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# Creating Resilience for an Increasingly Complex Electric Power System

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***The electric power sector, its regulators, and the public face the challenge of strengthening the sector's resilience against rare and devastating threats. These threats often extend beyond the electric sector, impacting other critical national infrastructure and communities. Determining the appropriate resilience measures to take and justifying their costs presents a significant challenge. The electric sector's evolving and increasingly complex nature and its growing interconnectedness with other intricate systems seriously challenge vulnerability assessments and resilience strategies. Compounding this issue is the difficulty in motivating investments to address extreme risks, as their infrequent occurrence can lead to a perceived lack of urgency.***

***Traditional cost-benefit and reliability analyses, the power sector's standard tools, prove inadequate for evaluating extreme risks within this increasingly complex system. A more appropriate approach is required to assess vulnerabilities and implement effective solutions. Complex Systems Science, which accounts for the evolving behaviors of the electric system, offers a promising alternative. This approach points toward an innovative grid architecture, the Resilient Community Grid, designed to address both reliability and resilience challenges created by both interdependence and the emerging complex behaviors of the modern electric grid.***

Extreme and rare threats to the rapidly-evolving electric power system can have ruinous impacts on society. These threats may arise from natural conditions such as severe weather, wildfires, earthquakes, solar flares causing geomagnetic disturbances volcanic eruptions, or coastal area tsunamis. Some threats may be manmade including physical or other types of attacks including cyber, electromagnetic pulse, or combinations. These can severely impact the electric power system, other critical infrastructure, and the public. Industry, regulators, and policy makers are increasingly aware of such threats and must make difficult investment decisions to improve resiliency.

Growing interdependence among the electric power system and other critical infrastructure sectors that support and depend on electricity increases the likelihood of ruinous impacts. The impact of such threats is intensified by the potential for cascading failure of an increasingly complex set of intertwined critical infrastructure networks. These networks include communications, natural gas, data, transportation, water, and wastewater. Extreme events that disrupt electricity could impact critical infrastructure dependent on it.

**What is Ruinous Impact?**

***Ruin,*** in risk analysis, is harm that is so severe that it prevents recovery. The harms captured by cost-benefit analyses are those with the opportunity for recovery with minimal to no lasting damage, such as a brief power outage that causes an inconvenience to end users as well as repair costs for the provider. Ruin is not captured by such analyses and is irreversible. Interdependencies and other vulnerabilities in the electric system make widespread, irreversible harm possible. This is a risk to power companies and infrastructure, but even more so to society.

Society is now so dependent on electricity that even disruptions that do not meet the risk-analysis criteria for ruin can create profound and long-lasting public health, economic, social, and political impacts.

## What is Resilience for the Electric Power System?

Resilience as used for the electric power system has many definitions and no consensus exists on exactly what this important concept means and how it differs from reliability.[1] Still, these definitions emphasize the abilities to withstand, adapt to, and recover from disruptions, generally including severe disruptions.

The focus of this paper is on resilience from rare and catastrophic threats including the abilities to withstand, adapt to, and recover from disruptions whether they are natural, manmade, or combinations. Figure 1 shows the relationships of different types of events and their impacts. The most extreme are complex and catastrophic black sky outages, illustrated on the right side of Figure 1. These are characterized by long-duration, wide-area power failures resulting in catastrophic and ruinous impact consequences. Unlike more common reliability events, which occur with sufficient frequency to enable statistical probability estimation of outages, black sky outages are infrequent and potentially unprecedented, making statistical prediction based on historical data impossible.

The unexpected happens; many electric grid and critical infrastructure facilities may be impacted (including potentially some outside the directly impacted area), and the impacts of interdependence become apparent, especially under evolving conditions.

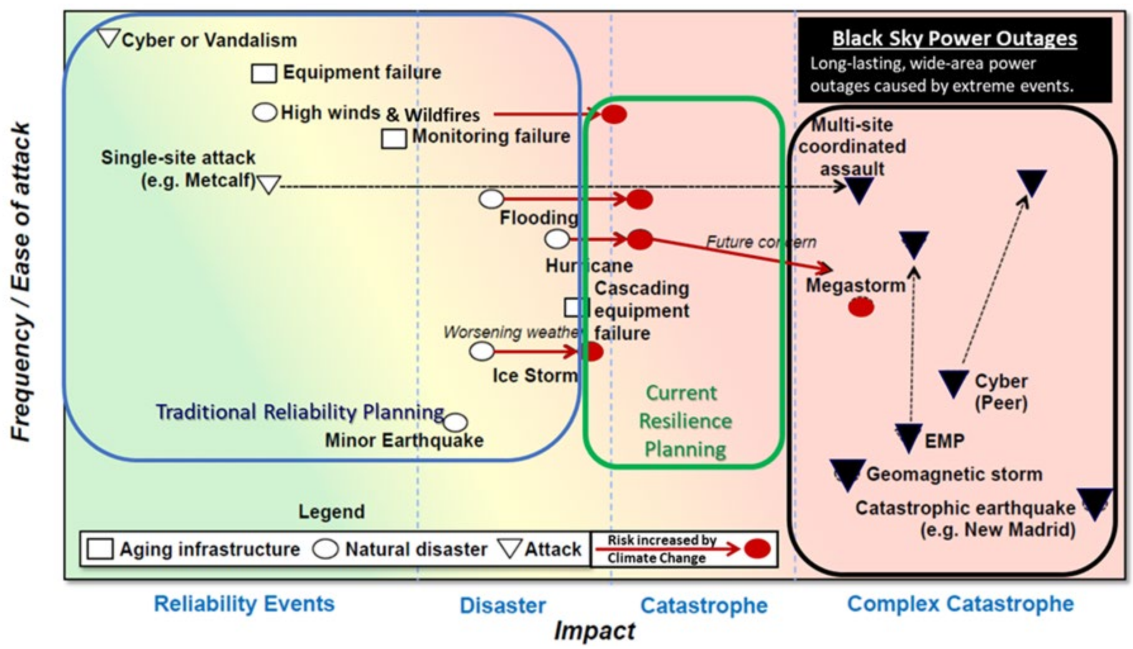


**Figure 1. Electric Reliability and Resilience, From Minor to Black Sky Outages**

Source: OnGrid Options, LLC based on Erik Limpaecher, "Resilient Energy Systems: Independent Infrastructure and Emergency Response," MIT Lincoln Laboratory, September 14, 2017.

Extreme outages and especially black sky outages pose both perception and institutional challenges. Their unprecedented and rare nature often leads to disbelief and underestimation of

[1] Organizations with different resilience definitions include the US Department of Energy, the Federal Energy Regulatory Commission, the North American Electric Reliability Council, the Institute of Electrical and Electronic Engineers, the National Infrastructure Advisory Council, the North American Transmission Forum, and the National Academy of Sciences. Some of these organizations even have internal groups with different definitions. Disagreement on definition makes the broad acceptance of any metrics for resilience even more difficult.

their likelihood.[2] The significant effort and cost of preparedness may further contribute to not prioritizing readiness. Despite this, these events do happen. Building resilience is crucial to mitigating the devastating consequences of rare but high-impact risks. Electric power faces many risks of this type, and these risks are amplified by numerous interdependencies.

## Challenges to Resilience Decision Making

The power industry and regulators are grappling with how to prioritize resiliency investments in the face of evolving challenges, but they do not have an effective analytical method. Widely-used methods for measuring reliability use statistical indices and cost-benefit analysis.[3] These methods are insufficient for managing extreme risks. Reliability indices are based on historical data of common minor events and fail to account for rare catastrophic events, rendering these metrics irrelevant. Cost-benefit analyses of rare ruinous events would rely on speculative estimations of unknowable probabilities, impacts, and recovery, and fail to capture potentially ruinous outcomes. Advanced techniques such as Bayesian statistics and real options analysis share these limitations. While these methods produce seemingly precise data, they ultimately mislead decision making regarding extreme risks, creating a false sense of accuracy, "the tyranny of illusory precision."

The absence of a reliable evaluation method is increasingly apparent, especially as stakeholders promote their own resources for grid resilience while simultaneously criticizing competitors, especially after outages.[4] Compounding this, there's a growing understanding of the grid's vulnerabilities and interconnectedness. The industry and regulators are now recognizing the potential for catastrophic, widespread outages—black sky events. Those that are most recognized because they have repeatedly occurred have been caused by severe weather—Superstorm Sandy in the Northeast, Hurricanes Fiona and Maria in Puerto Rico, and Winter Storm Uri in Texas. Still, there are other risks including flaws in the electric system, for example, an unexpected series of protective relay operational flaws caused a cascading outage in the US Northeast in 2003.[5] In April 2025 a widespread outage occurred throughout the Iberian Peninsula and southern France due to power plants not providing the voltage control for which they had contracted and then some plants going offline due to overvoltages.[6] The 2011 earthquake and tsunami that hit the Fukushima nuclear power plants and its local region caused a complex and long-lasting disaster with global implications.[7] The electric grid faces other threats with the potential for complex risks, for example, from combinations of cyberattacks and physical assaults. Russia, for example, has launched numerous physical and cyberattacks both before and after its 2022 invasion of Ukraine.[8]

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[2] This is simply human nature. For the long history of disbelief in rare extreme events see Nassim Nicholas Taleb, The Black Swan, Random House, 2007. A "black swan" is an unpredictable event that has significant consequences and is often rationalized in hindsight as if it were predictable. Electric power has many potential black swans.

[3] Reliability indices include SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), and CAIDI (Customer Average Interruption Duration Index).

[4] A prime example of finger-pointing occurred after Winter Storm Uri in February 2021 which left 4.2 million people without power in the South-Central states, including 3.5 million in Texas alone. Operators of natural gas power plants pointed to wind energy problems as the cause while wind energy operators pointed to natural gas plant outages.

[5] Federal Energy Regulatory Commission, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," at https://www.ferc.gov/sites/default/files/2020-05/ch1-3.pdf.

[6] "Report of the Committee for the Analysis of the Electricity Crisia of April 28, 2025," at https://www.lamoncloa.gob.es/consejodeministros/referencias/Paginas/2025/20250617-referencia-rueda-de-prensa-ministros.aspx.

[7] A global list of major outages can be found at https://en.wikipedia.org/wiki/List_of_major_power_outages.

[8] https://www.iea.org/reports/ukraines-energy-security-and-the-coming-winter/ukraines-energy-system-under-attack.

Utilities often justify decisions using "prudent utility practice," a regulatory standard typically defined as common industry methods. However, this can stifle innovation and encourage conformity. Furthermore, traditional cost-benefit analyses, ineffective for catastrophic risks, and standard reliability metrics, which overlook black sky scenarios, are often integrated into defining prudent utility practice.

The human tendency to underestimate risks based on limited experience is also an obstacle. The absence of widespread, long-term outages caused by events like solar flares, major earthquakes, volcanic eruptions, or large and complex infrastructure attacks can lead to a perception that such events are so unlikely they are not worth preparing for, particularly where they haven't already been experienced.

One further challenge is the vast numbers of points of vulnerability. The electric power sector in North America consists of a huge and complicated network spanning the entirety of the United States and Canada as well as parts of Mexico. It consists of four major synchronized interchanges including in the continental United States alone, 66 balancing authorities, over 7,300 power plants, 160,000 miles of transmission lines, 55,000 transmission substations, and millions of miles of distribution lines.[9] Beyond this are the communications, fuel, water, and other resource networks that supply it. Many of these present points of vulnerability to both manmade and natural threats, particularly on the transmission system. Protecting all of this all the time from all threats is virtually impossible. Protection must be prioritized, but how?

### The Evolving Electric Sector Complicates Resilience Decisions

The structure of the electric power sector is evolving in several ways:

1. Many independent but interacting and interdependent decision makers. Increasingly, these decision makers are on distribution circuits and within consumer facilities, even homes. Many of these decision makers have digital controls and communicate with each other or with control systems elsewhere over the internet. Increasingly, artificial intelligence (AI) is being used both by consumers and the power sector. Electric consumers, ranging from the largest industrial plants to small residential consumers, are now able to control their electricity use as well as generate and store electricity using digital devices and communications. These are the most numerous and diverse elements of the electric grid and are mostly at the distribution level. Distributed Energy Resources (DERs) are becoming increasingly common on the distribution system in addition to microgrids, demand response, and distributed generation and storage. Widespread deployment of DERs also vastly increases the number of points of vulnerability to cyberattacks if controlled by the balancing authority's Distributed Energy Resource Management System (DERMS).
2. More flexible and complicated technology for the electric grid. Technologies, many of them digital and networked, are being deployed at both the transmission and distribution levels to give grid operators greater visibility and control of the grid. At the same time, central station technologies such as advanced combined cycle and utility-scale solar and wind on the bulk power system are advancing and becoming more flexible. Flexibility is being increased

[9] Source: https://www.eia.gov/todayinenergy/detail.php?id=27152 and https://www.energy.gov/oe/articles/oe-report-solid-state-power-substation-technology-roadmap accessed June 12, 2025.

through electricity storage at both small and large scales and new control and communications systems are being implemented.

3. Transition from a hierarchical to a more networked system. Increasingly common DERs such as rooftop solar as well as demand response are shifting decision making to the grid edge. These are often connected through communications networks separate from those of the utility.

4. Growing interdependence. Interruptions in one sector have an impact on others and creates the potential for cascading interruptions. Such interdependence tends to be strongest in communities served by a single utility, but interruptions can also impact multiple, even distant, communities. Virtually the entire economy is increasingly dependent on the internet, which itself requires continuous supplies of large amounts of both electricity and water and a fiber optic network. Supply chains are typically part of the interdependencies and may not be local. Plants producing chemicals for water treatment, for example, may be located anywhere.

Figure 2 shows the numerous interdependencies of the electric power sector. Each of the entities with which the electric power sector is interdependent has its own interdependence networks, and many of these interdependencies differ from those of the electric power sector. Other than fuel, Figure 2 does not show supply chain dependence on the wide range of equipment and supplies required to build and operate all electric power sector facilities. Interruptions or problems with those supply chains or with the equipment and supplies they provide could also pose significant risks. Increasing digitalization of equipment for both the electric power sector and its customers could also pose cybersecurity risks for the grid, especially with equipment from other countries.

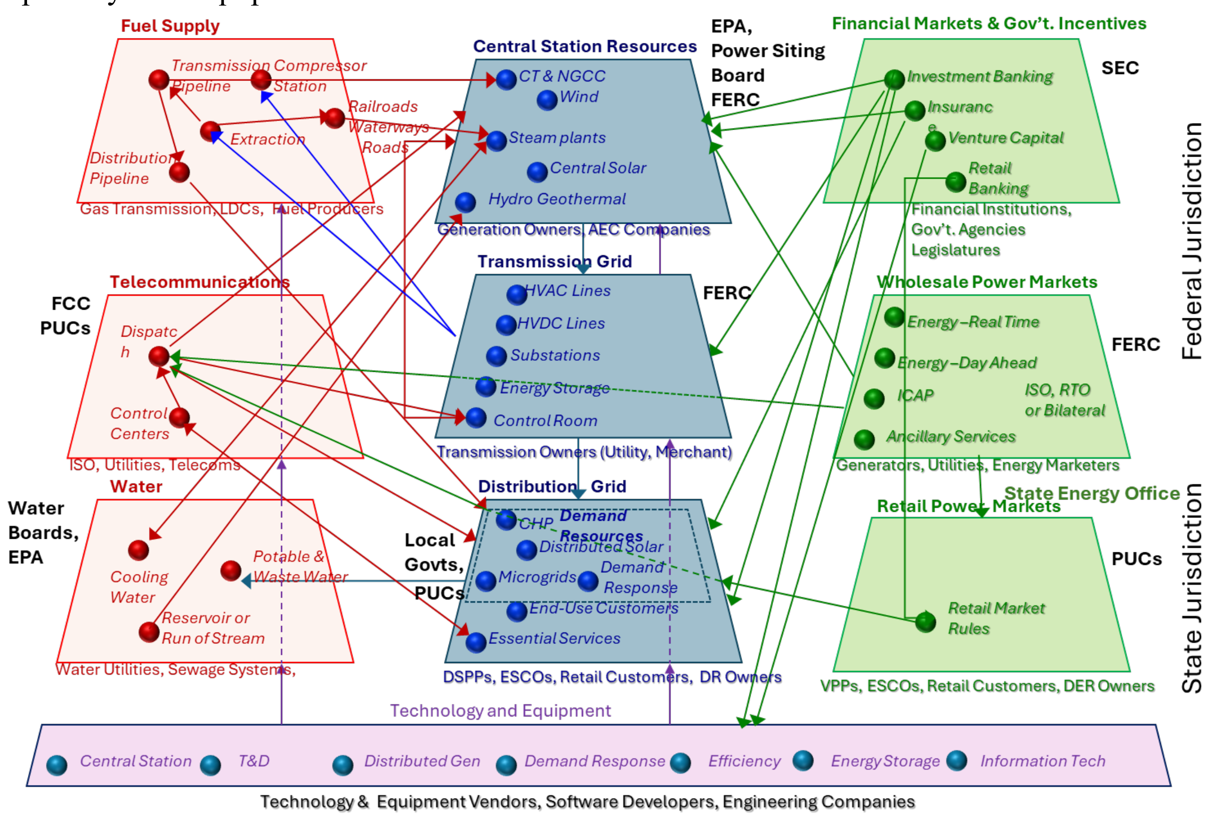


**Figure 2. Interdependencies of the US Electric Power Sector**
Source: OnGrid Options, LLC.

5. New and more intricate markets at the power distribution level. Such markets enable broader participation in the electric sector. The ability to control loads and generation and interact with the grid has led to the ability of some consumers to participate in electric markets. New types of entities such as Virtual Power Plants (VPPs) and community choice aggregators are being used in some states. Electric markets that once had central control and regulation and few participants are becoming more decentralized with many more participants and interactions. This evolution is ongoing with an uncertain future that varies by state and power market.
6. Rapid load growth. After decades at low levels, load growth is accelerating due to the development of new hyperscale AI and crypto-mining data centers and electrification of multiple sectors of the economy, most notably transportation. This increases the criticality of electricity to the security and wellbeing of populations and their communities.

### Emergent Complexity: A Further Complication to Resilience Decision Making

Changes in the electric power sector and interdependent infrastructure give rise to complex behaviors, including potential disruptions. To understand what is meant by complex behavior, we need to define the term "complex" in a way derived from information theory, which is different from the day-to-day definition. In information theory, complexity is the amount of information needed to describe a system. The more information required, the more complex is the system.[10] System behavior and vulnerabilities vary with complexity.

A new scientific field called Complex Systems Science (CSS) has been developed to analyze such behaviors. CSS evaluates how systems with many components operate and specifically how the components relate to each other, especially at different scales. CSS techniques come from science, systems analysis, engineering, economics, and management and provide insights into the behavior of a wide variety of systems, including aspects of the electric power system. Its principles can be used to address resilience.[11] The present paper does not provide a detailed description of CSS or its techniques, but it does apply insights from CSS to the electric power system. It describes what a complex system is, the extent to which the electric sector is becoming an emergent complex system, and what the principles of CSS mean for the electric power system's resilience.

One way to envision complexity is the "complexity profile" of a system showing the amount of information needed to describe a system as a function of scale. Figure 3 shows how the complexity profile of systems varies with the amount of information required to describe the system. Historically, electric system operators have relied on near coherent behavior, that is, top-down complete control of the entire electric system with an emphasis on realizing economies of scope and scale. This was enabled by relatively few controllable generating assets, one-way flow of electricity over a well-understood electric grid, and predictable consumer behavior. The opposite, random behavior of consumers, generation, and electric grid, simply isn't a viable electric system behavior. In between is complex system behavior which has its own characteristics.

[10] Yaneer Bar-Yam, Making Things Work, Solving Complex Problems in a Complex World, New England Complex Systems Institute-Knowledge Press, 2004 and A. Siegenfeld and Y. Bar-Yam, "An Introduction to Complex Systems Science and Its Applications," at https://onlinelibrary.wiley.com/doi/10.1155/2020/6105872.
[11] For example, see Nassim Nicholas Taleb, Antifragile, Things that Gain from Disorder, Random House, 2012.

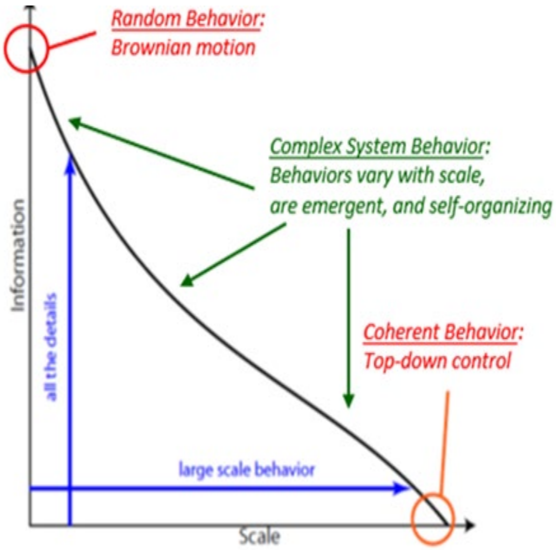


**Figure 3. Complexity and Scale**
Source: OnGrid Options based on New England Complex Systems Institute

Of course, total control with coherent behavior is not possible since loads are not completely predictable and unexpected weather conditions and faults or unplanned generation outages occur, but these conditions could generally be planned for and dealt with as they occur. The introduction of electricity markets at the wholesale level and, in some states, the retail level, coupled with new, autonomous agents such as DERs, changes the complexity profile of the grid, moving it further away from coherent behavior with more information being required to describe it.

Complex systems have five basic attributes: many parts at smaller scales and fewer at large, interdependence of parts and interactions, different behaviors at different scales, emergence, and self-organizing behavior. The electric power system exhibits these to varying degrees.

These basic attributes of complex systems are described below as they apply to the electric grid, and this is illustrated in Figure 4.

1. Many parts at smaller scales and fewer at large. Clearly, many more items of electric equipment operate independently at the smallest scale at consumer facilities behind the meter. The number of entities decreases as the scale becomes larger, first on the local distribution system and then on the transmission system.
2. Interdependence of parts and interactions. Changes in one part of the emergent complex system affect the whole. Many interdependencies exist both among components of the electric power sector and with the components of other sectors. The electric grid is a finely-balanced and managed electric network with a history of outages and is part of a network of networks in which changes or disruptions to one network can impact the others. These are increasing component intelligence and communications.
3. Different behaviors at different scales. The aggregation of loads at a regional scale or sometimes at a distribution feeder level looks very different from the loads of individual facilities or even end-uses within a facility. Yet the pattern of load aggregations across a utility or even a sector served by a utility may fit a systematic pattern. In vertically integrated electric markets with low DER penetration, behavior may be close to coherent. In areas with competitive markets and retail competition behavior is likely to be more complex.
4. Emergence of collective behaviors. This is what parts of a system do together that they would not do alone. Typically, electric loads of individual consumers and uses vary throughout the day but taken together, they give rise to the emergence of predictable load duration curves.
5. Self-organizing behavior consists of local interactions among parts that create global coordination and synergy. It is probably most evident in the power sector for virtual power plants. VPPs are a relatively new entity of the power industry that can create self-organizing

behavior. Community Choice Aggregators and Energy Service Companies (ESCOs) may also create self-organizing behaviors. All this varies with state regulation.[12]

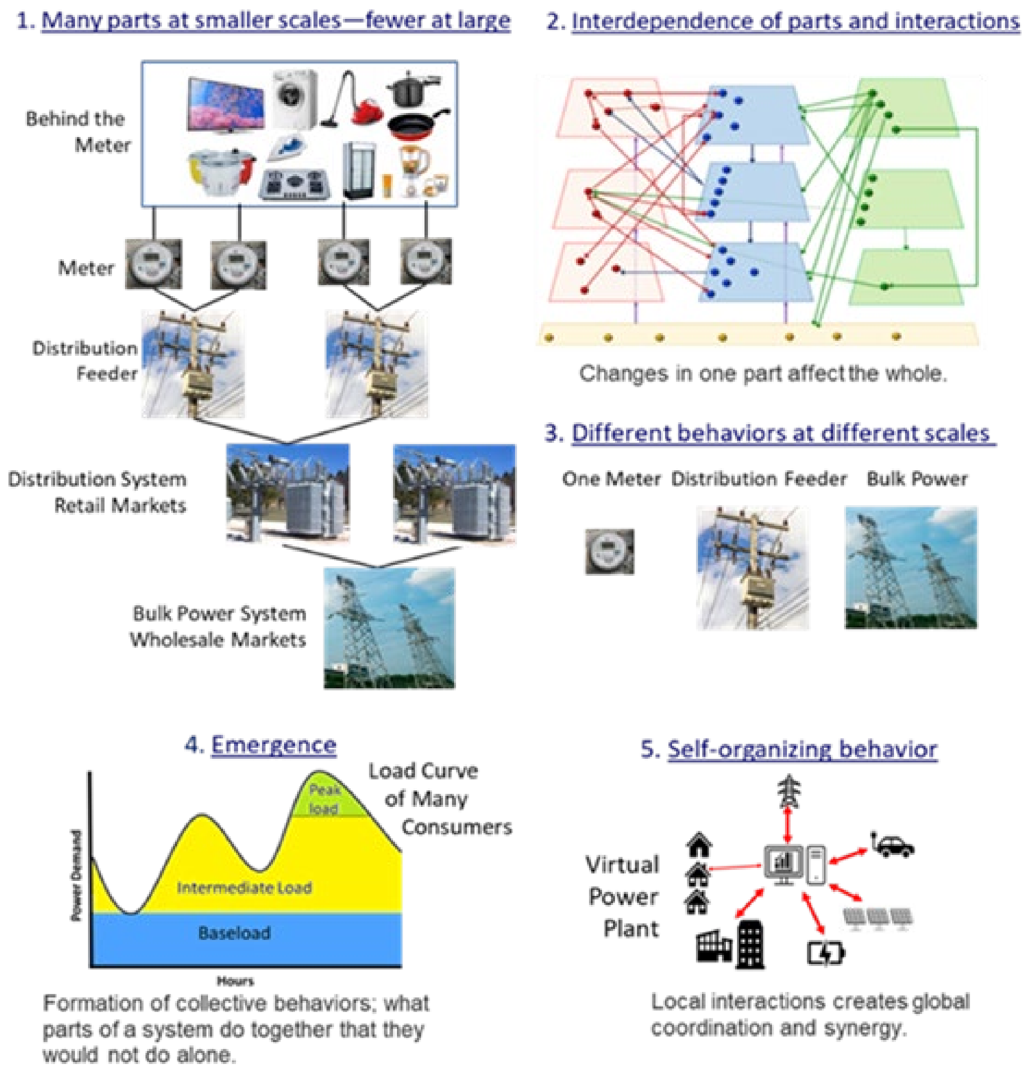


**Figure 4. Attributes and Behaviors of Complex Systems for the Electric Grid**
Source: OnGrid Options, LLC

The electric power system is becoming more networked, distributed, and interdependent, with more market and grid participants. The number and diversity of its parts is increasing, and new emergent behaviors are becoming more common. DER and energy storage, for example, are becoming more common at a small scale and their behavior requires more information to describe. It is changing and is moving up in its complexity profile, but it is likely to stay closer to coherent behavior than random behavior due to limitations on behaviors at different scales and self-organizing behavior.

[12] The most extreme type of independent behind-the-meter activity is "transactive energy" in which individual consumers (known as "prosumers") with rooftop solar or distributed storage or demand response may buy or sell power in response to market signals. Multiple prosumers could potentially exhibit self-organizing behavior. Although transactive energy experiments have been conducted in the United States, it has not been commercially implemented.

Calculus and statistics, the standard techniques of power system engineering and cost-benefit analysis, cannot be used to model the behavior of complex systems. These alone are unable to describe emergent self-organizing behavior of complex systems because the behavior of the whole is typically important, not one behavior.

The purpose of Complex Systems Science is to create actionable insights. Several CSS tools can be used to analyze resilience options. CSS is the study of how the relationship among parts of a system create collective behaviors of the system and how the system interacts and forms relationships with its environment. These tools include simulation, agent-based modeling, network analysis, fragility analysis, pattern recognition, concavity analysis, evolutionary engineering, and multiscale engineering. Each is already used to some extent for various purpose in the electric power sector in North America or Europe. AI is also increasingly being used by the electric sector for various purposes including some that could benefit resilience such as real time monitoring and anomaly detection.  Combined with CSS tools, AI may create even more powerful analyses.

Electric power is not the only widely-used system that does not exhibit coherent behavior on the complexity scale. Figure 5 illustrates other emergent complex systems necessary for modern life.


**Figure 5. Other Complex Systems Critical to Society**
Source: OnGrid Options, LLC

Each of the complex systems illustrated in Figure 5 can exhibit emergent complex system behavior to some degree, and each is also highly interdependent with the electric sector and the other systems. The most complex with the highest number of interdependencies are large cities.

## Creating Resilience for the Electric Power System

There are four basic principles for creating resilience of interdependent complex systems:

1. Focus on what is most important,
2. Address risks at an appropriate scale,
3. Reduce interdependence vulnerabilities, and
4. Ensure the system continues to operate properly.

Each is described below as it applies to electric power systems.

### 1. Focus on what is most important.

Each part of a complex system and its relationships with other parts has its own importance and vulnerabilities. Having multiple complex systems interdependent with electric power creates the potential for even more vulnerabilities. Addressing all vulnerabilities may be infeasible, so decisions must be made about what is important. The structure of the systems and the impacts of disruptions need to be understood so that what to protect can be prioritized.

Within the electric power system, power generation, storage resources, and load often cluster within communities of various sizes. Those clusters are what is most important. Although clusters are not everywhere, they contain a high percentage of the nation's population and critical infrastructure. The 2020 US Census found that 86 percent of the US population lived in metropolitan areas, each with its own critical infrastructure and often power generation and a transmission system.[13] Many smaller communities also have clusters of population, critical infrastructure, and grid resources. An effective approach to resilience must focus on protecting those clusters.

### 2. Address risks at an appropriate scale.

Since different behaviors take place at different scales, choosing the right scale to intervene is vital. The intervention must be viable, effective and affordable. An intermediate community scale provides such an approach.

- *Protecting the entire grid* would require a huge investment and still leave open the prospect of widespread outages due to unforeseen vulnerabilities and continued interdependencies, and it would be financially infeasible. Utilities need to choose which of the many threats to defend against and how to protect against them.[14]

[13] https://www.census.gov/programs-surveys/decennial-census/decade/2020/2020-census-main.html.

[14] National models show interconnectedness of critical infrastructure being developed but they do not address changing behavior, and it is unclear how those models will be used to develop concrete solutions in advance of crises. Moreover, depending on how they are used, the scale may be too large to understand the important interactions and impacts. While the threats are national, many of the behaviors and interdependencies are more local.

- *Protecting only selected individual facilities* leaves much of what is important unprotected and still leaves each individual facility vulnerable to threats affecting critical infrastructure in the other sectors on which it depends.
- *Protecting the grid at the intermediate scale of communities*. Communities are likely the scale at which resilience risks mostly arise and can be controlled because that is where most interdependencies take place. Action can be practically and economically taken at that scale. Grid constructs at this scale—Resilient Community Grids (RCGs)—can best create resilience. Moreover, cascading regional outages can, depending on the local transmission grid circuits and resources, be stopped at substations serving communities. An RCG protects sections of the grid that can operate independently by stopping the cascading outages from affecting them. These sections are selected based on the vulnerability of their communities, the importance of their interdependent critical infrastructure, the availability of generation resources, and their electric transmission and distribution system capabilities. The electric grid in these sections can be used to create the electric system resilience. Developing an intermediate scale construct also has other advantages by reducing grid investment needs, enabling better DER hosting, and prioritizing transmission grid investments.[15]

3. Reduce interdependence vulnerabilities.

This requires identifying and understanding the interdependencies, their potential impacts, and how to reduce the impacts. This is even more challenging when the other interdependent entity is also a complex system requiring protection.

An RCG protects related groups of interdependent critical infrastructure system components that can still support each other when the grid goes down (e.g., electricity, water, wastewater, telecommunications). These interdependencies are both within the electricity sector and with other critical infrastructure sectors. The electric power system has individual components of various types (e.g., power plants, the electric grid and consumers). Some of these at smaller scales make decisions independently of each other but can affect each other's behavior. This potentially leads to emergent behavior. Such emergent behavior poses risks to the infrastructure. Some of the interdependencies may be local to a community. Others may extend beyond the localities and balancing authorities.

RCGs take advantage of the fact that many critical infrastructure facilities are located close to power generation and storage resources. They tend to cluster together because the same site criteria used for power plant locations also have also been used to site critical infrastructure (e.g., industrial zoning, closeness to electric loads/customers, proximity to water, rail lines, gas pipelines and electric transmission).

4. Ensure the system continues to operate properly.

Measures to achieve this include:

- *Providing system redundancy and diversity*. Redundancy brings optionality to ride through difficult challenges. Redundancy using the same approach as the base system or other

[15] See OnGrid Options, LLC, "The Electric Power System's Missing Intermediate Scale," December 2024.

defenses, however, may have the same vulnerabilities. The systems that are used to control and provide cybersecurity are different from those of the overall regional electric grid. Redundancies are also more feasible and cost-effective for a section of the electric grid than for either the electric grid as a whole or a microgrid. A cybersecurity breach of the regional grid does not affect the RCG and the RCG provides a more difficult target. Multiple RCGs, each with a different system, compound the challenge facing cyber adversaries. Ideally, a mix of different generation resources should be used. Such diversity and redundancy are often unachievable in microgrids but are achievable in RCGs.

- *Creating fewer points of vulnerability.* This reduces risks, including the risks of unanticipated emergent behavior. Subsystems that can be independently operated can preserve at least some operations and create the opportunity to black start the rest of the system. Critical components of an RCG are fewer and can be more cost-effectively protected. Control and cyber systems in a RCG are open to many fewer people and at fewer sites than a typical utility electric system.

  Rapidly-increasing numbers of points of vulnerability are created by the rapidly growing numbers of DERs and other electronic equipment used by the power industry, especially with devices coming from international supply chains.[16] Some are planned to be controlled by facility owners, for example, through mobile phone apps. Others are controlled by a local utility through a DERMS, by VPP operators or by Community Choice Aggregators. Those that are connected to the internet may create cybersecurity risks that need to be managed both within and outside of an RCG. DER and controls within an RCG, however, can be a starting point for addressing this vulnerability.

- *Using a layered defense.* A layered defense may be used to assure the protection of the most important or sensitive assets. RCGs are a layer of defense between the regional T&D grid and protections at individual facilities. Other layers such as microgrids and emergency generators can be created within an RCG. Microgrids may be a prime candidate for some electric customers, but these ideally should rely on fuels different from those of the local grid. Microgrids are typically built to use the fuels that are most cost-effective, often the same as the local utility. Adequate supplies of different backup fuels can help.

  One layer of defense can be concealed presence. Adversaries planning both physical and cyberattacks will find it difficult to attack what they don't know exists and cannot understand or probe for vulnerabilities. RCGs will not operate under normal conditions. Their presence, extent, and configuration will not be widely known. Under normal conditions neither their control system nor their cybersecurity system are in operation and cannot be hacked. Under all conditions, these systems in an RCG will not be interconnected with any other systems.

- *Restoring the rest of the regional electric system*. Black start capable resources within an RCG can be used to black start the regional electric grid outside of the RCG. This would provide a new black start option better protected from the threats that might affect other black start capabilities outside of the RCG. Multiple RCGs within a balancing authority would help further. Balancing authorities currently black start the bulk power system by

[16] See Paul Stockton, "Surfing the Wave: Resilience Strategies for the Decentralizing Grid," Johns Hopkins University Applied Physics Laboratory, 2025 for a comprehensive assessment of these vulnerabilities at https://www.jhuapl.edu/sites/default/files/2025-03/SurfingTheWave-WEB.pdf.

creating a restoration plan with "cranking paths" from generating stations that can begin operation during a regional outage. RCGs not only create more options for operating generation, multiple RCGs could potentially create the possibility for multiple alternative cranking paths with multiple options for black start.

- *Enabling readiness*. Resilience cannot be achieved through just engineering alone. Decision makers and operators are an inherent part of the system. Personnel across both the electric system and other critical infrastructure sectors must understand the potential for unforeseen black sky events and be ready to respond. Traditional grid operation is focused on top-down control of large power plants and T&D systems by anticipating the variations of electric loads, outages, and resource availability. Sophisticated models have been developed to plan for such conditions and1` operate in diverse and challenging conditions. Those are not adequate, however, for black sky or other extreme events. Preparedness of critical infrastructure staff for the unexpected is also crucial for maintaining community resilience.

  Preparing for extreme events requires collaborative planning, coordination, and realistic practice across multiple organizations as well as flexible response capabilities. This necessitates training, such as multi-organizational table-top exercises or simulations. Considering the vast scale of the grid and critical infrastructure as well as the large numbers of people potentially involved, prioritizing key personnel and resources is crucial. Analytical tools from CSS not currently used in the electric power industry may be used individually or in combination to evaluate potential RCG designs and operation.

## Conclusions

The electric power sector faces challenges in achieving resilience. Rare, unpredictable, and extreme outage events can create ruinous impacts and they do happen. How to effectively and affordably plan for them has long been a challenge. The increasing complexity of the electric grid and its behavior adds to this challenge. Complex Systems Science (CSS) offers valuable insights into fundamental principles that can be used to create resilience while simultaneously meeting objectives such as affordability, reliability, and low environmental impact These insights provide the basic principles for building resilience.

Resilient Community Grids (RCGs) do not alter the behavior of individual grid components under normal conditions. RCGs uniquely align their design and operation with basic CSS principles to provide the most effective resilience for the electric system. RCGs can simplify an otherwise unmanageable problem and prevent the most extreme outages by focusing on what is most important, operating at the manageable and cost-effective intermediate scale of the communities they protect, reducing interdependence vulnerabilities, and enabling readiness to cope with the unexpected.

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