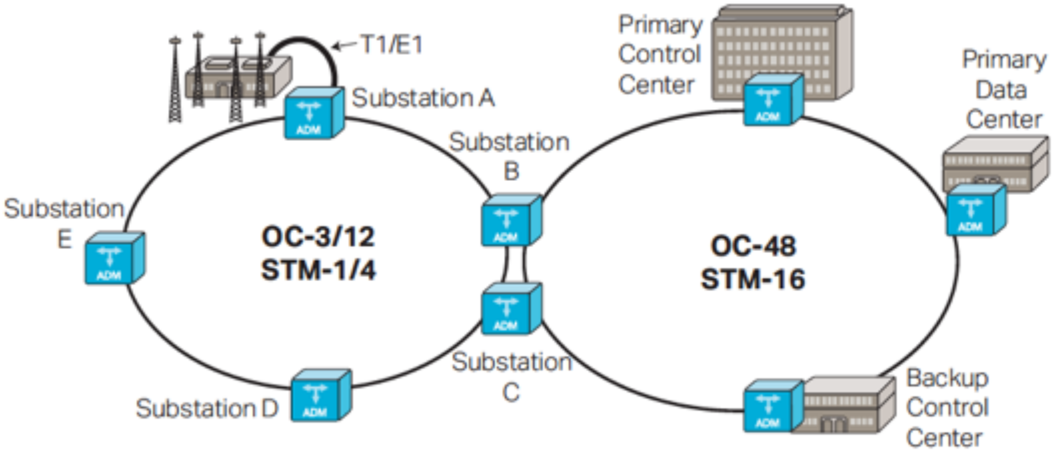


Figure 8: Example Utility Fiber Network (Ciena, 2017)

Since fibers are often installed along powerline right-of-way, the length of transmission lines can be used to estimate the number of fiber amplification points needed to connect the grid control centers with substations. Dividing the 450,000 miles of high voltage transmission lines by 80 miles between amplification points yields approximately 5,625 amplification points for the high voltage transmission network. For a first order estimate, another 3,125 amplification points in the distribution network could be added. The total number of amplifier sites for transmission and distribution is estimated at 8,750.

In addition to protecting the fiber optic amplifier locations, the fiber transceivers at substations and control rooms will need protection. The number of control rooms can be estimated from the number of electric utilities. Currently, the U.S. has more than 3,300 utilities. Some of the larger utilities may have multiple control centers, while smaller utilities may share an outsourced control center. This analysis assumes about 3,000 control centers. From the Homeland Infrastructure Foundation Level Data HFLID (U.S. Department of Homeland Security, 2020), and the UTC data, it is possible to estimate the number of substations connected by fiber optics. The estimated number of protected substations with fiber optics communications is 51,842 locations.

B.4.3 Microwave Radio

Microwave radio is a cost-effective means of communication for utilities serving remote areas. For radio communication, including point-to-point microwave, utilities use a combination of licensed and unlicensed frequency bands. The radios in the unlicensed bands are typically found in rural areas where interference by other transmitters is less likely.

The most commonly licensed microwave frequency bands in the U.S. are 6, 11, 18, and 23 GHz. A general best practice in microwave network design is to use higher frequencies for shorter paths and lower frequencies for longer paths, which helps optimize for reduced antenna sizes and overall better spectral efficiency. This usually translates to using the following frequency and antenna combinations in order of increasing path length based on the link performance criteria.

- 23 GHz with 1ft. antennas
- 23 or 18 GHz with 1ft. or 2ft. antennas
- 18 GHz with 2ft. or 3ft. antennas
- 11 GHz with 2ft. to 6ft. antennas
- 6 GHz with 3ft. to 6ft.+ antennas

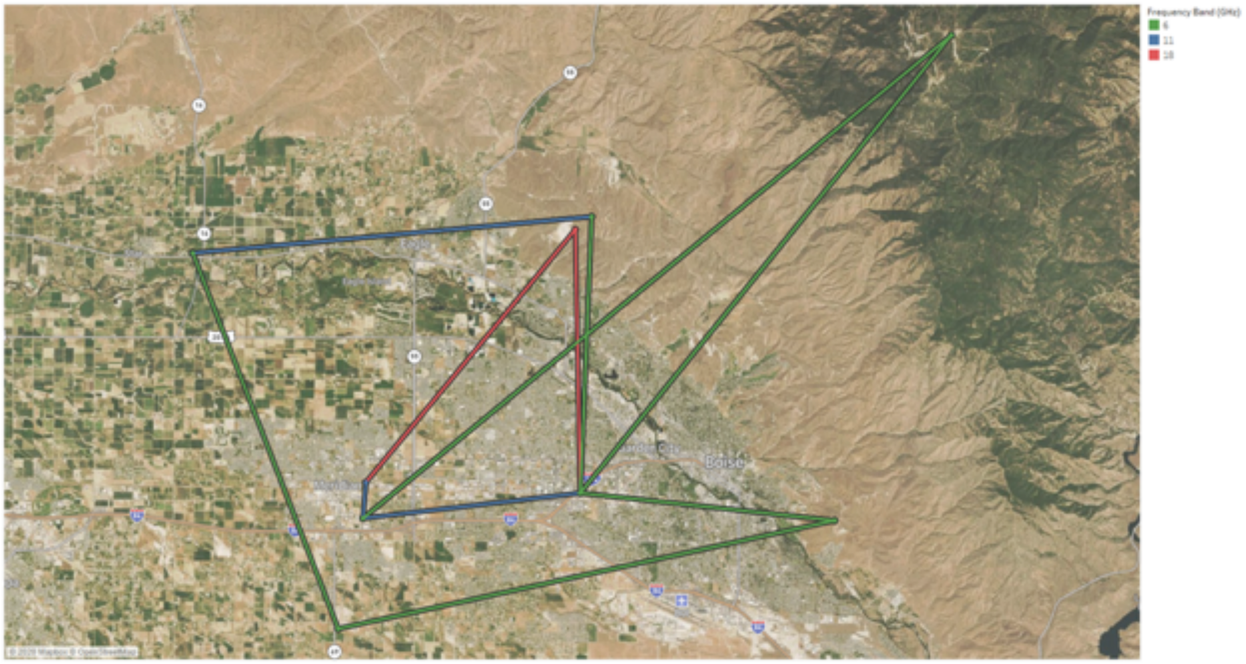


Figure 9: Sample Deployment 6 to 23 GHz Radio Links (Ceragon, 2017)

A snapshot of 6, 11, 18, and 23 GHz links in Figure 9 helps illustrate how frequency and path length are related.

Suppliers of digital microwave and millimeter radios include Alcatel Lucent, Aviat, Bridgewave, CBNL, Centron, Ceragon, Codan, DragonWave, Ericsson, FreeWave, Fujian, Ligowave, NEC, Radwin, and Trango. These companies produce equipment in multiple frequency bands to serve customer needs for short, medium, and long microwave paths of varying data capacity. Radios in all these frequencies can be used simultaneously in the same area.

B.4.4 Microwave Radio Design

The 6 GHz and 11 GHz microwave radios are the most widely used by utilities. Similar in design, these radios are provided in three variations: an all-indoor unit, a hybrid indoor/outdoor unit, and an all-outdoor unit.

B.4.4.1 All-Indoor Microwave Radios

Radio transceivers, network interfaces, and power supplies are typically mounted in 19" cabinets inside communications shelters adjacent to towers with microwave antennas. The equipment operates off of -48 VDC. A continuously shielded Heliax cable or waveguide connects the radio equipment in the shelter to the antenna on the tower. In this configuration, all active components are protected from weather and easily reached in the event of an outage or maintenance call. This configuration is most often used by utilities and public safety networks. A typical configuration includes:

- Rack Mounted Network Unit and Radio Unit
- OC3 and 16xT1 interface
- GigE interface
- Waveguide Antenna System
- Antenna and Mounts
- FCC Coordination
- Network and Radio Unit
- Installation and Project Management
- 1-year Service Contract

The site survey, permits, tower structural analysis, equipment shelter, concrete pad, grounding grid, tower, power source, and shielded cabinet are provided by the installation contractor, not by the radio equipment providers.

B.4.4.2 Hybrid Microwave Radios

The hybrid configuration places the radio transceiver next to the antenna on the tower. The network interfaces are located inside the shelter. This configuration uses power-over-ethernet (PoE) to power the radio and send data to and from the radio.

B.4.4.3 All-Outdoor Microwave Radios

The all-outdoor unit (ODU) contains the network processor, the ethernet subsystem, the modem, and the transceiver. The ODU is contained in a gasket-sealed metal housing with weather-tight connectors. The ODUs are modular and connect directly to the antennas. The integrated radio and antenna system bolts to the tower or building mounting system. The power supply is located indoors and is shielded using transient suppressors. The power supply is connected to the ODU with continuously copper-shielded Heliax cable where the shield is grounded to a low impedance grounding grid. ODUs require 35W to 40W of power at -48 VDC for the installation. They convert between 8W and 17W of electrical power into radiated RF signal. The ODU communicates with the substation equipment over fiber or ethernet. Examples of ODU units are shown in the top of Figure 10, while the all-indoor units are shown in the bottom of Figure 10.

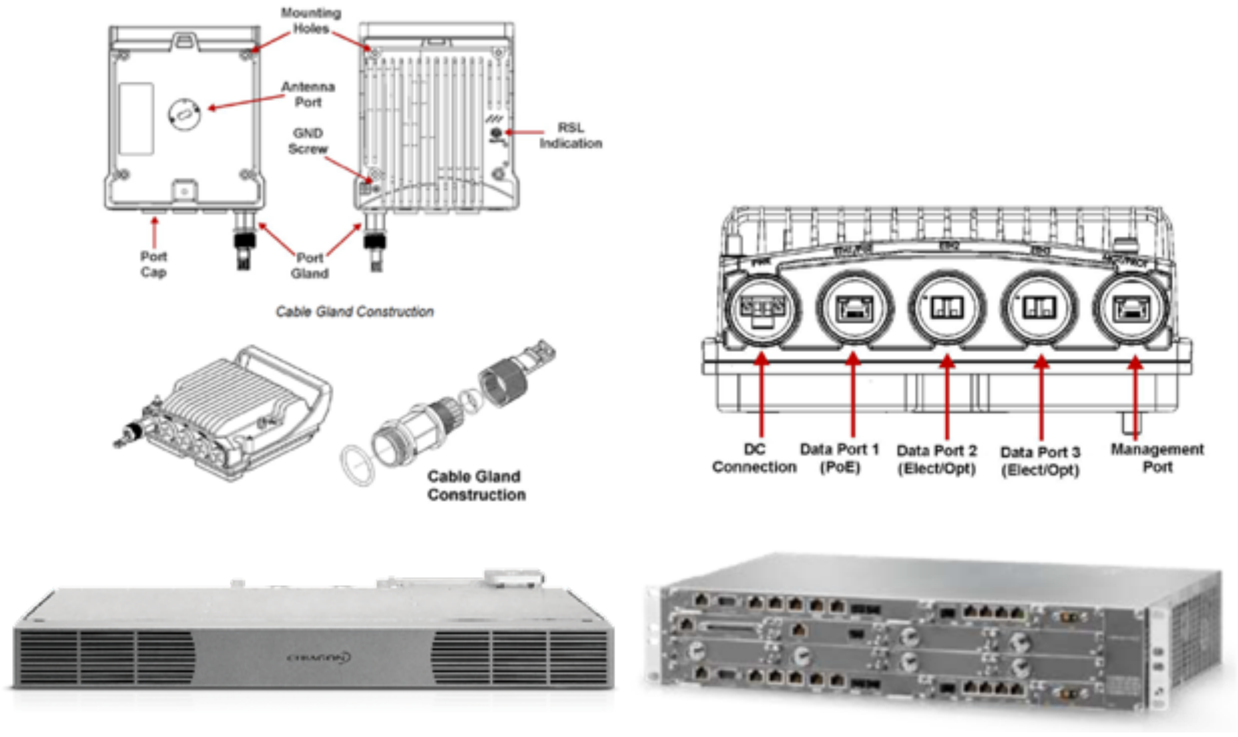


Figure 10: Microwave Radio Construction Details (Ceragon, 2017)

B.4.4.4 Microwave Radio Installation

A typical point-to-point microwave radio installation is shown in Figure 11. When installed, radio links need a clear line of site to the other radio. This usually necessitates a building top installation or a tower at each end to ensure that the RF signal path is above trees and intervening buildings.

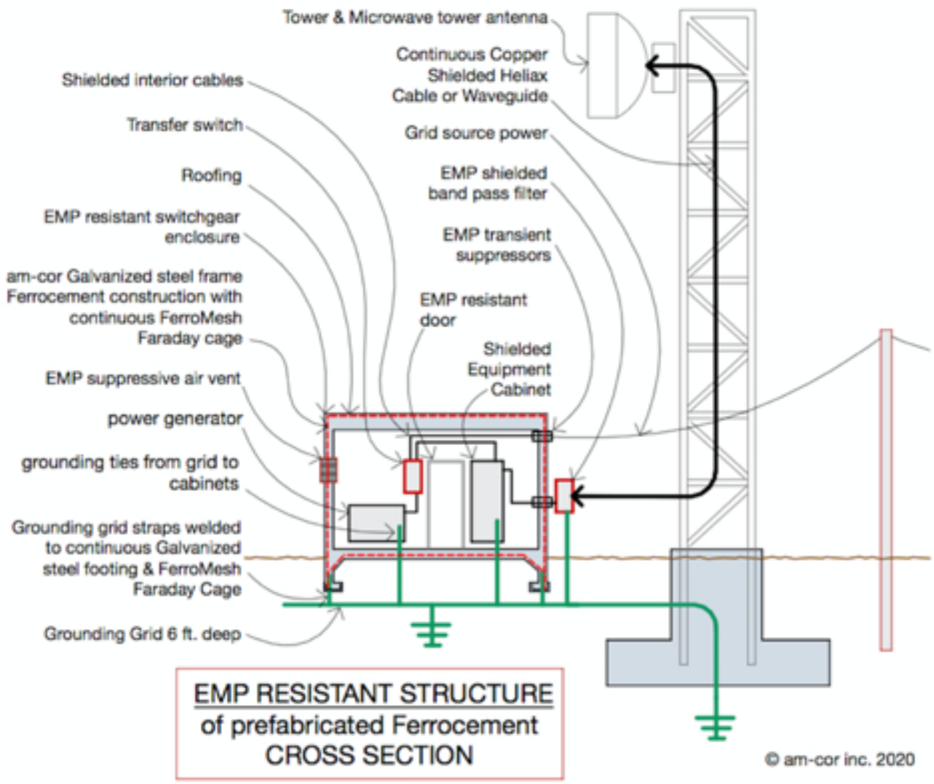


Figure 11: Grounding, Power, and Lightning Protection (Am-cor, 2020)

B.4.5 Satellite Communications

Utilities infrequently use satellite terminals to provide communications for remote locations outside the range of microwave links. Historically, satellite connectivity has been more expensive than fiber and line-of sight microwave for most sites. The higher cost has limited satellite communications to low-bandwidth (up to 400 kbps) or burst applications from remote locations. Inmarsat’s BGAN terminal in Figure 12 exemplifies a satellite terminal for remote monitoring and control.

Figure 12: Inmarsat B-GAN Flat Panel Antenna (Hughes, 2020)

Satellite bandwidth may become more cost-effective with new constellations of low earth orbit (LEO) and medium earth orbit (MEO) satellites being launched by SpaceX (Boyle, 2019), Telesat, OneWeb, AWS, and O3B. From the previous charts addressing transmission frequencies verses the length of “hops,” satellite links are positioned to compete with fiber and microwave radio links for path lengths exceeding 3 km.

The rural market for long-distance microwave links and fiber optic cables may begin to encounter significant competition from LEO satellite systems. Small, inexpensive LEO satellite transceivers will likely undercut the amortized cost fiber and line-of-sight microwave systems in rural areas. Satellite links could effectively connect substations with control centers over wide geographic areas in a star or mesh configuration. O3B already views its satellite offering as competition to fiber links. O3B currently provides high-capacity satellite circuits that could be used to connect substations with utility control centers. New satellite communication systems can offer a cost-effective solution for connecting thousands of remote sites as shown in Figure 13.

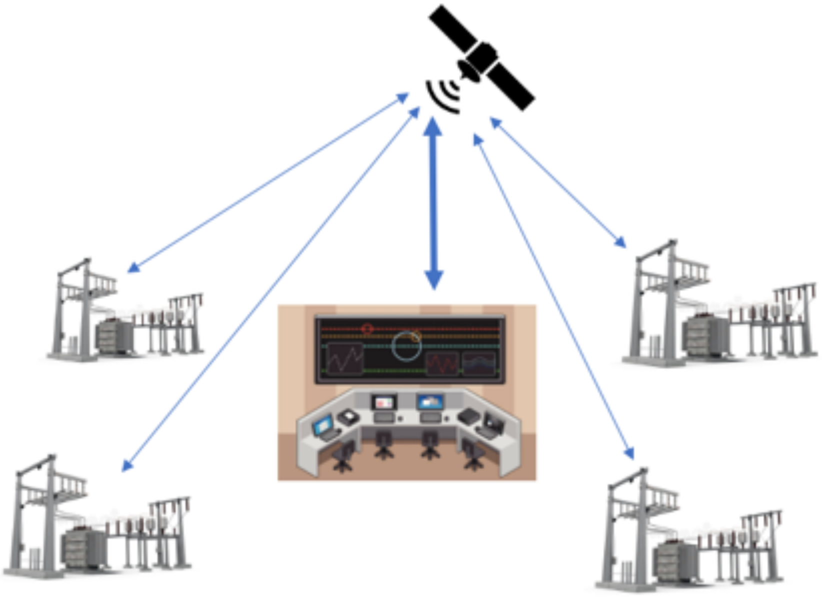


Figure 13: Satellite Connectivity for Substations

There is a potential risk in using satellite links for critical infrastructure. The satellites and ground stations may be vulnerable to an EMP event.

> *In the late 1950s and early 1960s there were sixteen high altitude nuclear detonation experiments, some of which contributed substantial additional trapped radiation, changing the morphology of the Van Allen electron belts, increasing their intensity, and hardening their energy spectrum. At least eight satellites that were in orbit during this time were damaged by long-term effects of nuclear-enhanced trapped radiation…. Although GEO and GPS satellites are critically important to U.S. military and economic security, it is satellites in Low Earth Orbit (LEO) that will dominate most of the discussion in this paper. These satellites are the ones that would be most affected by a high altitude EMP burst. (GEO and GPS satellites are unlikely to be severely damaged by EMP bursts having less than multi-megaton yields.)* (Defense Threat Reduction Agency, 2010)

The Defense Threat Reduction Agency (DTRA) indicates solar power arrays, power management systems, receivers and transmitters for communications, sensors, and altitude control systems of LEO satellites are vulnerable to resulting radiation as shown in Figure 14.

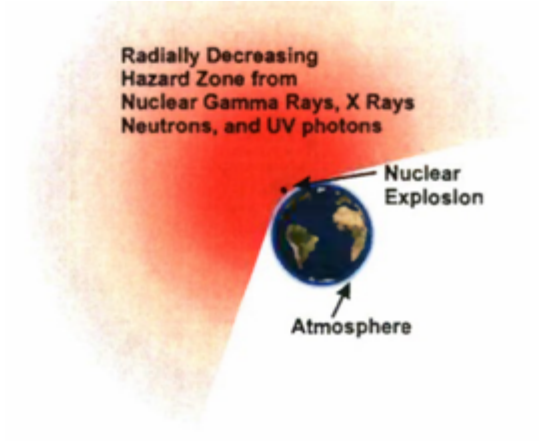


Figure 14: Earth Shielding of Satellites (Defense Threat Reduction Agency, 2010)

> *Where not shadowed by the Earth or shielded by atmospheric attenuation, X-rays, y-rays, neutrons, and ultraviolet (UV) photons travel great distances from a high-altitude nuclear detonation where they may inflict damage to satellites.* (Defense Threat Reduction Agency, 2010)

Certain types of ground terminal receivers may also be vulnerable to EMP. Ground terminals using parabolic antennas with waveguide or coax connections can install bandpass filters with protection circuitry designed to shunt the EMP pulse to ground. EMP protection for flat-panel, active-element, phased-array transceivers may be considerably more difficult given the small size of each element in the array. Because of the difficulty of protecting such communication transceivers from EMP events, it is proposed that satellite communication systems between control rooms and substations use parabolic reflectors with EMP-shielded bandpass filters between the antenna and the transceivers. Alternatively, utilities could use EMP-shielded fiber optic or microwave line-of-sight communications.

B.5 Communications for Repair Crews

Substation equipment will likely need repair after an EMP event. Utilities commonly dispatch repair crews with mobile radios. In case of emergencies, utilities also practice repair dispatch with satellite phones. The cost of EMP protection for mobile radios receiver units and satellite phones is not included in the cost estimates; this is an area for future study.

B.5.1 Mobile Radios

Utilities use mobile radios to communicate with their field service teams to repair downed lines, coordinate transformer servicing, and restart parts of the grid. Motorola and Tait provide the most widely used models.

Several utilities, including Dominion, PJM, Southern Company, and the New York Power Authority, are evaluating BNET software-defined radios produced by Rafael in Israel. The BNET radios, derived from military radios, are tested to survive an EMP event. They operate between 30 MHz and 512 MHz in narrowband or wideband modes using Frequency Hopping Spread Spectrum techniques. L-Band and S-Band radios are available options. The radios support packet voice and data and allow for the formation of ad hoc networks. These radios are designed to interface with existing land mobile radio systems and carrier backhaul and satellite networks. The radios also offer 256 AES encryption for the data channel.

Figure 15: Mobile Radio System (Hunt, 2019)

Mobile radio systems utilize a base station connected to an antenna mounted on a tall (e.g., 200-foot) tower as shown in Figure 15. For larger systems, multiple towers are used with repeater sites that connect to the base station. The ability to communicate is limited by the line-of-site between the handheld unit and the tower. To extend the communication range, repeaters can be mounted on drones or aerostats.

The radio base station equipment could be protected against EMP by using shielded cabinets within an enclosure at the base of the tower as shown in Figure 11. Spare radio units, with batteries removed, could be stored in shielded cases. The batteries could be stored in the case with the radios. The shielded equipment cabinets would need to include shielded power sources.

B.5.2 Satellite Phones

Satellite phones have typically been used as emergency replacements for mobile radios and to reach areas not covered by mobile radios. The service providers preferred by industrial users are Iridium, Inmarsat's IsatPhone, and Globalstar.

Satellite phones have the advantage of greater coverage than cellular phones since they connect directly with orbiting satellites and avoid the need for a local base station. It will be important to provide EMP protection for satellite gateways and Telemetry Tracking and Control (TT&C) sites that operate the satellite constellation. To improve resiliency, many satellite constellation operators have geo-diversity sites on other continents for command and control.

Cost for satellite phones can range from $500 to $1,200 per phone. The service plans range from $50 to $110 per month in fixed charges and average about $1 per minute for usage charges. Service prices are expected to drop substantially as new LEO constellations become operational.

For EMP protection, spare phones can be stored with the batteries removed in shielded cases. Some LEO constellations may survive an EMP event, depending on the height of an atmospheric detonation.

B.6 Factors for Selecting Communications Technology

When choosing between fiber and microwave radio connections, utilities consider the distance of the connection, the transmission data rate, and the cost. Utilities often use fiber for short distances. When this option is not cost effective, utilities often use microwave radio links.

Utilities consider several factors in selecting microwave bands. It may be easier to install radios in an unlicensed band instead of a licensed frequency band. If installation time is the most important factor, unlicensed bands may be attractive. However, unlicensed bands may encounter unwanted interference from other radios.

If a utility chooses the protection offered by a licensed band, the licensing process takes about 30 days and involves a frequency coordination study and FCC approval. Some microwave links may require tower construction or antenna mounting on existing buildings that, in turn, may require additional permits and inspection.

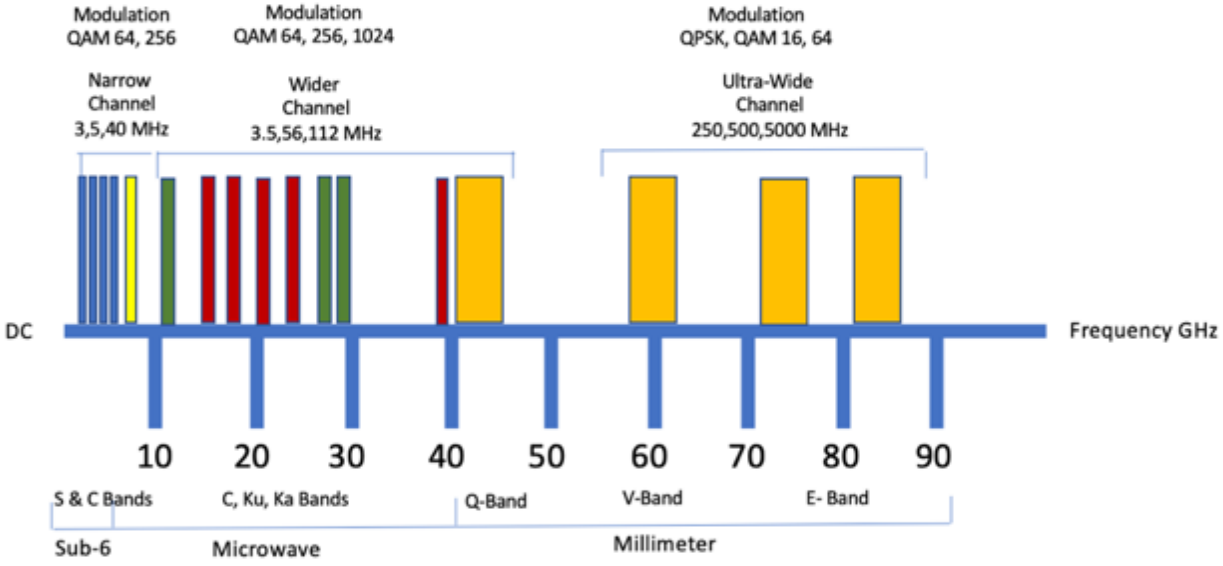


Figure 16: Frequency Spectrum, Channel Bandwidth, and Modulation

Higher transmission frequencies (e.g., 23, 28, 42, 60, and 80 GHz) use smaller antennas but have shorter range. Lower transmission frequencies (e.g., 6, 7, and 10 GHz) use larger antennas and have a longer range. The size of the antenna affects other costs such as the building mount or tower design. Bigger antennas have higher wind loads and require more robust mounts or towers. Figure 16 above shows the possible frequency ranges and modulation techniques for communication links.

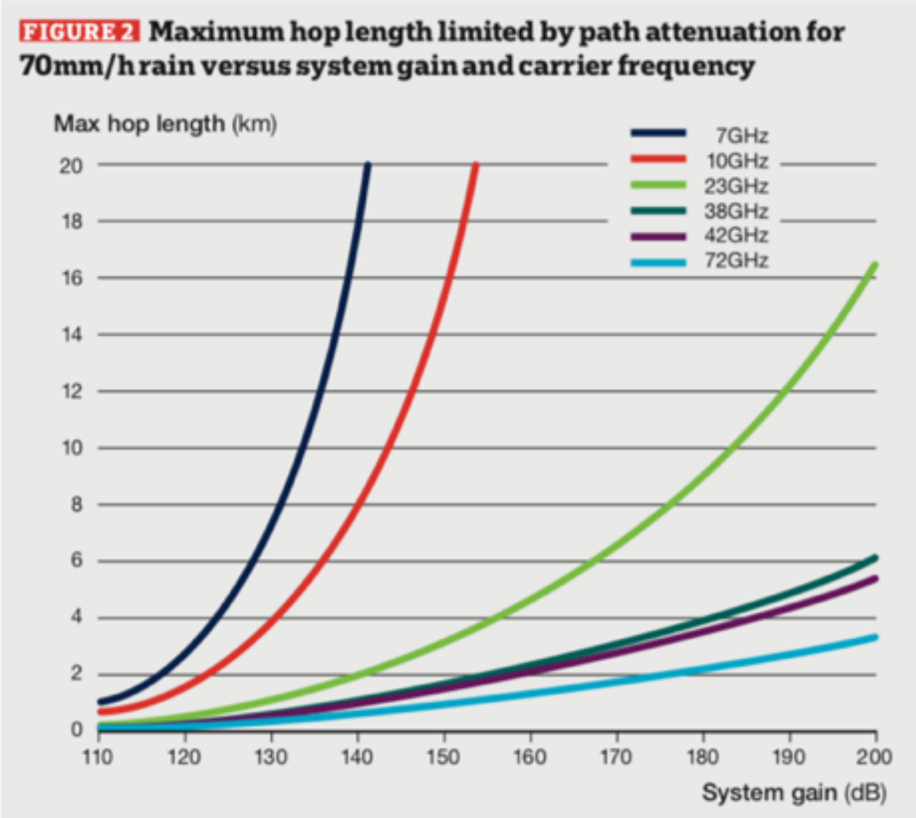


Figure 17: Maximum Hop Length Limited by Path Attenuation (EDSTAM, 2011)

The comparison in Figure 17 can be helpful in determining the appropriate transmission frequency based on the distance of the wireless connection or "hop." The 7 GHz and 10 GHz signals have better propagation through the atmosphere and require less system gain to achieve the same distance. The system gain is a function of the antenna size, modulation, and the transmit power on each end.

After selecting the radio transmission frequency, utilities may want to compare the cost with other transmission technologies. The cost comparison in Figure 18 can be useful to help utilities decide whether to install additional fiber to remote sites or to install a radio link.

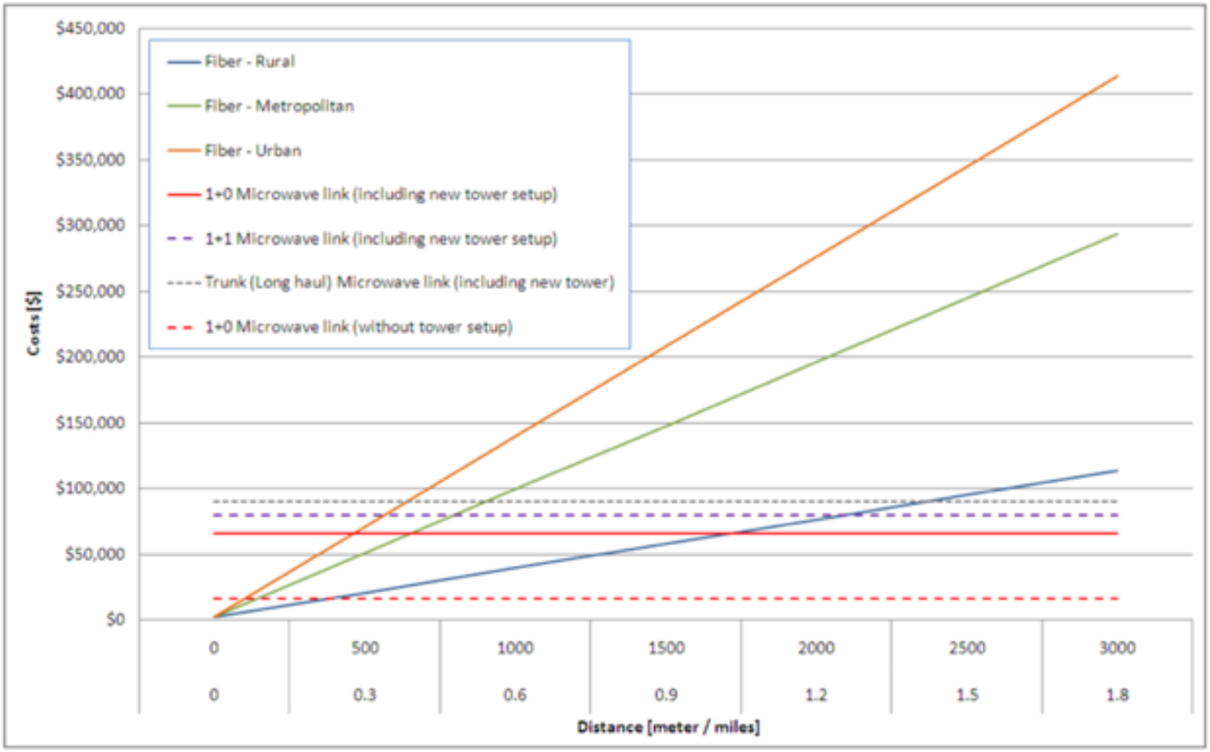


Figure 18: Microwave and Fiber Backhaul Solutions vs. Distance (Naveh, 2009)

The decision process used by an electric utility in selecting a frequency band could be characterized as follows in Figure 19:

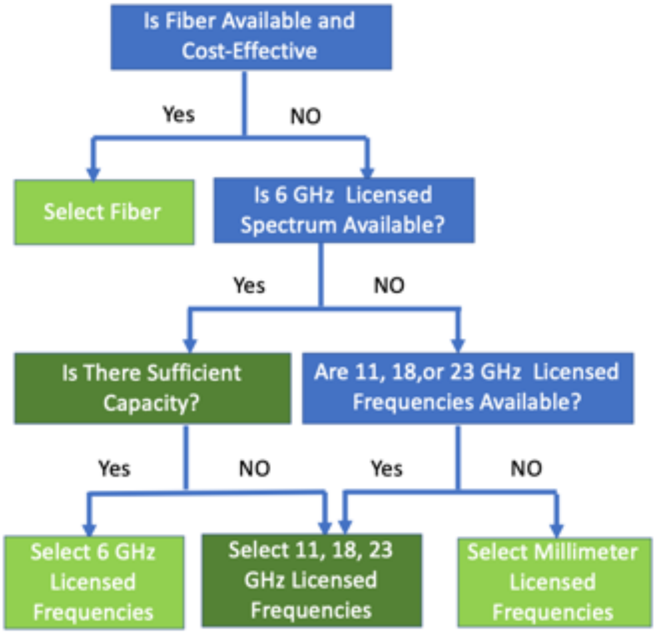
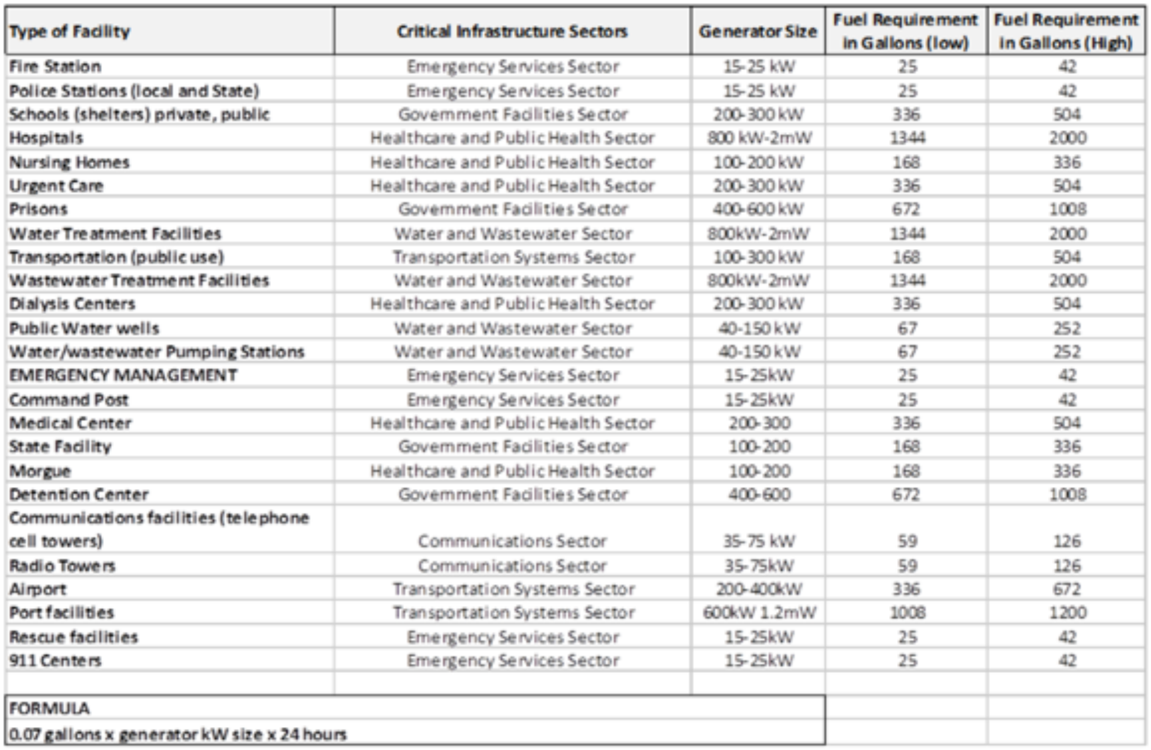


Figure 19: Backhaul Decision Tree

B.7 Timelines to Restore Grids

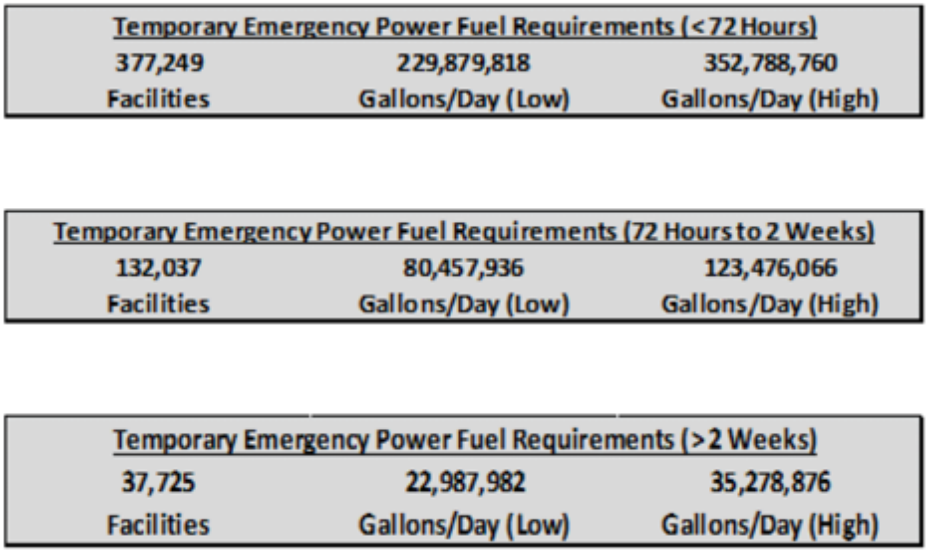
The Federal Emergency Management Agency (FEMA) analyzed the restoration from an extended grid outage. FEMA designates 377,249 facilities as critical in its national grid restoration plan. Figure 20 illustrates the amount of fuel required to run backup generators at these facilities.



Type of Facility	Critical Infrastructure Sectors	Generator Size	Fuel Requirement in Gallons (low)	Fuel Requirement in Gallons (High)
Fire Station	Emergency Services Sector	15-25 kW	25	42
Police Stations (local and State)	Emergency Services Sector	15-25 kW	25	42
Schools (shelters) private, public	Government Facilities Sector	200-300 kW	336	504
Hospitals	Healthcare and Public Health Sector	800 kW-2mW	1344	2000
Nursing Homes	Healthcare and Public Health Sector	100-200 kW	168	336
Urgent Care	Healthcare and Public Health Sector	200-300 kW	336	504
Prisons	Government Facilities Sector	400-600 kW	672	1008
Water Treatment Facilities	Water and Wastewater Sector	800kW-2mW	1344	2000
Transportation (public use)	Transportation Systems Sector	100-300 kW	168	504
Wastewater Treatment Facilities	Water and Wastewater Sector	800kW-2mW	1344	2000
Dialysis Centers	Healthcare and Public Health Sector	200-300 kW	336	504
Public Water wells	Water and Wastewater Sector	40-150 kW	67	252
Water/wastewater Pumping Stations	Water and Wastewater Sector	40-150 kW	67	252
EMERGENCY MANAGEMENT	Emergency Services Sector	15-25kW	25	42
Command Post	Emergency Services Sector	15-25kW	25	42
Medical Center	Healthcare and Public Health Sector	200-300	336	504
State Facility	Government Facilities Sector	100-200	168	336
Morgue	Healthcare and Public Health Sector	100-200	168	336
Detention Center	Government Facilities Sector	400-600	672	1008
Communications facilities (telephone cell towers)	Communications Sector	35-75 kW	59	126
Radio Towers	Communications Sector	35-75kW	59	126
Airport	Transportation Systems Sector	200-400kW	336	672
Port facilities	Transportation Systems Sector	600kW 1.2mW	1008	1200
Rescue facilities	Emergency Services Sector	15-25kW	25	42
911 Centers	Emergency Services Sector	15-25kW	25	42
FORMULA				
0.07 gallons x generator kW size x 24 hours				

Figure 20: Fuel Usage by Facility Type (FEMA, 2017)

As a grid outage progresses, the logistics of providing fuel to each of these facilities rapidly becomes unsustainable (see Figure 21). After 72 hours, the number of critical facilities supported falls to 132,037 sites. After two weeks, only 37,725 sites can be sustained nationwide.



Temporary Emergency Power Fuel Requirements (<72 Hours)

377,249	229,879,818	352,788,760
Facilities	Gallons/Day (Low)	Gallons/Day (High)

Temporary Emergency Power Fuel Requirements (72 Hours to 2 Weeks)

132,037	80,457,936	123,476,066
Facilities	Gallons/Day (Low)	Gallons/Day (High)

Temporary Emergency Power Fuel Requirements (>2 Weeks)

37,725	22,987,982	35,278,876
Facilities	Gallons/Day (Low)	Gallons/Day (High)

Figure 21: Supported Critical Facilities After 2 Weeks (FEMA, 2017)

To maintain communication between control centers and substations, each site requires its own power supply capable of operating independently of the grid for several months without refueling.

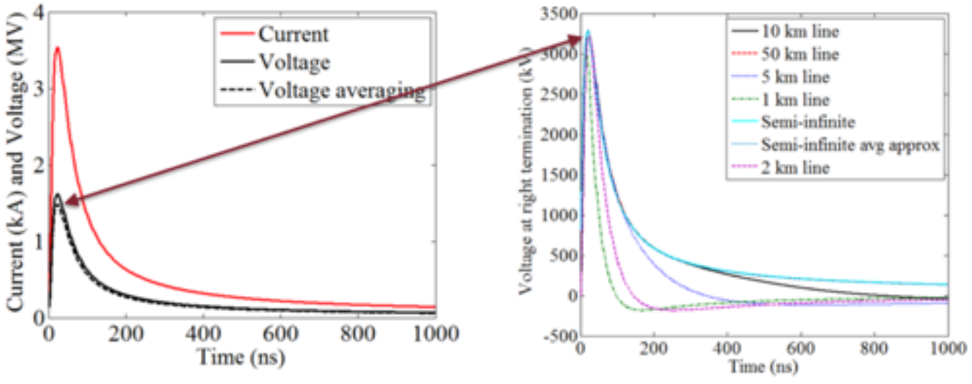
B.8 Testing for Electromagnetic Vulnerability

Testing EMP effects on equipment is difficult and complex. A number of testing labs – both private and government-owned – exist throughout the country. The U.S. Government has several EMP test facilities including Pax River, White Sands, China Lake, Little Mountain Test Range, Sandia National Lab, and Los Alamos National Lab.

Historically, EMP testing has been limited by the capability of the test equipment. Many EMP specifications and test procedures were developed in the 1960s, based on parameters of test equipment at that time. Instead of measuring the entire frequency band of the EMP pulse at one time, procedures were developed to examine a narrow window of frequencies and move the frequency "window" across the frequency band to measure effectiveness of shielding. Advances in instantaneous bandwidth and processor speeds have greatly improved signal processing. Today, it is possible to examine the entire frequency band all at once. This could be important, since materials may behave differently when they are excited at all frequencies simultaneously.

The Defense Threat Reduction Agency (DTRA) is tasked with evaluating the EMP testing capability of private labs. This evaluation can be difficult, since labs approach testing differently. Some use low power emitters in small anechoic chambers; others use high-power emitters in large metal chambers. Some test facilities rely on absorbing the pulse and subsequent reflections; others use distance and time-of-arrival to eliminate interfering reflections.

Government EMP testing labs are constructed in remote areas to conduct tests at high power levels. The power levels are so significant that the outdoor ranges must deconflict the EMP test pulses with cars, ships, airplanes, and satellites. The EMP test standard (MIL_STD_188_125) calls for 50 kV per meter electric fields. Sandia National Lab uses an indoor shielded lab to test at much higher electric fields than the military specification. The data presented to the North American Electric Reliability Corporation (NERC) EMP Task force is between 1500 kV and 3200 kV as shown in Figure 22. It may be reasonable to conclude from this data that adversaries have increased the effectiveness of their weapons over the last 50 years and that MIL-SPEC_188_125 may no longer reflect the current state of adversarial technology.



Matched Impedance Termination

Open Termination

Figure 22: EMP Coupling to Transmission Lines (NERC, 2019)

Some organizations helped sponsor EMP testing of equipment at various laboratories. The Electric Infrastructure Security (EIS) Council sponsored testing in conjunction with DTRA at the S.A.R.A test lab in Colorado. This EMP testing was conducted on digital protective relays used in substations (SARA, 2017). DTRA also sponsored testing on the digital control systems for substations and reported the results to the NERC EMP Task Force (NERC, 2019).

In the tests, the signal lines and the incoming AC power lines used metal oxide varistor (MOVs) for protection. The ethernet ports used spark gaps for protection. The tests included radiation and current pulse injection. The radiation tests showed non-latching upset of unprotected relays and control equipment at 32 kV/m. The current pulse injection showed upset at 200 Amp surges and permanent damage at 400 Amp surges for the unprotected equipment power supplies. When protected, the equipment showed upsets at 400 Amp surges and damage to the power supplies at 5000 Amp surges.

While the DTRA-sponsored testing helps model EMP effects on equipment, there is concern that the MOVs may not be fast enough to handle 1 nanosecond EMP pulses. MOVs also have a finite life and may not be able to handle multiple pulses from high power microwave weapons or multiple detonations. The testing may also need to include higher levels of injected current pulses and higher voltage levels.

B.8.1 Additional Testing

Additional testing is needed to build on the work done by S.A.R.A and the EIS Council. For example, communications and control equipment and its associated cabling could be tested as a system. Shielded cabinets could be tested to the IEC-64000 specification using wideband and narrowband swept pulses. Once the shielding effectiveness of the cabinets has been verified and characterized, then the equipment from various manufacturers could be integrated into the shielded cabinets for a systems-level test. A series of tests could focus on an operating system in which 1 nanosecond rise time pulses from a 35-kilojoule source would be increased in amplitude until the electric field strength reached 50,000 Volts per meter. Probes could be placed externally and internally to verify the system's functionality as well as the efficacy of the shielding.

B.8.2 Proposed Equipment for EMP Testing

To test communications and control equipment as a system, it is important to include a wider range of equipment than just the digital relays. The proposed equipment in Table B.5.1 includes the shielded equipment cabinets, communications equipment for fiber and microwave communications, diagnostic equipment for substations, power management, and power sources and the cabling to connect them as a system.

	Radio Connected Substations	Fiber Connected Substations	Fiber Amplification Point	Network Control Center
Shielded Cabinets	Y	Y	Y	Y
Line-of-site Microwave Radio Transceivers	Y			Y
Hydrogen Fuel Cells	Y	Y	Y	Y
Synchrophasors	Y	Y		Y
Digital Fault Recorders	Y	Y		Y
Digital Protective Relays	Y	Y		Y
Fiber Optic Multiplexer		Y		Y
Fiber Amplifiers			Y	

Table B.8.2. 1: Equipment Proposed for Additional Testing

Appendix C: Strategies for Electromagnetic Protection

C.1 Post-EMP Event Assumptions

In the aftermath of an EMP event, utility managers must quickly determine what parts of the critical infrastructure still function and what can be rapidly restored. The electric grid will likely go through a black start process to systematically restore generation and associated loads. A functioning communication system is essential during this black start process. Factors to be considered include the collapse of demand and the survival of generators, transformers, relays, substation control equipment, service vehicles, and test equipment.

C.1.1 Collapse of Demand

Customer equipment over a wide geographic area may be damaged or destroyed by the induced currents on power lines and ground-induced currents resulting from an EMP event. Utilities will need to rapidly balance their power generation, transmission, and distribution to avoid destabilization of the grid as the demand for electricity suddenly changes. Real-time measurements of frequency, phase, voltage, and current in thousands of points throughout the grid and millions of end points will depend the survivability of the sensors and communications.

C.1.2 Coordination Among Utilities

Careful coordination will be required between the operators of generation plants, transmission systems, and distribution systems to recover from an EMP-induced national grid outage. Each organization’s repair and operations staffs must coordinate with counterparts to match the power generation with demand.

C.1.3 Availability and Mobility of Repair Crews

The availability of repair crews and vehicles will impact time required to repair and re-energize substations. The anticipated restoration time is a key factor in determining the amount of fuel needed to maintain operation of the communication equipment.

The degree of survivability of vehicle electronics after an EMP event is uncertain. Many cars and trucks operate with unshielded sensors and microprocessors, which may be vulnerable to and debilitated by EMP. Some manufacturers have shielded vehicle electronics from on-board RF transmissions (e.g., cell phones and WIFI hot spots) and from external sources (e.g., nearby radars and radio stations). While helpful for daily use, such protections are insufficient for an EMP event that can generate electric fields 250 times stronger than nearby radars. Vehicle sensor and microprocessor-based control systems would likely fail.

An EMP may decrement the availability of service personnel to restore power, at least doubling the recovery time. Some service personnel may be unwilling to leave their families without power, water, and food for extended periods, as seen in the aftermath of hurricanes in Puerto Rico in 2017. To reduce absenteeism, utilities may need to make provisions for work crews and their families. Looting and theft of fuel and vehicles are also concerns during times of national crisis. Utilities may need to provide armed protection for each work crew.

C.1.4 Limitations of Mutual Aid

Utilities have established mutual aid agreements to assist each other during natural disasters. However, almost all utilities will be simultaneously affected in the event of nationwide, coordinated RF attacks, solar storms, and other large-scale EMP events. Each utility may need to be self-sufficient in its recovery.

C.1.5 Availability of Spares

Availability of equipment will be a factor in re-energizing the substation in synchronization with the grid. Utilities must communicate with network control centers, substations, and service crews to coordinate delivery of equipment and spares. The repair crews may also need to bring test equipment and spares to ascertain the substation’s viability.

C.2 Protection Strategies

Effective electromagnetic protection can be accomplished at the system level and equipment levels. A protection strategy for the former considers the synergistic operation of all equipment including the sensors, processors, protection circuitry, communications equipment at the substation, equipment at intermediate communication points, and equipment at the control centers. Equipment-level protection applies when designing individual pieces of equipment within a system. Equipment-level specifications are usually a subset of the system-level specifications. Individual pieces of equipment may consist of hundreds of parts from various manufacturers. The original equipment manufacturer (OEM) specifies the performance of the various parts and then verifies the performance as the equipment is assembled. When assembled, the equipment undergoes EMP testing.

Because there is a large installed base of existing communications and control equipment, EMP protection at the equipment level may be limited to new build opportunities or upgrades. For existing sites, it may be more expedient to shield the environments containing the equipment rather than encouraging hundreds of companies to build their equipment to new specifications.

C.3 Equipment-Level Protection

Equipment-level protection is an effective EMP strategy for equipment that cannot be enclosed in a Faraday cage (a six-sided conductive enclosure that comprises a protective environment). For example, microwave radio outdoor unit (ODUs) are often mounted on tall towers with hundreds of feet of cabling, necessitating protection at the equipment level.

The ODU radio housings are metal and grounded but may not have a continuous conductive surface to protect the internal electronics. The microwave radio power supply and ethernet switch, located in a shelter at the base of the tower, may be the most vulnerable since they are connected to the utility’s electric grid. The indoor equipment may have unshielded ethernet cables that could act as antennas during an EMP event. A surge suppressor using metal oxide varistor (MOVs) or gas ionization may not react fast enough to intercept an EMP pulse with a 1 nanosecond rise time.

EMP protection for electric utility microwave radio system requires shielding not only the radios and power supplies, but also the network control system. If radio links are used to monitor and control substations, the substation industrial control system also needs protection. By starting with the radio transmitter and receiver (transceiver), it is possible to protect the system all the way to the sensors in the substation.

Receivers in microwave radios typically have a bandpass filter that only allows frequencies within the receive band to be processed. Common bandpass filters offer 80 dB of attenuation for out-of-band signals. Since 90 percent of the energy of an EMP event is below 100 MHz, a bandpass filter could provide protection. However, radio frequency (RF) weapons can use any microwave frequency and the bandpass filter may not be effective against a weapon transmitting specifically in the receive band. To protect against in-band signals above the threshold of damage for the receiver, a different type of bandpass filter must be used that can detect an EMP event, attenuate excessive in-band signals, and ground out-of-band energy. The EMP-protected bandpass filter in Figure 23 could be added between the ODU and the antenna feed.

Figure 23: EMP-Shielded Bandpass Filter (Advanced Fusion Systems, 2020)

The ODU housings are typically made in two pieces bolted together with an O-ring gasket weather seal. To create a continuous conductive surface, a thin coating of silver paste can be applied to the metal mating surfaces. Fifty grams of silver paste, currently valued at about $445, could accommodate at least 25 radios, adding about $10 to $20 per radio in material cost. Labor and testing might similarly increase the cost.

Heliax cable can be used to protect the outdoor unit from an induced current surge on the power or communication cable. Heliax has a full copper shield that can be grounded at one end to protect the power and signals transmitted through the center conductor. This grounded shielding prevents the electric field produced by the EMP from creating an induced current surge in the cable that could damage the radio electronics.

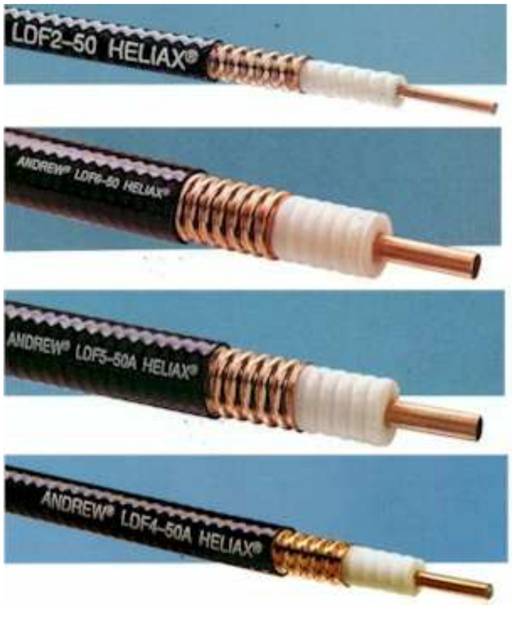


Figure 24: Heliax for Radio Antenna Connections (Broadcast Supply Worldwide, 2018)

The Andrew ½ inch Heliax Superflexible Dielectric Cable is currently available for under $4.50 per foot. An antenna installation may need from 100 to 200 feet of Heliax cable. The cost to replace the existing PoE cable with Heliax using factory terminated cables could cost $1,500 to $2,500 per site, assuming two people working two hours, plus materials and test equipment.

Existing technologies can protect outdoor microwave radios from EMP. The cost of the protective technologies is moderate or even minimal; however, implementing them would require testing for standard radio configurations. While this EMP protection could be added to radios in the field, a better approach might be to exchange them for EMP-protected units, lab tested and placed in an exchange program

C.4 System-Level Protection

As an alternative to component-level EMP protection, utilities could place communication equipment in Faraday cages. In this configuration, penetrations for cooling, fiber optic cables, or power cables are protected by various technologies to prevent RF energy from coupling to and damaging the equipment. Shielded cases and cabinets can serve as small Faraday cages. Properly shielded buildings can also serve as Faraday cages.

C.4.1 EMP-Shielded Cases

Substations can use shielded cases to store on-site spares such as sensors or control electronics or solar panels for deployment following an EMP event. They can also be useful for other applications, such as transport of sensitive equipment. Some cases are designed with shielded air filters and feedthroughs to allow continued operation of equipment during an EMP event. Shielded cases range in cost from hundreds of dollars for injection molded plastic cases to $40,000 or more for filtered, composite rack enclosures, depending on size, performance, and filtering requirements. Cases can be made from metal or advanced lightweight conductive composites. Shielding composite cases are shown in Figure 25 and Figure 26.

Figure 25: Lightweight Shielding Plastic Cases (Faraday Cases, 2020)

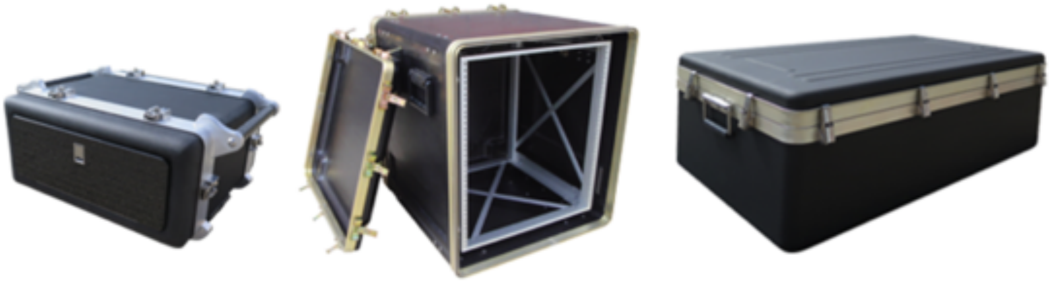


Figure 26: Lightweight Shielded Composite Cases (Faraday Cases, 2020)

C.4.2 Conductive Paints, Wallpaper, Stucco, Tile, and Conduits

Utility networks consist of tens of thousands of equipment buildings. An alternative to shielded cabinets is coating the inside of equipment shelters with conductive paints, wallpaper, or stucco with nickel-coated carbon fiber materials. The floors can be treated with conductive paints and bonded with conductive adhesives as shown in Figure 27. Conductive conduits can protect cabling between the equipment shelter and the measurement points. Composite materials are light weight and corrosion resistant and can be applied to concrete panels to create a conductive surface. The coated surface would need to be connected to a low impedance grounding grid. At about $4 to $20 per square foot installed cost, the approximate cost is about $12,200 to protect a 10 ft. by 10 ft. by 8 ft. structure (total surface area of 560 square ft., including the roof and floor). The door of the structure, air filter, and cable feedthroughs would likely need to be replaced with RF-shielded versions, adding another $16,000 to $20,000 to the cost (including labor and testing).

Figure 27: Conductive Paints, Caulks, Wallpapers, Window Screens, Stucco, Concretes, and Conduits (Faraday Cases, 2020)

C.4.3 Shielded Cabinets

Several manufacturers provide EMP-shielded cabinets of various sizes that can be used to protect indoor electronics. Many options meet National Security Agency's stringent shielding requirements for Tempest, as well as EMP. The shielded cabinet in Figure 28 is tested for both magnetic and electric fields. In small quantity, the cabinets cost between $25,000 and $32,000. A large quantity purchase could reduce the price by 30 to 40 percent. Manufacturers include Equipto, Trusted Systems, Holland Shielding, ETS Lindgren, and Universal Shielding. These cabinets can include EMP-shielded air filters welded into the cabinet, waveguide filters, and feedthroughs for fiber optic cables and hydrogen gas.

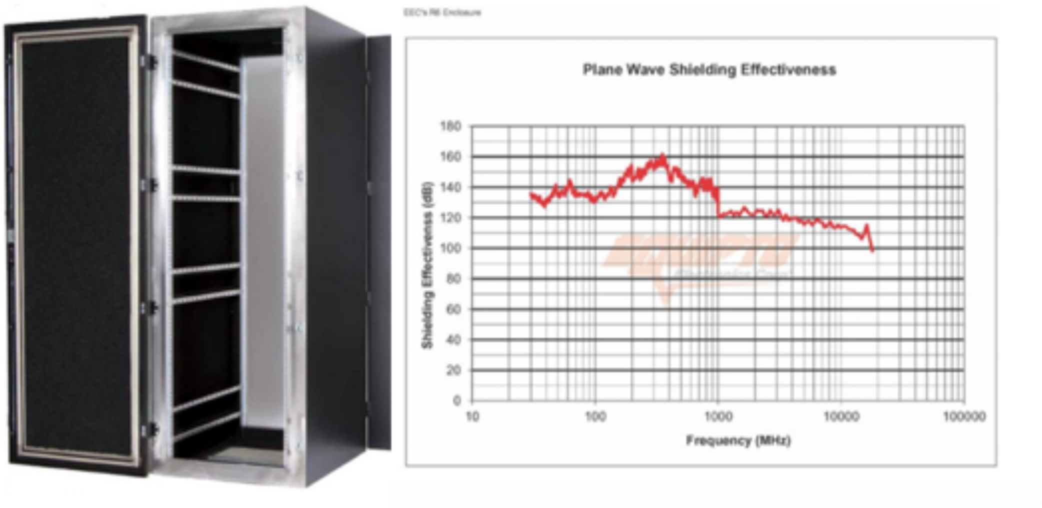


Figure 28: Shielded Rack Electric Field Performance (Equipto Electronics Corp, 2020)

C.4.4 Ferrocement Structures

Ferrocement is a construction system using reinforced cement (cement, sand and water) applied over a metal mesh using a trowel. Using this method, small buildings can be constructed to serve as Faraday cages for sites with multiple cabinets of equipment needing EMP protection. Such enclosures, commonly used for military equipment, might be used for electric grid infrastructure. Several approaches can be used to construct these buildings, such as using a panelized metal stud and welded steel-mesh design in which the doors and air filters are preinstalled and welded to the panels.

Ferrocement utilizing nickel-coated carbon fibers is troweled into the mesh forming a ½ inch thick unibody structure that is tied to a low impedance grounding grid below or adjacent to the structure. To provide additional RF and ballistic protection, a second internal mesh can be welded to the inside edge of the studs. An internal layer of ferrocement can then be applied. The gap between the layers can be filled with sand or rubberized materials to absorb the energy of a ballistic round. Once the grounding grid is in place and the footers have been poured, the building can be constructed with a crew of three people in a single day.

The approximate construction cost for a 10 ft. by 10 ft. by 8 ft. exterior shell is about $50,000 including the RF-shielded door and honeycomb air filter. Additional cost would be incurred for the plumbing, wiring, lighting, interior finish, air conditioning, generator, automatic transfer switch, and ground grid.

Figure 29: Ferrocement Structure (Am-cor, 2020)

C.4.5 Concrete with RF Shielding Properties

To construct new buildings, special types of concrete can be used that incorporates integral metal meshes and materials that absorb or reflect radio frequencies. This technology can provide a cost-effective solution for blast, ballistic, and electromagnetic shielding as shown in Figure 30. It provides about 10 dB of attenuation for each inch of panel thickness. This allows the RF shielding performance to be designed to the customer's need. Since the entire material provides shielding, the structure retains its RF performance even if the exterior or interior is chipped.

Figure 30: Shielding Concrete RF Performance (Omni-Threat Structures, 2020)

To achieve thinner panels with lower shipping weights, conductive coatings can be combined with the concrete. The metal meshes in the concrete panels are welded to each other and to the door frame. Both are welded to the low impedance grounding grid straps. The cost depends on the site's location and the logistics of shipping the shielding concrete mix to the location. The cost is about $475,000 for a fully finished EMP-shielded structure of 20 ft. by 12 ft. by 10 ft. with waveguides, 3.0 ft. RF-shielded door, redundant 2-ton air conditioning units, power connections, 25 kW propane generator, automatic transfer switch, breaker panel, interior lighting, rubberized tile, wiring, cable trays, piping, interior finishes, grounding grid, footers, and a 1,000-gallon propane tank.

C.4.6 RF-Shielded Doors

RF-shielded doors with conductive seals are critical to protecting sensitive electronics by preventing RF pulses from penetrating the shelter. In fact, doors are often the weak point in RF shielding for existing facilities. RF-shielded doors provide a conductive connection around the door opening that grounds the door surface to the frame. RF-shielded doors often use replaceable beryllium copper finger stock around the edge of the door frame. The latching mechanism of the door presses a knife edge protrusion on the door's edge against the metal finger stock on the door frame. As the door's knife edge compresses the finger stock, a metal-to-metal seal is created by the bending of the finger stock.

Figure 31: Copper Beryllium Finger Stock for Door Seals (Comtest Engineering, 2020)

The doors may also use "precision-machined aluminum hinges with thrust bearings for sag-free mounting and smooth operation" (ETS Lindgren, 2020). In small quantity, RF-shielded doors cost between $8,000 and $16,000 for a 3 ft. by 7ft. door, depending on the vendor, specifications, and delivery schedule. Manufacturers include ETS Lindgren, Universal Shielding, and Holland Shielding.

Figure 32: RF-Shielded Door (Comtest Engineering, 2020)

C.4.7 Seam-Welded Steel Containers

Several manufacturers provide EMP-shielded, seam-welded steel containers designed to protect various type of power systems and equipment. Manufacturers include ARMAG, Triton Defense, and Holland Shielding.

Figure 33: EMP-Shielded Diesel Generator (ARMAG, Corporation, 2020)

The EMP-shielded containers are designed to protect diesel, propane, or natural gas generators. The air inlet and exhaust vents of the container use a honeycomb filter structure with covered louvers to allow airflow while preventing the EMP radio frequencies from entering the container. Power filters and power grid tubes can be used to protect generators from induced current surges on the power lines from the generators to the equipment. The EMP-shielded containers can range from $150,000 to $250,000, depending on requirements for air conditioning, lighting, fire suppression, size, materials, construction, and testing. The seam-welded steel containers are transportable and can be relocated as needed.

C.4.8 Low Impedance Grounding

A low impedance grounding is one of the most important aspects of effective EMP shielding. By switching the surge to a low impedance grounding grid, the equipment can be protected from EMP effects. However, most grounding grids are built for lightning and are not designed to protect against RF weapons or EMP.

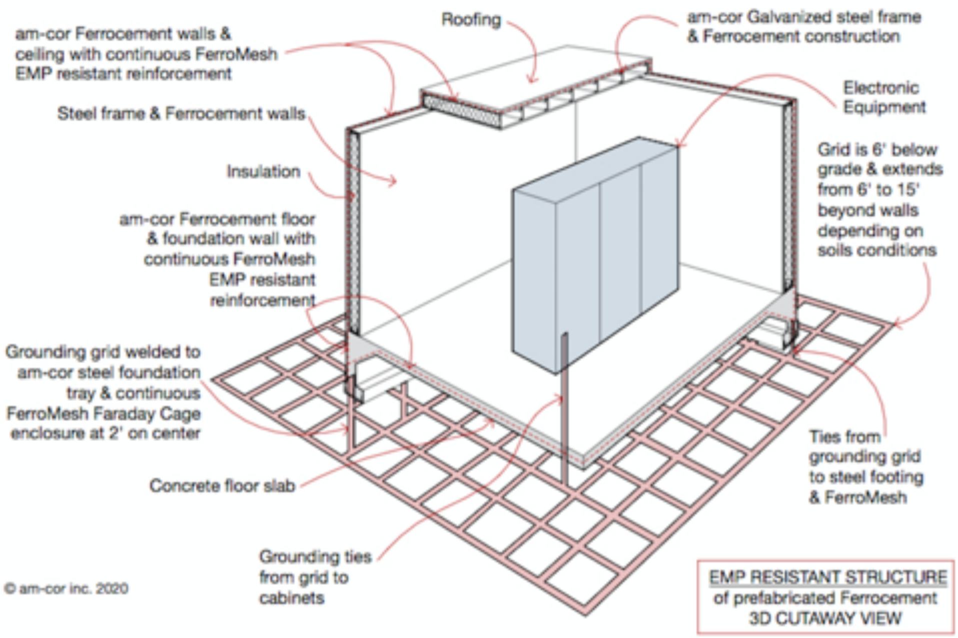


Figure 34: Low Impedance Grounding Grid (Am-cor, 2020)

Standard grounding often uses round metal conductors. To achieve better performance, low impedance grounding grids use wide, flat conductors welded together using a high temperature chemical reaction called "Cadwelding." The grounding grid is shown in Figure 34. The ratio of the width to the thickness of copper straps can provide a significantly lower impedance, as much as 600:1.

> *"RF currents tend to conduct along the surface of a conductor rather than through the middle (a behavior known as the "skin effect"). This makes wide straps more efficient at handling high frequency currents than round, solid wire and a better choice for both RF grounding and lightning applications. The rapidly pulsating DC currents encountered during a lightning strike can be compared to high level RF currents. Copper strap handles these currents more effectively than the same amount of copper in wire form"* (Georgia Copper, 2020).

It's also possible to add ground enhancement materials (GEM) to boost conductivity of the soil. To protect the electronics a 16 ft. by 16 ft. low impedance grounding grid 6 ft. below the surface would cost about $29,000 installed.

C.5 Long-Duration Backup Power Options

Long-duration backup power generation is essential for black starting the grid. To operate communication equipment until the power is restored, utility control centers and substations need on-site, EMP-protected, power generation systems operating independently from the grid.

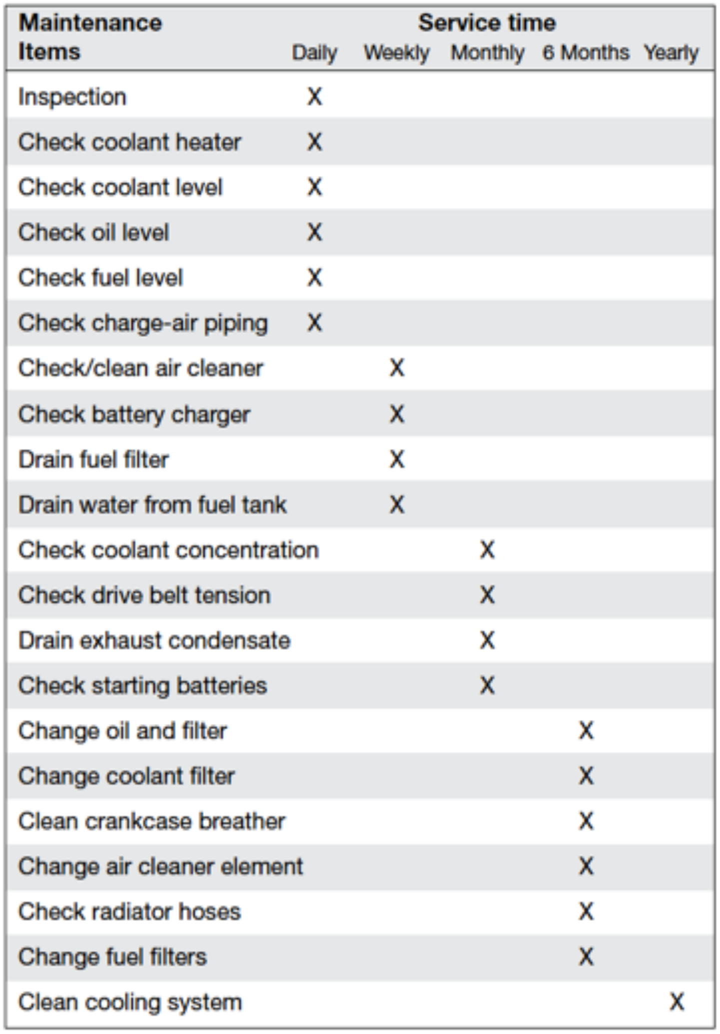
C.5.1 Diesel, Propane, and Natural Gas Generators

Many countries manufacture generators: Action, Aggreko, Algen Power Generation, Alimar, Ausonia, Atlas Copco, Baldor, Bruno, Caterpillar, C.G.M., Dagartech, Gruppi Elettrognei SRL, Cukurova, Cummins, Detroit, Endress, FG Wilson, Gelec Energy, Genesal, Generac, Genpower, Gillette, Grupel, Harrington, Himoinsa, Inmesol, Kohler, Manlift, Maverick, MTU, Olympian, PCA Power, Pramac, Southwest Products, Teksan, Trio, Vital Generator, Welland, Visa S.p.a., Yor Power, and Zwart Techniek (Ayemba, 2019).

In the U.S., Generac offers one of the smallest diesel generators designed for primary power generation. It provides 8 kW of power at full load that costs about $8,500. The generator uses 0.2 gallons of diesel fuel per hour at ¼ load (2 kW) and 0.6 gallons per hour at full load (Global Power Supply, 2020). When operating at a 2 kW power output, the generator consumes about 864 gallons in 180 days of operation. A 1,000-gallon storage tank located outside the shielded enclosure could provide sufficient fuel storage. Any electronics, such as a pump, would need to be within the protected enclosure.

Storing diesel fuel for months or years requires periodic maintenance. The storage tanks need to be rust-free and tested every 30 days for water and biofilm contamination. Biocides need to be added to the fuel every 90 days to prevent microbial contamination (Bell Performance, 2020). Biocides cost between $0.10 to $0.20 per gallon, depending on the manufacturer and quantity. Since diesel fuel oxidizes, fuel filters need to be inspected every 90 days and changed when necessary.

Diesel generators require periodic maintenance. Typically, oil changes are conducted every 100 to 500 hours of operation, depending on the manufacturer and the duty cycle. A typical schedule for daily, weekly, monthly, biannual and yearly maintenance of diesel engines is provided in Figure 35.

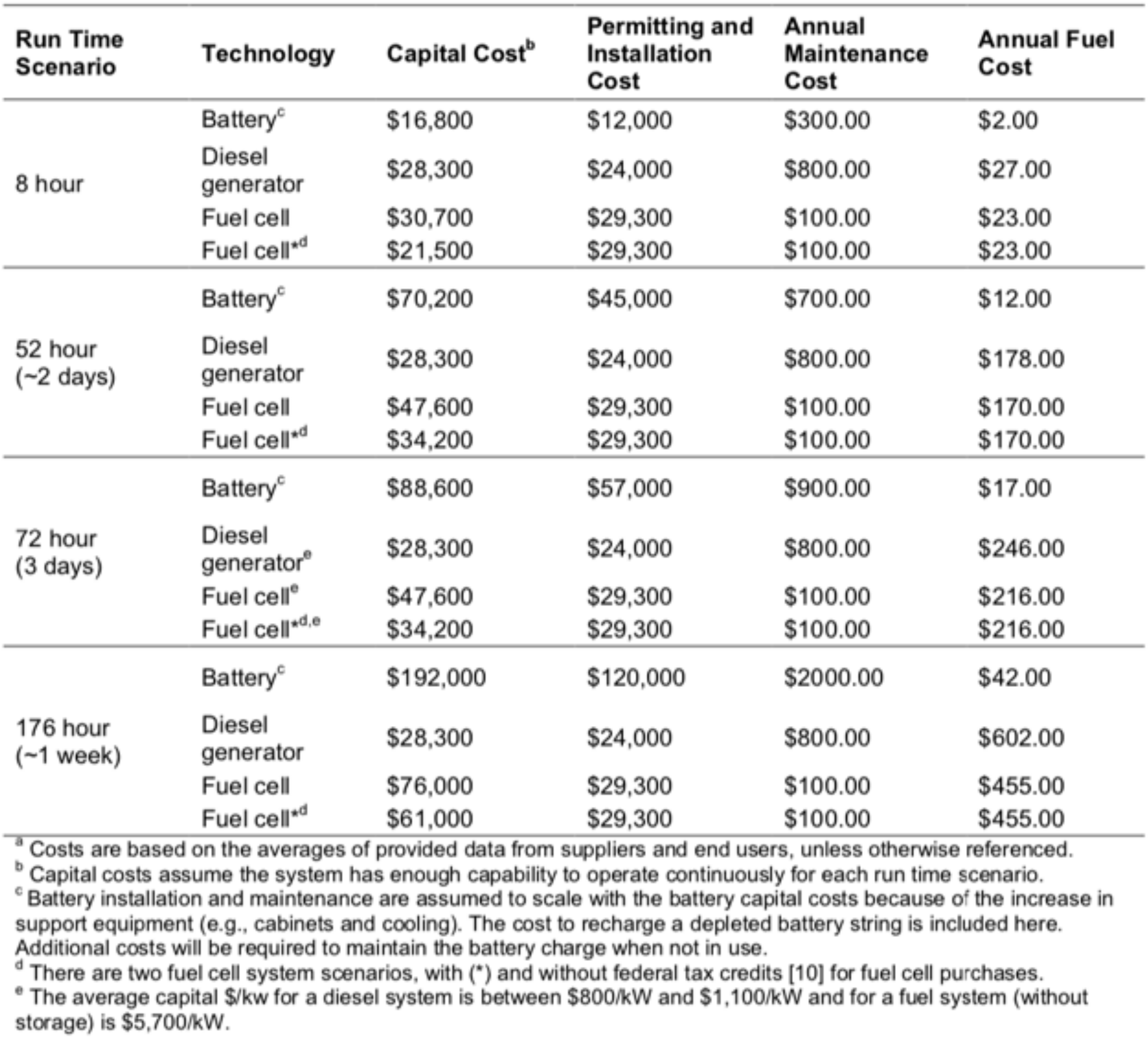


Maintenance Items	Service time				
	Daily	Weekly	Monthly	6 Months	Yearly
Inspection	X				
Check coolant heater	X				
Check coolant level	X				
Check oil level	X				
Check fuel level	X				
Check charge-air piping	X				
Check/clean air cleaner		X			
Check battery charger		X			
Drain fuel filter		X			
Drain water from fuel tank		X			
Check coolant concentration			X		
Check drive belt tension			X		
Drain exhaust condensate			X		
Check starting batteries			X		
Change oil and filter				X	
Change coolant filter				X	
Clean crankcase breather				X	
Change air cleaner element				X	
Check radiator hoses				X	
Change fuel filters				X	
Clean cooling system					X

Figure 35: Diesel Generator Maintenance Schedule (Cummins Power Generation, 2007)

The cost of a utility visit to a substation can average from $250 to $500 in addition to parts required for a repair or servicing (Yakel, 2017). To reduce ongoing operational costs, some utilities use larger generators to quickly charge supercapacitors. The supercapacitors slowly charge batteries, which then power the equipment. This approach minimizes the generator runtime and extends time between service visits.

Shielded generators may be better suited for large power requirements such as network control facilities. The Department of Energy's National Renewable Energy Laboratory (NREL) analyzed backup power systems for a 1-week outage, comparing installation and operational costs as shown in Figure 36.



Run Time Scenario	Technology	Capital Cost[b]	Permitting and Installation Cost	Annual Maintenance Cost	Annual Fuel Cost
8 hour	Battery[c]	$16,800	$12,000	$300.00	$2.00
	Diesel generator	$28,300	$24,000	$800.00	$27.00
	Fuel cell	$30,700	$29,300	$100.00	$23.00
	Fuel cell*[d]	$21,500	$29,300	$100.00	$23.00
52 hour (~2 days)	Battery[c]	$70,200	$45,000	$700.00	$12.00
	Diesel generator	$28,300	$24,000	$800.00	$178.00
	Fuel cell	$47,600	$29,300	$100.00	$170.00
	Fuel cell*[d]	$34,200	$29,300	$100.00	$170.00
72 hour (3 days)	Battery[c]	$88,600	$57,000	$900.00	$17.00
	Diesel generator[e]	$28,300	$24,000	$800.00	$246.00
	Fuel cell[e]	$47,600	$29,300	$100.00	$216.00
	Fuel cell*[d,e]	$34,200	$29,300	$100.00	$216.00
176 hour (~1 week)	Battery[c]	$192,000	$120,000	$2000.00	$42.00
	Diesel generator	$28,300	$24,000	$800.00	$602.00
	Fuel cell	$76,000	$29,300	$100.00	$455.00
	Fuel cell*[d]	$61,000	$29,300	$100.00	$455.00

[a] Costs are based on the averages of provided data from suppliers and end users, unless otherwise referenced.

[b] Capital costs assume the system has enough capability to operate continuously for each run time scenario.

[c] Battery installation and maintenance are assumed to scale with the battery capital costs because of the increase in support equipment (e.g., cabinets and cooling). The cost to recharge a depleted battery string is included here. Additional costs will be required to maintain the battery charge when not in use.

[d] There are two fuel cell system scenarios, with (*) and without federal tax credits [10] for fuel cell purchases.

[e] The average capital $/kw for a diesel system is between $800/kW and $1,100/kW and for a fuel system (without storage) is $5,700/kW.

Figure 36: Capital, Permitting, Installation, Maintenance, and Fuel Costs (J. Kurtz, 2014)

As the grid outage continues, the efficiency of the generator, availability of fuel, and periodic maintenance become increasingly important factors in selecting power generation technology.

The initial costs of reciprocating generators are attractive. However, most units are considerably larger in capacity than required by the fiber amplification and microwave radio locations. The frequency of maintenance and the logistics cost of deploying maintenance personnel to thousands of remote sites monthly are of concern. The reciprocating generators seem better suited to power large loads, such as control centers. Fully tested solutions from companies such as ARMAG are readily available for shielding these larger generators.

C.5.2 Combined Heat and Power Systems

To power network control centers, combined heat and power (CHP) systems (as shown in Figure 37) can offer significant advantages. Natural gas turbines with several months of liquefied natural gas storage in dual wall, steel ISO tanks provide compact, shielded solutions for on-site power generation. The exhaust from the turbines can be used for heating or to create chilled water from an absorption chiller. The combined cycle efficiency of power generation plus the heating and cooling can be over 70 percent.

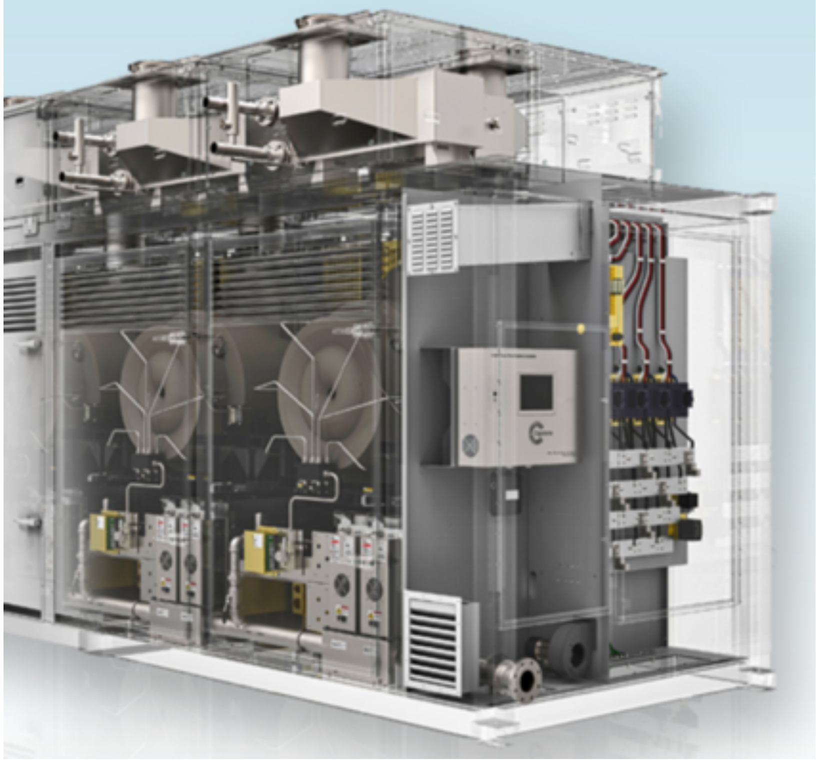


Figure 37: Natural Gas Turbine (Capstone Turbines, 2020)

A CHP system using two 200 KW turbines running at 75 percent of peak load with two 80-ton exhaust fired absorption chillers produces about 300 kW of power and 160 tons of cooling. The installed cost is about $1.4 million per network control center.

C.5.3 Fuel Cells

In addition to generators, several other technologies can be used for powering the communications equipment. These power sources include methanol, ethanol, ammonia, and hydrogen fuel cells. To survive an EMP, fuel cells would need to be placed in shielded enclosures. With their small size (10 to 14 rack units out of a total of 44 rack units), a redundant set of hydrogen fuel cells can be placed in a shielded rack without the need for a separate building (as shown in Figure 38 and Figure 39). This leaves plenty of space for communications equipment.

The most reliable fuel cells are those that use fuel with the least contaminants. For this reason, hydrogen fuel cells are the optimal choice for critical loads. The leading companies offering hydrogen fuel cells include Altergy, Plug Power, Ballard, and Hydrogenics.

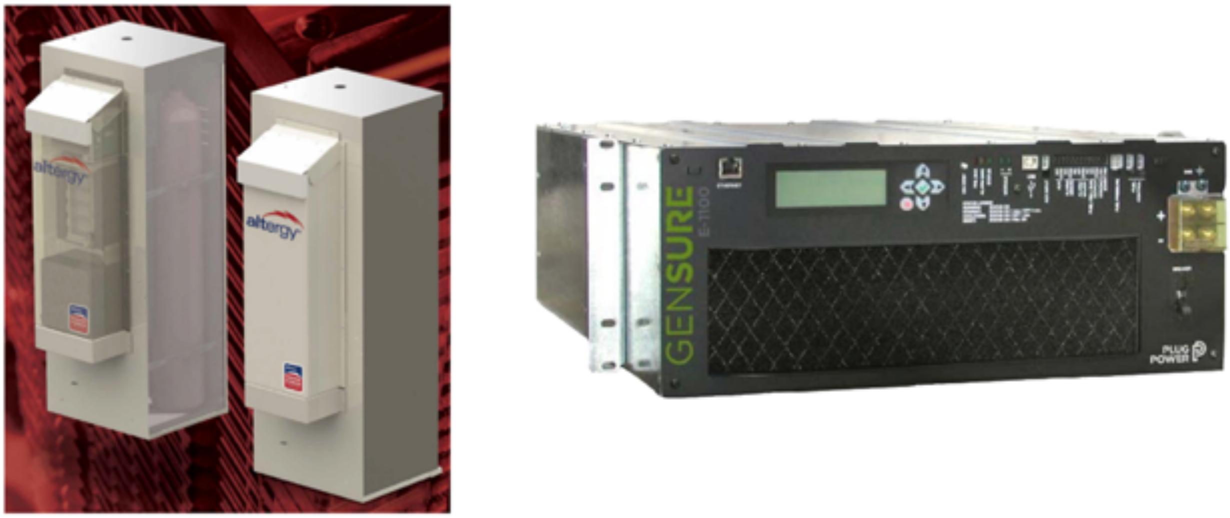


Figure 38: Hydrogen Fuel Cells (Altergy, 2020) (Plug Power, 2016)

With an electrical load of 1 kW or less for communications and control equipment, fuel cells require very little maintenance – perhaps only an annual visit to clean filters. They are a much closer match to the requirement at substations and fiber amplification points than diesel or propane generators.

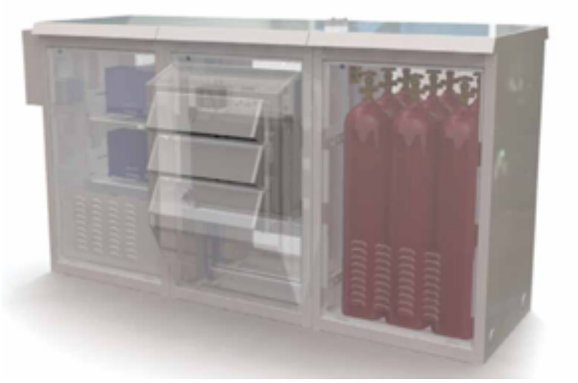


Figure 39: Hydrogen Fuel Cell System (Altergy, 2020)

Hydrogen fuel cells have the advantage of being very compact and highly efficient for power requirements up to 5 kW. Their small size reduces the cost of electromagnetic shielding. They can be rack mounted in shielded cabinets. Since they do not emit toxic or high temperature gases, the permitting process is easier than reciprocating engines. Fuel cells also offer attractive lifecycle costs as shown in Figure 40.

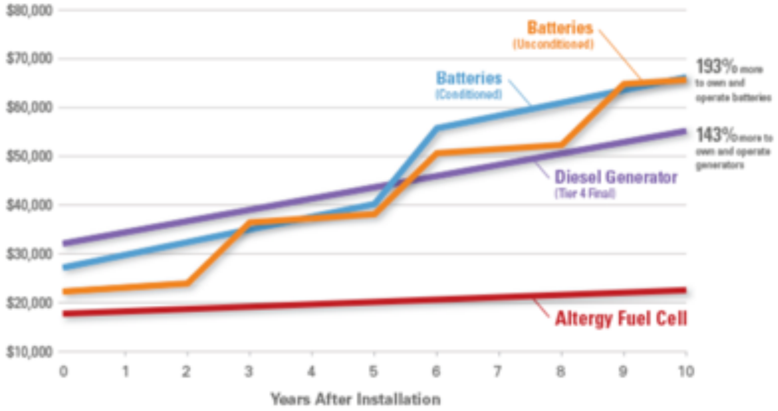


Figure 40: Lifecycle Cost Comparison (Altergy, 2020)

However, the cost and difficulty of storing hydrogen is concerning. Fortunately, carbon fiber-wrapped aluminum tanks have been developed for the transportation market. These tanks provide a portable source of fuel that can be located at substations without the need for EMP protection of the fuel tanks.

C.5.4 Hydrogen Storage

Hydrogen gas is explosive and is often considered dangerous. How can it be safely stored? How explosive is it contrasted with other fuels? Fortunately, these topics have been extensively studied. The faster a gas rises, the quicker it dissipates in the atmosphere, reducing risk to personnel and equipment. Being lighter than air, hydrogen rises at about 45 mph. Gasoline vapor and propane, alternatively, are heavier than air and present an ongoing risk.

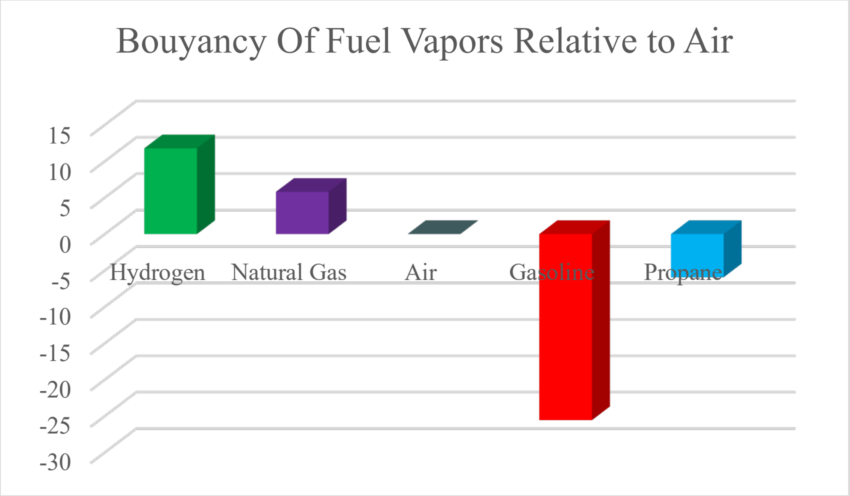


Figure 41: Comparison of Hydrogen Rise Times with Other Fuels[5]

Another important safety consideration is the explosive nature of the fuel. Gasoline is 22 times more explosive than hydrogen, as shown in Figure 42.

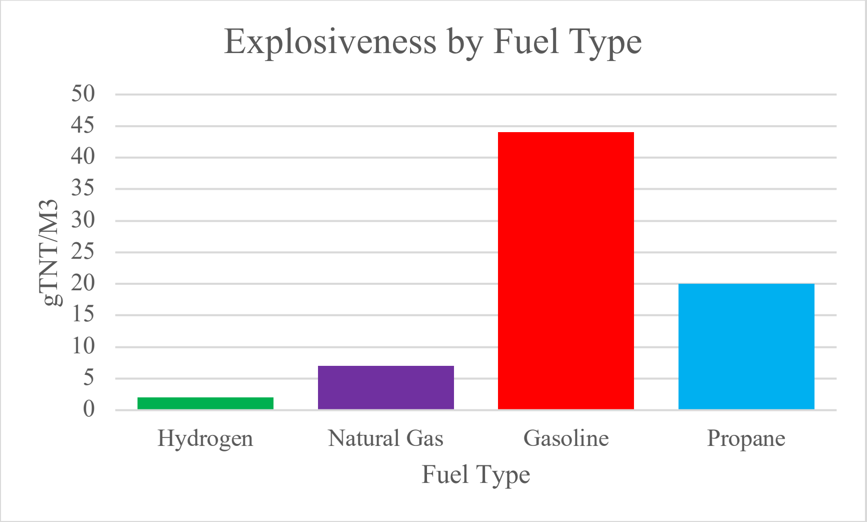


Figure 42: Hydrogen Explosiveness Compared to Other Fuels (Pearson, 2018)

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[5] Buoyancy relative to air was calculated using FB = (ρair - ρgas) × g × V, where FB = Buoyant force (in Newton); g = gravitational acceleration = 9.8066 m/s² = 9.8066 N/kg; V = volume (in m³).

Prior to being commercially offered, fuel cell solutions are tested, certified, and listed by OSHA-approved testing labs. Leading suppliers of fuel cell systems certify that they meet or exceed the requirements of:

- The State Fire and Building Codes
- NFPA 1 – Uniform Fire Code
- NFPA 2 – Hydrogen Technologies Code
- ANSI/CSA FC-1 – Standard for Stationary Fuel Cell Power Systems
- NFPA 55 – Standard for Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks
- NFPA 853 – Standard for the Installation of Stationary Fuel Cell Power Systems
- NFPA 70 – The National Electric Code (NEC)
- The International Fire Code (IFC) & resulting State Fire Codes
- Federal Communications Commission (FCC) – Part 15 Radiated & Conducted Emissions Limits

Each system, as it is installed, goes through the permitting and zoning process. The process requirements are unique to specific jurisdictions. In California, the systems are certified by the California Air Resources Board (CARB) as zero emission power generators. These zero emission systems are exempt from the permit requirements of all air pollution control and air quality management districts.

The government and private industry have invested millions of dollars in developing competing technologies for storing hydrogen. It can be stored as a liquid at extremely low temperatures in vacuum-sealed containers called cryogenic "Dewars." However, considerable loss of hydrogen occurs over time due to gasification. Hydrogen can also be stored as a solid in material such as AlH3 (ALANE), but the production cost is still quite high. Compressing gaseous hydrogen seems to be the most cost-effective storage solution. Short-term power requirements can be satisfied using steel cylinders for storage. For longer-term, high-capacity storage, medium pressure (3,000 psi, and 5,000 psi) and high pressure (10,000 psi) aluminum tanks wrapped in carbon fiber (Type 3) have been developed for the automotive industry.

Figure 43: Hydrogen Type 3 Fuel Storage System (Steelhead, 2020)

The Type 3 hydrogen storage tanks, less susceptible to hydrogen permeation and embrittlement (see Figure 43), provide a more economical solution for extended storage than the steel tanks. The cost of installing redundant 1 KW hydrogen fuel cells in a shielded cabinet with 180 days of hydrogen storage for a 350 W constant electrical load is about $120,000 per site in small quantity.

C.5.5 Stirling Engine Generators

Stirling engine generators are a viable solution to EMP-survivable power generation. They offer the advantage of using multiple fuel sources for power generation and can be cost effective when coupled with low-cost propane storage tanks. Additional effort is needed to package the power generation systems and their controls in EMP-shielded enclosures.

Heat for Stirling generators can be sourced from natural gas, propane, hydrogen, alcohol, or even wood pellets. While existing manufactures have not designed the system for EMP protection, it is possible to shield the systems or to repackage the Stirling engines in shielded cabinets. A 180-day supply of propane for a 1 kW load would require a 2,000-gallon tank with about 1,200 gallons of fuel.

Several commercial companies provide Stirling engines. Qnergy and MicroGen manufacture the Sterling engines that are incorporated into combined heat and power systems (see Figure 44). CHP systems using Stirling engines are provided by Qnergy, Combined Energy Technology, HELEC, Okofen and others. ARPA-E is investing in Sterling engines as part of its GENSETS program.

> *"A Stirling engine uses a working gas such as helium, which is housed in a sealed environment. When heated by the natural gas-fueled burner, the gas expands causing a piston to move and interact with a linear alternator to produce electricity. As the gas cools and contracts, the process resets before repeating again."* (ARPA-E, 2019)

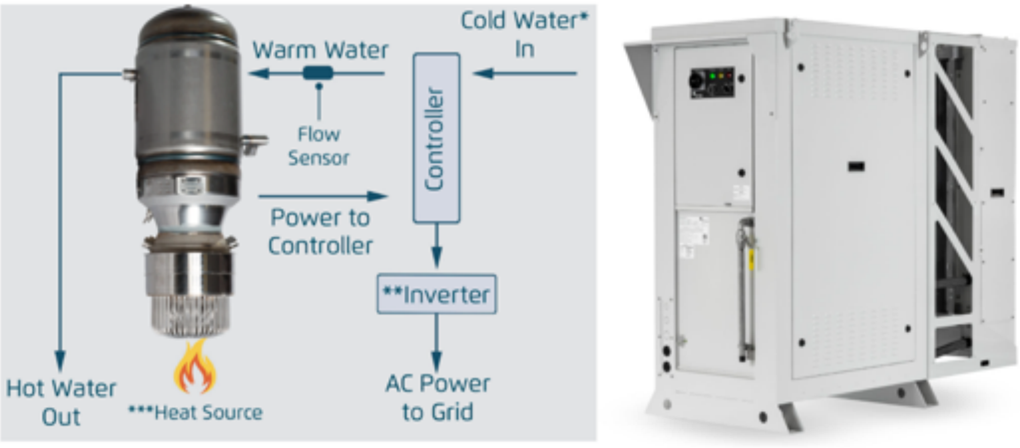

Figure 44: Stirling Engine Remote Power System (Qnergy, 2020)

C.5.6 Stored Electricity in Supercapacitors

Utilities are increasingly using supercapacitors to store energy (see Figure 45). Supercapacitors can store the rapidly varying renewable energy (e.g., solar, thermal, and wind) and charge batteries at their optimal rate. They can minimize the runtime of reciprocating generators capturing the energy from the generators and then charge the batteries at their optimal but slower rate. This combination of renewables, reciprocating generators, supercapacitors, and batteries could provide a viable solution for long-duration energy storage. Additional study is needed to verify the supercapacitor storage performance and costs. Manufacturers of supercapacitors include Skelaton, Eaton, Tesla (formally Maxwell), and several others.

Figure 45: -48V Supercapacitors (Electronic Design, 2016)

C.5.7 Solar Photovoltaic Power Systems

Long-duration power options include solar arrays stored in EMP-shielded cases that can be assembled on pre-installed mounts after an EMP event and small, shielded hydropower systems (if a river is nearby). Redundant microwave radios, ethernet routers, and programmable logic controllers (PLCs) would require about 350 W of constant power.

Figure 46: Solar Array Package (4 kW) (Wholesale Solar, 2020)

Solar Power System	Continuous Power	Adjusted Watt Hours Per Day	Lithium Battery Size (5 Cloudy Days)	PV Panels
Non-Redundant	200 W	10,074	50.4 kWh	15
Redundant System	425W	21,408	107 kWh	30

Table C.5.7. 1: Solar Array Sizing (Wholesale Solar, 2020)

It is uncertain whether photovoltaic (PV) solar cells would survive an EMP event outside a protected case. The rapid change in electric field strength may cause a piezo electric stress effect in the crystalline structure of the solar cells, leading to failure. The logistics of deploying teams to 68,992 substations to remove solar panels from shielded cases and install them on preinstalled mounts is daunting. If a second EMP event occurred after the PV solar arrays were deployed, they would likely fail.

Several companies provide packaged solar power systems. As shown in Figure 46, a solar array of 300 W industrial grade solar panels, a charge controller, Lithium-ion batteries and pre-installed mounts to power a single radio, ethernet router, and PLC.

C.5.8 Wind Turbines

Wind turbines offer another possibility for long-duration power generation after an electromagnetic pulse without the logistics of refueling, provided electronics are properly shielded. However, several factors limit the widespread use of wind turbines as a backup power source. The power generated is governed by the amount and consistency of wind at a given location on a yearly basis. It is also determined by the height of the wind turbine and the size of the area swept by the turbine blades. A five-kilowatt wind turbine to charge the supercapacitors and batteries would cost about $50,000 per site (see Figure 47).

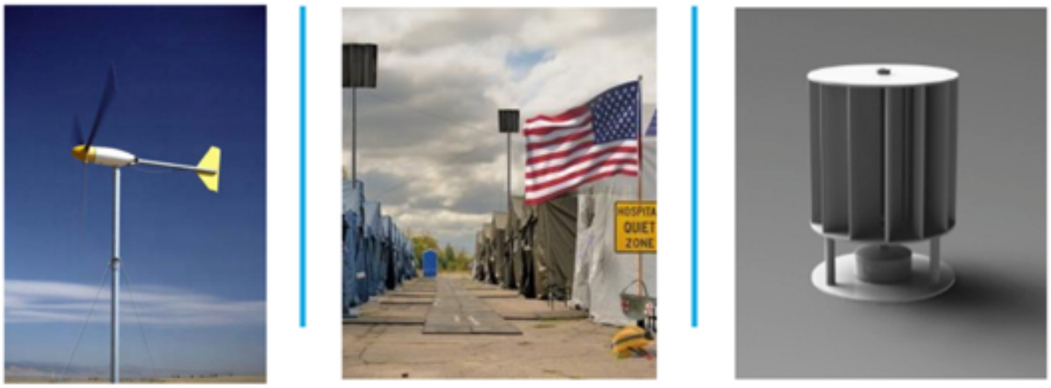

Figure 47: Wind Turbines for Substations (Bergey, 2020) (Vortexas, 2020)

Large wind turbine generators, as shown in Figure 48, have the control electronics and the generator within the enclosed hub (called the nacelle) of the structure. It may be possible to work with the turbine manufacturers to shield these components from EMP events. The power lines could be protected using power grid tubes connected to low impedance grounding grids.

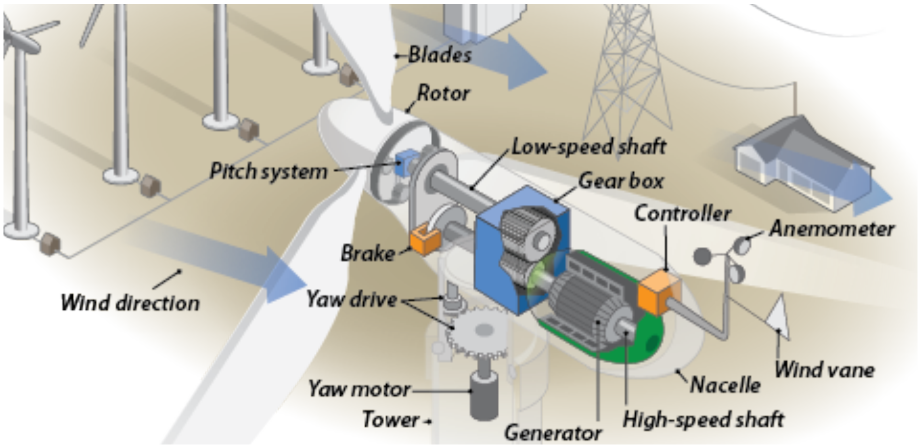

Figure 48: Wind Turbine Cross Section (Wind Energy Technologies Office, 2020)

Since wind conditions and available space vary by substation location, further research is needed to determine which substations would benefit most from wind turbines.

C.5.9 Organic Photovoltaic (OPV) Solar Cells

OPV solar cells, as shown in Figure 49, are made using Fullerenes and may be unaffected by an EMP event. Fullerenes are carbon atoms that form molecules in the shapes of hollow spheres, ellipsoids, or tubes. Since organic solar cells based on fullerenes do not contain metals, they may be less susceptible to electromagnetic pulse than traditional silicon solar cells. Additional testing is needed to verify the resilience of OPVs to electromagnetic pulses.

Figure 49: Organic Photovoltaic (OPV) Solar Cell (Epishine, 2020)

Appendix D: List of Acronyms

AC	Alternating Current
A	Amps
ADSL	Asymmetric Digital Subscriber Line
AlH_3	Aluminum Hydride (Alane)
BGAN	Broadband Global Area Network
CAT 5	Category 5 Ethernet twisted pair network cable
CME	Coronal Mass Ejections (from the Sun)
dB	decibel
dBm	decibel-milliwatts
DARPA	Defense Advanced Research Projects Agency
DTRA	Defense Threat Reduction Agency
DC	Direct Current
DFR	Digital Fault Recorder
DPR	Digital Protective Relays
DoD	Department of Defense
DoE	Department of Energy
DWDM	Dense Wave Division Multiplexing
E1	Very fast component of nuclear EMP pulse
E2	"Intermediate time" component of nuclear EMP pulse, similar to lightning
E3	Geomagnetically induced currents in long electrical or other conductors from an EMP pulse

EEI	Edison Electric Institute
EHV	Extra High-Voltage
EMP	Electromagnetic Pulse
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FL	Fault Locators
GEM	Ground Enhancement Materials
GEO	Geosynchronous Earth Orbit
GHz	Gigahertz
GIC	Geomagnetically Induced Current
Gig-E	Gigabit Ethernet Interface
GMD	Geomagnetic Disturbance
GSU	Generator Step-up (transformer)
HDSL	High Speed Digital Subscriber Line
HEMP	High-altitude Electromagnetic Pulse
HILF	High Impact Low Frequency
HUD	U.S. Department of Housing and Urban Development
HV	High Voltage
HVDC	High Voltage Direct Current
Hz	Hertz
IDU	Indoor Unit

IED	Intelligent Electronic Devices
ISO	International Organization for Standardization
kV	Kilovolt
LEO	Low Earth Orbit
LNA	Low Noise Amplifiers
LNB	Low Noise Block down converters
MEO	Medium Earth Orbit
MOV	Metal Oxide Varistor
MW	Megawatts
MWh	Megawatt-hour
NERC	North America Electric Reliability Corporation
NPR	National Public Radio
NREL	National Renewal Energy Laboratory
ODU	Outdoor Unit
OPV	Organic Photovoltaic Solar Cells
PLC	Programmable Logic Controller
PoE	Power over Ethernet (cable)
PV	Photovoltaic
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying (Modulation)
RADAR	Radio Detecting and Ranging
RTU	Remote Terminal Unit

SCADA	Supervisory Control and Data Acquisition
SER	Sequence of Event Recorder
SVC	Static VAR Compensators
SEL	Schweitzer Engineering Laboratories
SONET	Synchronous Optical Networking
TT&C	Telemetry Tracking and Control earth station
UPS	Uninterruptible Power Supply
USDA	U.S. Department of Agriculture
VHF	Very High Frequency
VDC	Volts Direct Current
VOLL	Value of Lost Load
V/m	Volts per meter
W	Watts
WIFI	Trademark for wireless fidelity
$/kWh	U.S. Dollars per Kilowatt Hour

Works Cited

Advanced Fusion Systems. (2019, December). High Power Microwave Antenna. Newtown, Connecticut, USA.

Advanced Fusion Systems. (2020, January). EMP Protected Bandpass Filter. Newtown, Connecticut, USA. Retrieved from Advanced Fusion Systems.

AFL. (2019). *AFL - Joye, Carson.* Retrieved from Optical Fiber and the Future Electric Utility: https://learn.aflglobal.com/white-papers/optical-fiber-and-the-future-electric-utility

Altergy. (2020, January). *Altergy* . Retrieved from Hydrogen Fuel Cells: https://www.altergy.com/wp-content/uploads/2017/09/Altergy_Nacelle_Data_sheet_ATP_web.pdf

Am-cor. (2020, January). *Am-cor*. Retrieved from Ferrocement Structures: https://www.am-cor.com/#hero-foot-tab-target

American Diabetes Association. (2015, December). *Diabetes Fast Facts.* Retrieved from Diabetes.org: https://professional.diabetes.org/sites/professional.diabetes.org/files/media/fast_facts_12-2015a.pdf

ARMAG, Corporation. (2020, January). *Shielded Generator Shelters*. Retrieved from ARMAG Products: https://www.armagcorp.com/products/shielded-buildings/shielded-generator-shelters/

ARPA-E. (2019, December). *Free Piston Stirling Engine Based 1KW Generator*. Retrieved from ARPA-E GenSets Program: https://arpa-e.energy.gov/?q=slick-sheet-project/free-piston-stirling-engine-based-1kw-generator

Ayemba, D. (2019, November 8). *Construction Review Online.* Retrieved from Top generator manufacturers in the world: https://constructionreviewonline.com/2017/03/top10generatormanufacturers/

Bell Performance. (2020, January). *Steps to Prevent Fuel Contamination*. Retrieved from Bell Performance: https://www.bellperformance.com/bell-performs-blog/blog/steps-to-prevent-fuel-contamination

Bergey. (2020, January). *Wind Turbines*. Retrieved from Remote Power Solutions: http://www.bergey.com

Black & Veatch. (2020, January). *2020 Black & Veatch Strategic Directions Smart Utilities Report.* Retrieved from Black & Veatch: https://www.bv.com/sites/default/files/2020-01/20%20Smart%20Utilities%20SDR_WEB.pdf

Boyle, A. (2019, February 8). *SpaceX seeks FCC approval for up to 1M Starlink satellite earth stations.* Retrieved from Geekwire: https://www.geekwire.com/2019/spacex-fcc-starlink-million-earth-stations/

Broadcast Supply Worldwide. (2018). *Broadcast Cable*. Retrieved from Andrew FSJ4-50B 1/2" HELIAX® Superflexible Foam Dielectric Cable: https://www.bswusa.com/Cable-Air-and-Foam-Andrew-FSJ4-50B-P6338.aspx

Capstone Turbines. (2020, January). *Next-Generation Microturbines*. Retrieved from Capstone Turbine: https://www.capstoneturbine.com

Center for Disaster Philanthropy. (2018, May 23). *Disaster Philanthropy, Robert Ottenhoff.* Retrieved from How $1 Invested in Mitigation Saves $6 in Future Disaster Costs: https://disasterphilanthropy.org/blog/preparedness/1-invested-mitigation-saves-6-future-disaster-costs/

Ceragon. (2017, October). *FibeAir IP-20 Platform -Utilities.* Retrieved from FIBEAIR® IP-20 PLATFORM: https://www.ceragon.com/resources/brochures/fibeair-ip-20-platform-utilities-brochure

Ciena. (2017). *A Practical Approach to Utility Network Modernization.* Retrieved from Ciena.com: https://www.ciena.com/insights/app-notes/A-Practical-Approach-to-Utility-Network-Modernization.html

Ciena. (2020, January). *Ciena Products and Services* . Retrieved from Ciena 6500-D2 Packet Optical Platform: https://www.ciena.com/products/6500-D2/

Clark, S. (2020, February 10). *Spaceflight Now*. Retrieved from Iran fails in satellite launch attempt: https://spaceflightnow.com/2020/02/10/iran-fails-in-satellite-launch-attempt/

Comtest Engineering. (2020). *ComTest Engineering BV*. Retrieved from RF Shielded Doors: https://www.comtest.eu/wp-content/uploads/2019/02/RF-Shielded-Doors-Comtest-Engineering.pdf

Cummins Power Generation. (2007). *Cummins Power Generation Power Topic #7004, Loehlein, Timothy A.* Retrieved from Maintenance is one key to diesel generator set reliability: https://www.academia.edu/11193895/Maintenance_is_one_key_to_diesel_generator_set_reliability

Defense Intelligence Agency. (2017, June). *Defense Intelligence Ballistic Missile Analysis Committee*. Retrieved from BALLISTIC AND CRUISE MISSILE THREAT: https://www.nasic.af.mil/Portals/19/images/Fact%20Sheet%20Images/2017%20Ballistic%20and%20Cruise%20Missile%20Threat_Final_small.pdf?ver=2017-07-21-083234-343

Defense Threat Reduction Agency. (2010, August). Retrieved from Collateral Damage to Satellites from an EMP Attack: https://apps.dtic.mil/dtic/tr/fulltext/u2/a531197.pdf

Delores J. Knipp1, 2. ,. (2018, October 25). *On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary, and Call to Action.* Retrieved from wiley.com: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018SW002024

Edison Electric Institute. (2020, January). *Transmission.* Retrieved from Circuit Miles of Transmission: https://www.eei.org/issuesandpolicy/transmission/Pages/default.aspx

EDSTAM, J. H. (2011, January). *Ericsson Review.* Retrieved from Microwave capacity evolution: https://pdfs.semanticscholar.org/0fe5/d05fb66b8a59e81dcdf81d389fc4c5436fbe.pdf

ElectraNet. (2020, March 11). *ElectraNet.* Retrieved from Transmission Substations: https://www.electranet.com.au/our-approach/safety/transmission-substations/

Electronic Design. (2016, August 16). *Electronic Design, Guerra, Maria*. Retrieved from Can Supercapacitors Surpass Batteries for Energy Storage?: https://www.electronicdesign.com/power-management/article/21801779/can-supercapacitors-surpass-batteries-for-energy-storage

EMP Commission. (2017, July). *The First EMP Commission.* Retrieved from RECOMMENDED E3 HEMP HEAVE ELECTRIC FIELD WAVEFORM FOR THE CRITICAL INFRASTRUCTURES: http://www.firstempcommission.org/uploads/1/1/9/5/119571849/recommended_e3_waveform_for_critical_infrastructures_-_final_april2018.pdf

Energy Information Agency. (2017). *eia.gov.* Retrieved from Distributed Generation and Combined Heat & Power System Characteristics and Costs in the Buildings Sector: https://www.eia.gov/analysis/studies/buildings/distrigen/pdf/dg_chp.pdf

Epishine. (2020, January). *Harvesting light to create a sustainable world*. Retrieved from Ambient light is wireless power: https://epishine.com

EPRI. (2019, June 15). *Transmission Resiliency Decision Support Framework.* Retrieved from Selective Deployment of Protected Communications and SCADA Systems: https://www.epri.com/#/?lang=en-US

Equipto Electronics Corp. (2020, January). *Equipto Products*. Retrieved from R6 High-End Shielded Cabinets: https://www.equiptoelec.com/products/r6-high-end-shielded-cabinets/

ETS Lindgren. (2020, March). *ETS-Lindgren's Single Knife Edge™ (SKE) Door*. Retrieved from ETS Lindgren: http://www.ets-lindgren.com/products/shielding/rf-shielded-doors/11004/1100401

Faraday Cases. (2020, January). *Faraday Cases*. Retrieved from EMP Shielded Cases: https://faradaycases.com/cases/

FCC. (2020, January). *The Rural Digital Opportunity Fund*. Retrieved from Broadband networks in rural America: https://www.fcc.gov/about-fcc/fcc-initiatives/bridging-digital-divide-all-americans

FCC. (2020, January). *Universal Service*. Retrieved from FCC: https://www.fcc.gov/general/universal-service

FCC Database. (2020, January 7). *FCC.gov*. Retrieved from Advanced License Search: https://wireless2.fcc.gov/UlsApp/UlsSearch/searchAdvanced.jsp;JSESSIONID_ULSSEARCH=16XrpVNP9VfpcQfbL1lppKJtMgKnvqxKt3QpMnRzv85ZfJZfGwXY!-1885326479!-1987816417

Federal Register. (2019, August 30). *Allocations, Common Application, Waivers, and Alternative Requirements for Community Development Block Grant Mitigation Grantees*. Retrieved from A Notice by the Housing and Urban Development Department: https://www.federalregister.gov/documents/2019/08/30/2019-18607/allocations-common-application-waivers-and-alternative-requirements-for-community-development-block

FEMA. (2017, June). *FEMA.gov.* Retrieved from Power Outage Incident Annex to the Response and Recovery Federal Interagency Operational Plans: https://www.fema.gov/media-library-data/1512398599047-7565406438d0820111177a9a2d4ee3c6/POIA_Final_7-2017v2_(Compliant_pda)_508.pdf

Foreign Affairs. (2018, June 6). *Foreign Affairs, Bruce Bechtol*. Retrieved from North Korea's Illegal Weapons Trade The Proliferation Threat From Pyongyang: https://www.foreignaffairs.com/articles/north-korea/2018-06-06/north-koreas-illegal-weapons-trade

Georgia Copper. (2020, January). *GACopper.com*. Retrieved from Why use Copper Ground Strap? : https://www.gacopper.com

Global Power Supply. (2020, January). *Global Power Supply*. Retrieved from Power Generation Calculators: https://www.globalpwr.com/power-calculator/

Harris Williams & Co. (2014, August). *Harris Williams White Paper.* Retrieved from Transmission & Distribution Infrastructure: https://www.harriswilliams.com/sites/default/files/industry_reports/ep_td_white_paper_06_10_14_final.pdf

Hunt, D. (2019, December). Mobile Radio Tower Photograph. Culpeper, VA, USA.

J. Kurtz, G. S. (2014, September). *NREL*. Retrieved from Backup Power Cost of Ownership Analysis and Incumbent Technology Comparison: https://www.energy.gov/sites/prod/files/2014/10/f19/fcto_backup_pwr_cost_of_ownership_analysis_report.pdf

Jokovlievic, S. (2003, May). *Data Collecting and Processing for Substation Integration Enhancement.* Retrieved from Texas A&M University: https://pdfs.semanticscholar.org/288c/47dff4c63a4ac0195005c4e6458e7698077a.pdf

Kappenman, J. (2010, January). *Metatech Corporation Meta-R-319.* Retrieved from Geomagnetic Storms and Their Impacts on the U.S. Power Grid: https://www.ferc.gov/industries/electric/indus-act/reliability/cybersecurity/ferc_meta-R-319.pdf

McGeehan, T. (2020, February 25). VP, E-Finity, Capstone Distributor. (D. Winks, Interviewer)

Metatech James Gilbert, John Kappenman, William Radasky, Edward Savage. (2010, January). *Meta-R-321*. Retrieved from The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid: http://www.futurescience.com/emp/ferc_Meta-R-321.pdf

Michael Gonzales, J. (2015). *The Forgotten History; The Mining Campaigns of Vietnam 1967-1973.* Retrieved from Angelo State University: https://www.angelo.edu/content/files/21974-a

NASA. (2009, March 13). *The Day the Sun Brought Darkness*. Retrieved from NASA Dr. Sten Odenwald NASA Astronomer ADNET/Catholic University: https://www.nasa.gov/topics/earth/features/sun_darkness.html

Naveh, T. (2009, October). *Ceragon Whitepaper.* Retrieved from Mobile Backhaul: Fiber vs. Microwave Case Study Analyzing Various Backhaul Technology Strategies: https://www.winncom.com/images/stories/Ceragon_Mobile_Backhaul_Fiber_Microwave_WP.pdf

NERC. (2009, November). *Energy.gov.* Retrieved from High-Impact, Low-Frequency Event Risk to the North American Bulk Power System: https://www.energy.gov/sites/prod/files/High-Impact%20Low-Frequency%20Event%20Risk%20to%20the%20North%20American%20Bulk%20Power%20System%20-%202010.pdf

NERC. (2019, July 25). *NERC EMP Task Force Workshop.* Retrieved from EMP Task Force Work Plan: https://drive.google.com/file/d/1PhzHEMdmwACVo_TQVioP-KkTZqFTyKMi/view

NIAC. (2018, December). *Surviving a Catastrophic Power Outage.* Retrieved from National Infrastructure Advisory Council: https://www.cisa.gov/publication/niac-catastrophic-power-outage-study

NIH. (2016, December). *National Institute of Diabetes and Digestive and Kidney Diseases.* Retrieved from Kidney Disease Statistics for the United States: https://www.niddk.nih.gov/health-information/health-statistics/kidney-disease

Nokia Bell Labs. (1974, November). *Outage of the l4 system and the geomagnetic disturbances of 4 august 1972.* Retrieved from The Bell System Technical Journal, vol. 53, no. 9, pp. 1817-1837: https://ieeexplore.ieee.org/document/6773728

NPR. (2017, September 3). *North Korea Brandishes What It Says Is A Missile-Ready H-Bomb.* Retrieved from NPR.org, Emma Bowman: https://www.npr.org/sections/thetwo-way/2017/09/03/548201793/north-korea-brandishes-what-it-says-is-a-missile-ready-h-bomb

Oak Ridge National Laboratory. (2010, January). *Electromagnetic Pulse: Effects on the U.S. Power Grid.* Retrieved from https://www.ferc.gov/industries/electric/indus-act/reliability/cybersecurity/ferc_executive_summary.pdf

Omni-Threat Structures. (2020, January). *Electromagnetic Pulse (EMP) Shielding*. Retrieved from The OTS EMSS – Multi-Threat Protection in a Single Structure: https://www.omnithreatstructures.com/shielding/

Pearson, M. (2018, July 12). *Ballard Hydrogen Fuel Cells*. Retrieved from Dispelling Common Hydrogen Safety Myths: https://blog.ballard.com/hydrogen-safety-myths

Plug Power. (2016, March). *Fuel Cells for Backup Power.* Retrieved from Product Catalog: https://www.plugpower.com/wp-content/uploads/2016/03/GenSureProductCatalogsm_012716.pdf

Qnergy. (2020). *Reliable Remote Power*. Retrieved from Stirling Engines: https://www.qnergy.com/remote-power/

SARA. (2017, June). *Electromagnetic Black Sky Responses of Power and Control Equipment.* Retrieved from EIS Council, Dave Fromme, John Robinson, Greg Edmiston PhD, and Andrew Mattei: https://www.eiscouncil.org/App_Data/Upload/bf84f1fb-595b-4a77-9a8d-c4ef00dc580f.pdf

Savage, E., Gilbert, J., & Radasky, W. (2010, January). *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid.*

Scientific American. (2019, September 24). *New Studies Warn of Cataclysmic Solar Superstorms*. Retrieved from Scientific American, Jonathan O'Callaghan: https://www.scientificamerican.com/article/new-studies-warn-of-cataclysmic-solar-superstorms/

Steel in the Air. (2013, April 23). *Steel in the Air - Ken Schmidt.* Retrieved from How To Build Your Own Cell Tower: https://www.steelintheair.com/building-your-own-cell-tower-checklist/

Steelhead. (2020, January). *Composite Hydrogen Storage Vessels.* Retrieved from Hydrogen Storage Cube: https://steelheadcomposites.com

The Balance. (2020, January 30). *theBalalnce.com.* Retrieved from US GDP Statistics and How to Use Them: https://www.thebalance.com/u-s-gdp-5-latest-statistics-and-how-to-use-them-3306041

Trezise, S. (2020, January 7). *PPC A Belden Company.* Retrieved from Mixing fiber and power lines in aerial fiber deployments: https://www.ppc-online.com/blog/mixing-fiber-and-power-lines-in-aerial-fiber-deployments

U.S. Department of Energy. (2015, July). *United States Electricity Industry Primer.* Retrieved from Energy.Gov: https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf

U.S. Department of Energy. (2018, March). *Annual U.S. Transmission Data Review.* Retrieved from Circuit Miles of Transmission: https://www.energy.gov/sites/prod/files/2018/03/f49/2018%20Transmission%20Data%20Review%20FINAL.pdf

U.S. Department of Energy. (2020, January). *Electric Power Monthly.* Retrieved from US Energy Information Administration: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01

U.S. Department of Homeland Security. (2020, April 7). *Homeland Infrastructure Foundation Level Data HFLID.* Retrieved from HFLID geoplatform: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-substations

U.S. Energy Information Administration. (2020, January 7). *Nearly half of all U.S. electricity customers have smart meters*. Retrieved from EIA.Gov: https://www.eia.gov/todayinenergy/detail.php?id=34012

US. EIA. (2018). *2018 Average Monthly Bill- Residential.* Retrieved from EIA.gov: https://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf

USDA. (2020, January). *USDA*. Retrieved from Reconnect Program: https://www.usda.gov/reconnect/program-overview

UTC. (2019, April). *Comments of the Utilities Technology Council.* Retrieved from UTC Network Baseline Survey—April 2019 Update: https://utc.org/wp-content/uploads/2019/04/UTC-Utility-Network-Baseline-Final.0419.pdf

Vaughan, E. (2019, September 18). *Environmental and Energy Study Institute*. Retrieved from New FEMA and HUD Grants Support Resilience to Climate Change Impacts: https://www.eesi.org/articles/view/new-fema-and-hud-grants-support-resilience-to-climate-change-impacts

Versa Technology. (2020, January 7). *Versa Technology.* Retrieved from Digital Subscriber Line Access Multiplexer - DSLAM: https://www.versatek.com/product/24-port-vdsl2-ip-dslam/

Vortexas. (2020, January). *Wind Turbines*. Retrieved from Micro & Nano Wind Energy Solutions: https://www.vortexis.com/about-us.html

Wang, T. (2019, July 30). Largest Gas and Electric Utilities in the U.S. as of April 2019.

Washington Post. (2013, October 31). *The scary Halloween solar storm of 2003: a warning for today's space weather*. Retrieved from Washington Post, Steve Tracton : https://www.washingtonpost.com/news/capital-weather-gang/wp/2013/10/31/the-scary-halloween-solar-storm-of-2003-a-warning-for-todays-space-weather/

Wholesale Solar. (2020, January). *Solar Panel Guide*. Retrieved from Off-grid Packages: https://www.wholesalesolar.com/off-grid-packages

Wind Energy Technologies Office. (2020, January). *Wind Turbines*. Retrieved from The Inside of a Wind Turbine: https://www.energy.gov/eere/wind/inside-wind-turbine

Yakel, J. (2017, March 20). *S&C Electric Company*. Retrieved from The Real Cost of a Truck Roll: https://www.sandc.com/en/gridtalk/2017/march/20/the-real-cost-of-a-truck-roll/