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The Great Solar Storm of 2012?

By Kennedy Maize

The 2009 blockbuster movie 2012 *about a global cataclysm combined Hollywood special effects with supposed predictions by Nostradamus; a Mayan calendar that ends on December 21, 2012; and a very rare planetary alignment that supposedly occurs on the same day. Hollywood producers seldom let technical accuracy get in the way of a good story, but suppose, this one time, the story has an element of truth.*

The event begins with a giant thermonuclear explosion on the sun. The fusion of hydrogen atoms swells up and bursts open on the sun's surface, spewing a stew of radiation and gas particles trapped in the solar wind. The continuous but variable flow of particles and magnetic fields from the sun creates gusts that can quickly reach Earth. Within hours, a space storm, a "coronal mass ejection" (CME), accompanied by a beautiful aurora borealis or "northern lights" display of shimmering celestial curtains, bombards Earth with geomagnetic disturbances.

The consequences are dramatic: disruptions to communications satellites, interference with global positioning systems (GPS) and air traffic control, and, most telling, taking down the high-voltage electric transmission system over wide swaths of the planet, blacking out more than 130 million people in the U.S. alone. Secondary effects due to the loss of the grid involve water system failures, severe disruptions to natural gas pipelines, factories shut down for weeks or months, food rotting in unrefrigerated warehouses, and unquantifiable costs to the world economy.

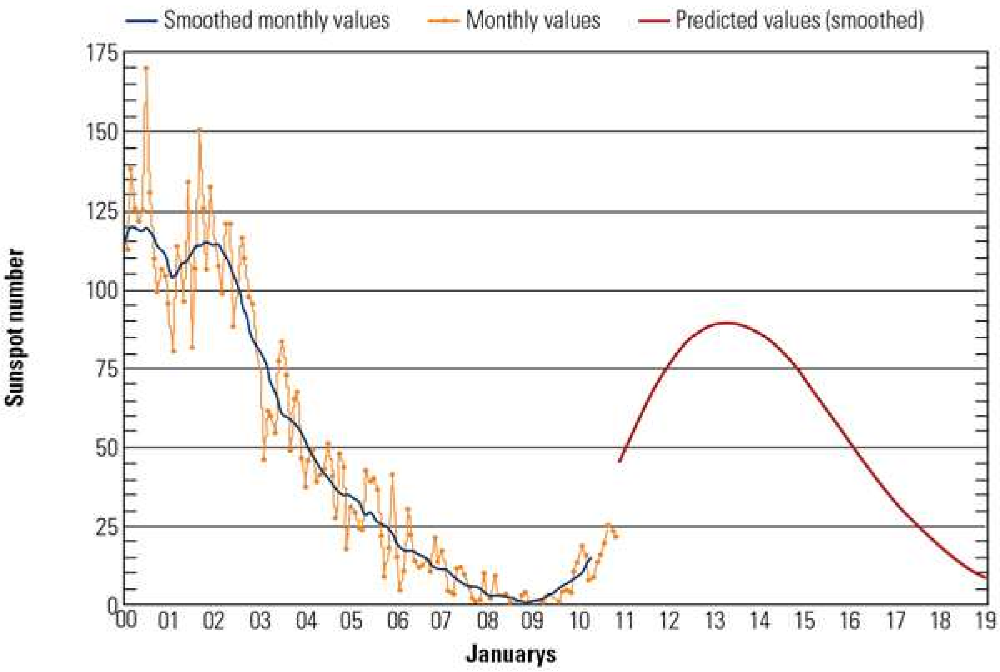
The cost of damage to the U.S. totals $1 trillion to $2 trillion. More than 300 grounded electrical high-voltage transformers in the U.S. suffer damages so serious that they need to be replaced, putting intolerable strain on an already stressed supply chain. Recovery takes as much as a decade, as the results wreck havoc with the U.S. and world infrastructure and economy.

"This is not science fiction. It is fact," says Joe McClelland, director of the office of emergency response at the Federal Energy Regulatory Commission (FERC). It has happened before, he points out, but with far less severe economic consequences. It is likely to happen again and, according to space scientists, it could happen in the next few years, as a period of unusually calm solar weather reverses, picks up energy, and gets nasty. Many predictions suggest that the "big one" could come this year or next.

Solar Storms Could Strengthen

The effects of solar storms have been the subject of numerous recent studies and analyses, including sophisticated computer simulations, funded by the electric industry and the government. There is much studying of once and future geomagnetic storms and what to do about them. It isn't clear that these studies, serious as they have been, will offer any concrete protections to the electric infrastructure in the event of a large solar geomagnetic storm. Predicting solar storms appears to be, in the reckoning of one industry veteran, "a crap shoot."

By many indications, our globe may be entering a period of greatly increased jeopardy from solar attacks. Solar activity, as astronomers have known for centuries, follows a roughly 11-year cycle, heralded by visible disturbances on the surface of the sun, known as sun spots (Figure 1). Sun spot activity shows that today the sun is at the end of a rather extended period of little activity, a "solar minimum."



1. Stormy weather coming. The cyclical nature of the number of sunspots is predictive of the severity and number of expected solar storms—more sunspots mean more solar storms of increasing intensity. Data collected through November 2010 are shown, with predicted values in red. According to the Solar Cycle 24 Prediction Panel, the minimum of the current 11-year cycle occurred in December 2008. *Source: NOAA*

National Oceanic and Atmospheric Administration (NOAA) physicist Douglas Biesecker noted an increase in sunspot activity in early 2008, which he described "as like the first robin of spring. In this case, it's an early omen of solar storms that will gradually increase over the next few years."

The fear shared by scientists at the National Aeronautics and Space Administration (NASA) and NOAA is that our planet could be entering a particularly vicious "solar maximum." The sidebar describes the various satellites that are keeping an eye on the sun.

Space Weather Watchers

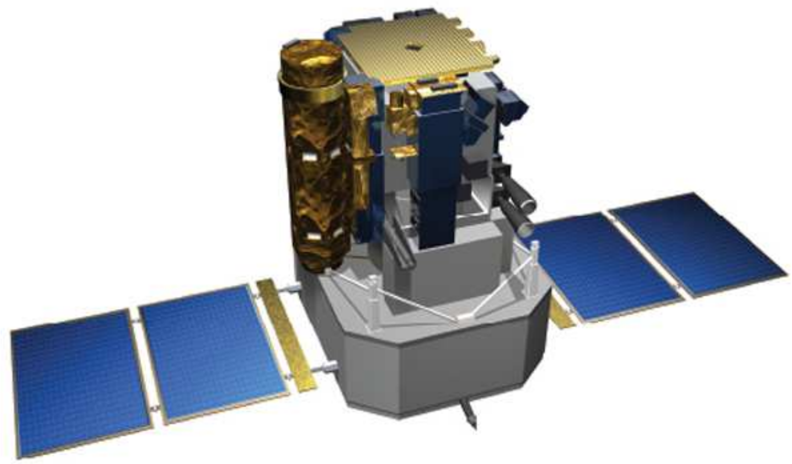
The National Oceanic and Atmospheric Administration (NOAA) manages the Space Weather Prediction Center as part of the National Weather Service and has a separate website (http://www.swpc.noaa.gov/elecpower/) that provides electric utilities with alerts and space weather forecasts. Although the center uses data from multiple satellites—including ACE and STEREO, described below—NOAA is unable to provide predictions fast enough that they would be useful to the power industry, according to industry officials.

NASA also attempts to provide space weather forecasts. Several space satellites that are managed by NASA watch Earth's sun, attempting to learn about the little-understood phenomena of solar eruptions and solar storms. One goal is to provide warning of potentially catastrophic storms with enough lead time that humans can take preventive action.

Four primary satellites continuously watch the sun and report myriad data daily. In general, each satellite is purpose-built to collect particular data. The data collected by each satellite, including photographs and videos, are reported daily on web pages accessible by the public.

SOHO

The oldest sun-gazing satellite, launched in 1995, is SOHO, the Solar and Heliospheric Observatory. It was developed jointly by the European Space Agency and NASA and is flown by NASA out of the Goddard Space Flight Center in Maryland, near Washington, D.C. This satellite moves around the sun in a dance step with Earth at the L1 Legrangian Point. According to a NASA fact sheet, the combined gravity of Earth and the sun keeps the satellite locked in a direct line between the sun and our planet, about 1.5 million kilometers (km) away, providing an uninterrupted view of the ultimate source of all Earth's energy (Figure 2).



2. Eye in the sky. The SOHO satellite was launched, according to NASA, to "study the sun from its deep core to the outer corona and the solar wind." The satellite, launched in 1995, weighs about 2 tons and is about 25 feet across. *Source: NASA*

SOHO tries to answer three fundamental questions about the sun: What are the structure and dynamics of the sun's interior? Why is there a solar corona, or halo, and how is it heated to temperatures of about 1 million degrees C? Where does the solar wind come from, and how does it accelerate?

ACE

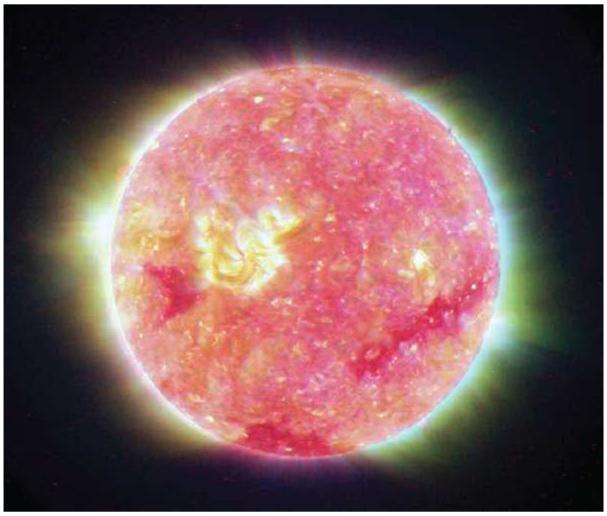
Launched in 1997, NASA's ACE (Advanced Composition Explorer) satellite provides real-time data used in NOAA's Space Weather Prediction Center for forecasts and warnings of solar storms. It, too, operates some 1.5 million km from Earth near the L1 point and is equipped to stay in orbit until 2024. Goddard also flies the ACE craft.

ACE features an array of equipment that includes a cosmic ray isotope spectrometer to determine the chemical isotopes that make up galactic cosmic rays; two spectrometers, each tuned for a different set of measurements, to analyze the chemical composition of the solar wind and intersteller matter; an ultra-low-energy isotope spectrometer to measure ion flux; electron, proton, and alpha particle monitors; and a magnetometer.

STEREO

Launched in 2006, NASA's STEREO (Solar Terrestrial Relations Observatory) provides a three-dimensional look at solar phenomena. Two nearly identical observatories—one ahead of Earth in its orbit and the other trailing behind—trace the flow of energy and matter from the sun to Earth. They reveal the 3-D structure of coronal mass ejections, the violent eruptions of matter from the sun that can disrupt satellites and power grids.

Johns Hopkins University's Applied Physics Laboratory outside Washington, D.C., built and operates STEREO. According to a Johns Hopkins fact sheet, each of the observatories is about the size of a large wooden desk and has solar photovoltaic power arrays about the length of a large school bus (Figure 3). Data from the twin observatories "will allow scientists to track the buildup and liftoff of magnetic energy from the Sun and the trajectory of Earth-bound coronal mass ejections in 3D," says the Baltimore-based university.



3. Visualizing solar storms. STEREO captures a mosaic of ultraviolet images in different wavelengths and can then combine them into a single 3-D figure, as shown. Each wavelength allows scientists to study different feature of the sun. If you have a pair of 3-D glasses, you may want to watch a 3-D video of the sun prepared using STEREO images. Go to www.nasa.gov and search on "STEREO". *Source: NASA*

NASA has an iPhone app, 3D Sun, that uses STEREO data to allow users to rotate our home star, zoom in on active regions, and monitor solar activity. It is available from the Apple app store or from http://3dsun.org.

AMPERE

Last August, the Johns Hopkins physics lab, Boeing Co. and Iridium Communications announced a new system that uses commercial satellites to monitor solar activity. In a world of snazzy acronyms, this system is known as AMPERE, for Active Magnetosphere and Planetary Electrodynamics Response Experiment. The system is said to provide real-time magnetic field measurements to forecast space weather with data gathered from the new instruments mounted on Iridium's fleet of commercial communications satellites. The project is funded by a $4 million National Science Foundation grant. A press release claims, "This is the first step in developing a system that enables 24-hour tracking of Earth's response to supersonic blasts of plasma ejected from the Sun at collection rates fast enough to one day enable forecasters to predict space weather effects."

Storm Crashes Canadian Grid

What happens when a solar storm strikes somewhere on our planet? In early 1989, a solar storm—not a particularly severe event by historical records—erupted, creating a gust in the solar wind that reached northern Canada in a matter of days. The arrival of the solar particles caused severe disturbances in the planet's magnetic field. That was the beginning.

Here's how a NASA web site (http://www.nasa.gov/topics/earth/features/sun_darkness.html) describes what happened: "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. The solar flare that accompanied the outburst immediately caused short-wave radio interference, including the jamming of radio signals from Radio Free Europe into Russia. It was thought that the signals had been jammed by the Kremlin, but it was only the sun acting up!"

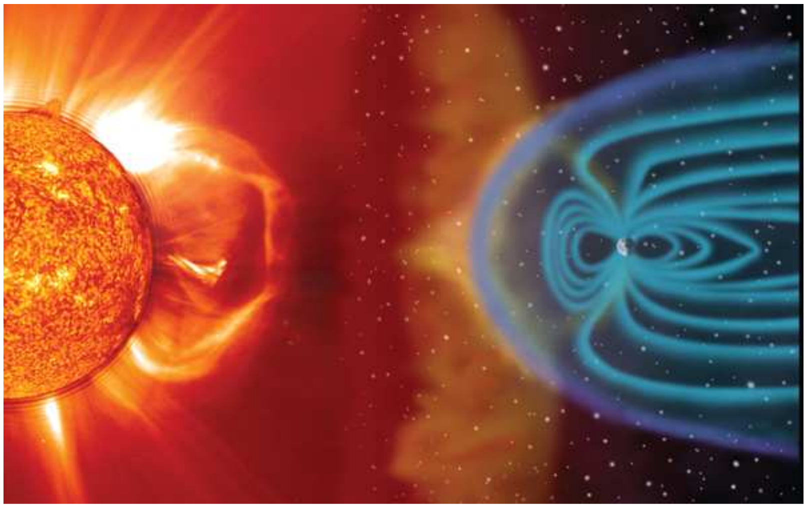
On March 13, 1989, notes a NERC report, seven static VAR compensators on Hydro-Québec's (HQ) giant La Grande high-voltage transmission network shut down in a matter of seconds. Induced direct current from the solar storm caused the transmission system voltage to drop, frequency to rise, and the line to trip off. The rest of the HQ transmission system collapsed in seconds. It took nine hours to restore 18,000 MW of power to the network. The solar storm left considerable wreckage in its path, including two La Grande 4 generating station step-up transformers, thyristor and capacitor banks at several units, and static VAR compensators across the system that were damaged or destroyed.

The damage was not confined to the Canadian system. Perhaps the most chilling effect of the storm was a thousand miles away in New Jersey, where the 1,160-MW Salem 1 nuclear power plant sits on an artificial island at the mouth of the Delaware River, along with two other nuclear units. The solar storm induced current on the PJM 500-kV transmission system, which damaged the Salem Unit 1 step-up transformer, resulting in "large melted masses of copper and copper shot." The transformer's winding insulation confined the damage, and the plant did not trip off during the solar attack. Engineers discovered the damage after the storm, but the transformer had to be replaced, at a cost of millions of dollars.

The effects on the North American electrical grid were profound. According to NASA astronomer Sten Odenwald, "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 Authority 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.

"In space, some satellites actually tumbled out of control for several hours. NASA's TDRS-1 communication satellite recorded over 250 anomalies as high-energy particles invaded the satellite's sensitive electronics. Even the Space Shuttle *Discovery* was having its own mysterious problems. A sensor on one of the tanks supplying hydrogen to a fuel cell was showing unusually high pressure readings on March 13. The problem went away just as mysteriously after the solar storm subsided."Solar Tsunami Coming

A 1990 North American Electric Reliability Council (now the North American Electric Reliability Corp., NERC) report analyzing the 1989 solar storm defined the physics of a solar disturbance (Figure 4). "As the solar particles arrive at the earth," said the report, "they cause rapid fluctuations of the earth's geomagnetic field. This, in turn, produces an induced earth-surface potential and geomagnetically induced currents, or GIC. GIC appears as a quasi-dc current (an ac waveform with a period of several minutes), and for all intents and purposes, appears as dc to the bulk electric system. The consequences of this dc current are to drive transformer cores into saturation. This, in turn, causes significant heating from stray flux, increases var losses that depress system voltages, and can damage the transformer itself."



4. Electrical connection. According to NASA, “Solar storms, which occur frequently, can disrupt communication and navigational equipment, damage satellites, and even cause blackouts.” In this artist’s view of a solar storm, the purple line indicates the bow shock, the outer edge of the magnetosphere; the blue lines surrounding Earth represent its protective magnetosphere. “The magnetic cloud of plasma can extend to 30 million miles wide by the time it reaches Earth. The magnetic field orientation of the coronal mass ejection (CME) is a major factor as to whether the Earth will suffer many consequences from any given CME. After a CME blasts from the Sun towards Earth, a cloud of charged particles impacts our magnetosphere in 2 to 4 days. Thus, the Earth is electrically connected to the Sun,” explains NASA. *Source: NASA*

In the flat language of engineering, the NERC analysis adds that the induced currents “can precipitate a multiple-contingency incident, which, under certain operating conditions, can jeopardize the integrity of the bulk electric systems in North America. Specifically, harmonic currents can cause overcurrent relays to trip capacitor banks because capacitors offer a lower impedance path for harmonics. Similarly, static var compensators can trip for over-current or over-voltage protection.” The complex events resulting from the induced currents can take generators down along with the grid, as generators “are not immune to harmonic current.” Even units that don’t trip “are susceptible to damage from turbine blade vibration.”

There is now evidence that the 1989 storm had impacts far beyond North America. A June 2010 NERC study of power system risks (http://www.nerc.com/files/HILF.pdf) noted, “Large geomagnetic storms can have a global reach and produce impacts to other developed power grids around the world. For example in England, the March 1989 storm is suspected to have caused damage to two 400kV transformers. The operators of the power grid in England also understand that, since 1989, their power grid has become significantly more dependent on transmission system static var and switched capacitance devices for system voltage regulation, thus making their system more vulnerable to future geomagnetic storms. Even recent and much lower intensity storms, such as those in late October 2003, provide evidence of increasing vulnerability.” A minor 2003 storm even reached the Southern Hemisphere, according to NERC, producing “lower intensity, but long duration GIC disturbances in South Africa” that “caused permanent damages and loss of 15 EHV transformers in the [South African] Eskom system.”

Remarkably, the 1989 solar storm was not particularly ferocious. As Luke Van der Zel of the Electric Power Research Institute told *POWER,* “In historical context, 1989 was minor. There is evidence that larger storms have been seen.” In 1859, the largest known storm, called the “Carrington Event,” struck Earth. A 2009 National Academy of Sciences workshop on space weather described this 1859 storm as “by several measures the most severe space weather event on record. It produced several days of spectacular auroral displays, even at unusually low latitudes, and significantly disrupted telegraph services around the world. It is named after the British astronomer Richard Carrington, who observed the intense white-light flare associated with the subsequent geomagnetic storm.”

More to the modern point, another gigantic storm struck the planet in May 1921, causing substantial destruction. Government experts have defined the 1921 storm as a 1-in-100-year event, which doesn’t mean it can’t happen more frequently than that but simply gives an indication of its severity. In addition to the 1989 storm that took down Hydro-Québec, a minor solar storm in October-November 2003 took down the U.S. Federal Aviation Administration's new GPS-based navigation system for 30 hours and damaged electrical systems from Scandinavia to South Africa.

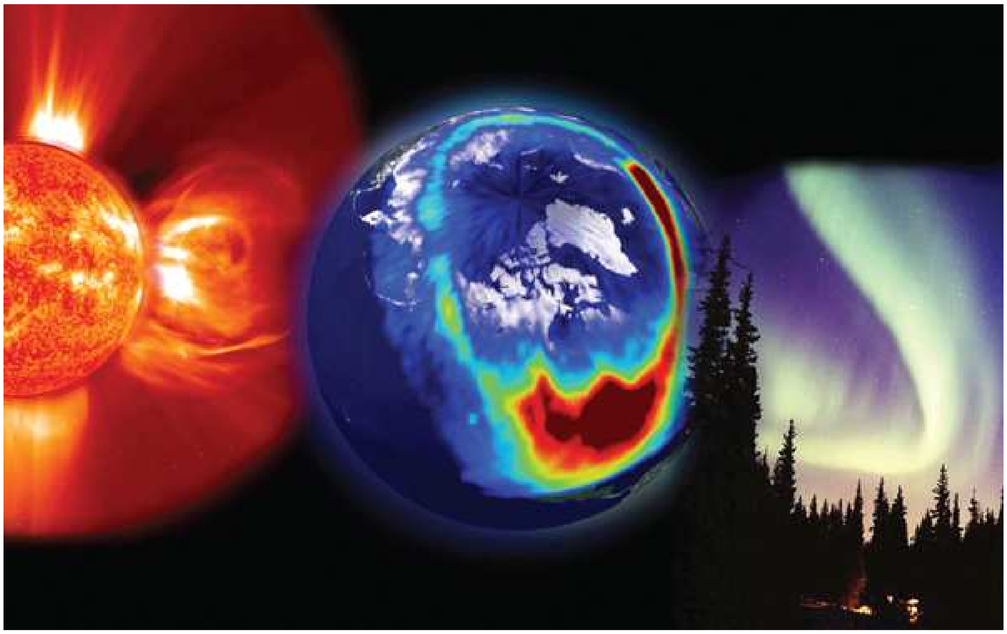
Modern storms have caused and potentially can cause much more damage and disruption than earlier events, because electrical and electronic infrastructures around the world are more ubiquitous, complex, and connected. NASA scientist Tony Phillips notes that "power grids may be more vulnerable than ever. The problem is interconnectedness. In recent years, utilities have joined grids together to allow long-distance transmission of low-cost power to areas of sudden demand." Interconnectedness, Phillips observes, "makes the system susceptible to wide ranging 'cascading failures.'"

Solar storm expert John Kappenman adds that larger, longer, and bigger transmission systems add to the vulnerability to GICs, by reducing the resistance of the grid. "The miles of high-voltage transmission voltage in the U.S. have increased by a factor of 10 over the last 50 years," Kappenman said in an interview. "We now have a much larger antenna in place."

To address the modern impacts of solar storms, NASA commissioned a National Academy of Sciences 2008 report, "Severe Space Weather Events—Understanding Societal and Economic Impacts" (at http://www.nap.edu search for report 12507). A team led by Kappenman modeled the potential effects of the May 1921 storm on the modern U.S. system. That study, which is the basis of all further analysis to date, found that the risks involved loss of more than 350 high-voltage transformers and power outages to more than 130,000 million Americans. The loss of electricity would spread across the physical infrastructure and would include "water distribution affected within several hours; perishable foods and medications lost in 12-24 hours; loss of heating/air conditioning, sewage disposal, phone service, fuel re-supply and so on."

Globally Unprepared

Is the world ready for these sorts of events? Specifically, is the U.S. electrical system, the most highly developed in the world, equipped to prevent or cope with a disastrous solar storm? The question goes to both the engineering of the physical power system and the intellectual and regulatory environment that surrounds the physical system. The answer is far from obvious. Although the threat of geomagnetic storms is well understood in the electric industry, and much effort is being devoted to understanding and preparing for this troubling contingency, whether those efforts will prove protective or able to address the adverse consequences is unclear (Figure 5).



5. Three views of space weather. NASA notes that there are three principal "visual" elements of space weather. With the help of satellite imaging, we are able to "see" the surface of the sun and CME events (left), the ultraviolet activity in Earth's atmosphere (center), and, under the right atmospheric conditions, aurora. *Source: NASA*

The Electric Power Research Institute (EPRI) has been devoting considerable effort to studying geomagnetic storms since the 1989 event. EPRI has produced voluminous work on the impacts of solar storms on electric systems, working through its SUNBURST project, which aims to "monitor, study, and mitigate" geomagnetically induced currents on the power grid. A late 2008 update on SUNBURST from EPRI warns, "With the solar cycle just passing the minimum and solar storm activity at a 50-year record low, it is easy to temporarily forget about solar storms and GICs. However, the new cycle has started, and predictions indicate that the next solar peak could be 30-50% higher than the peak of the last cycle."

Although EPRI can provide invaluable information, implementing the work of the industry's research arm is the responsibility of individual utilities, and each storm event will be different. That means, noted EPRI's Van der Zel, that contingency planning is difficult, requiring both individual utility effort and regional cooperation. "Every storm is different and difficult and complex to model," he said. In addition, "every utility's generation and transmission configuration is unique and each transformer has its own overlay of risk."

Complicating the response picture, solar storms, though potentially catastrophic, are not very predictable, in either frequency or strength. They represent what the industry has come to call "high-impact, low-frequency" (HILF) risks. Solar storms get grouped under this rubric with electromagnetic pulse events, which might be caused by the detonation of atomic bombs by an enemy hoping to take down the high-voltage grid—an added complexity for utility response planning. Other HILF risks in the utility planning process include the more mundane, such as conventional weather effects, including tornadoes and hurricanes.

Ed Legge at the Edison Electric Institute, which represents U.S. investor-owned electric utilities, said, "The whole idea is, how do you build for something where you don't know what the severity will be? How do you manage the risk? Do electric customers need to start paying extra?" Legge added that utilities have already spent large amounts on preparations for HILF risks, but passing costs on to customers, either in advance, or after a catastrophe, will be difficult in a political environment characterized by what he terms "an anti-rate-increase fervor." Legge said, "When it comes down to it, it comes down to what state regulators are willing to do. They are the place where we have to recover the costs."

The National Association of Regulatory Utility Commissioners, the Washington lobbying group for state regulators, is well aware of the issues presented by solar storms and has been working with it members, NERC, and other groups, such as the National Association of State Energy Offices, the Department of Energy (DOE), and the Department of Homeland Security (DHS). But regulators are caught in a priority trap, one that also ensnares utilities. More visible and immediate issues, such as tree trimming and conventional storm response, dominate the daily regulatory agenda in the area of emergency response.

FERC, working with the DHS, would be at the front line of a response to a major solar storm. But the agency says it lacks authority under the Federal Power Act to take decisive action in response to a solar emergency in a balkanized industry where the lines between federal and state authority are vague and controversial. The DOE, which follows this issue through its Office of Electricity Delivery and Energy Reliability, can fund research and development (R&D) to prevent damage, but its role is limited beyond that.

Congress has also gotten into the act, driven both by FERC's professed need for more authority over state actions in an emergency and concerns from the insurance industry. Last April, insurance giant Zurich Services Corp. published an analysis of the exposure of various industries to solar storms, including the prospect of replacing large high-voltage, grounded transformers at $10 million a pop. The study concluded that a large solar storm would be an event "beyond insurance." That prompted some in the 111th Congress to take up the issue.

Rep. Roscoe Bartlett (R-Md.) was the chief sponsor of a bill—H.R. 5026, known as the "GRID Act"—that would have given FERC the authority it says it needs to respond to a solar storm emergency. The bill passed the House unanimously last year, but the Senate Energy Committee, working on legislation aimed at electromagnetic pulse protection, failed to include solar storms in its bill. Nothing passed the last Congress, but there likely will be an attempt to resurrect legislation in the new Congress that convened in January.

In the meantime, EPRI and the DHS are working on a project to design prototype recovery transformers that could temporarily replace damaged equipment after a storm. As described at an online conference last December, the Recovery Transformer

(RecX) Project would build and pre-position truck-mounted single-phase 345-kV transformers as temporary fixes if a conventional three-phase, 345-kV machine were damaged. The idea, says the DHS, is to design a transformer "that is smaller and easier to transport and quick to install. Eventually, the project would produce solid-state transformers that are smaller and lighter and could be transported by helicopter. So far, according to several officials, the federal government has put up about $20 million for R&D for the RecX Project.

But deciding to build, buy, and preposition the backup transformers, note government officials, is a matter for the private sector, using private funds. That triggers the panoply of problems associated with the U.S. power sector, including multiple entities, sector rivalries (such as those between public power and the investor-owned utilities), and blurred jurisdiction.

Is all the current activity sufficient to protect the country in case of a solar storm of serious magnitude? Solar storm chaser Kappenman has doubts. "The problem is, today's power grid has not really been exposed to these large storms," he said. The industry plans are all based on storms of the magnitude of the 1989 event, but that's the wrong target, said Kappenman. "We now understand that storms 10 times worse can occur and have occurred. We are operating against an unprecedented challenge. This is the largest natural disaster the country could face and it is certain to happen, given enough time."

— ***Kennedy Maize*** *is executive editor of MANAGING POWER and a POWER contributing editor.*

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