Reimagining Grid Resilience

A Framework For Addressing Catastrophic Threats to the US Electricity Grid in an Era of Transformational Change

BY MARK DYSON AND BECKY LI

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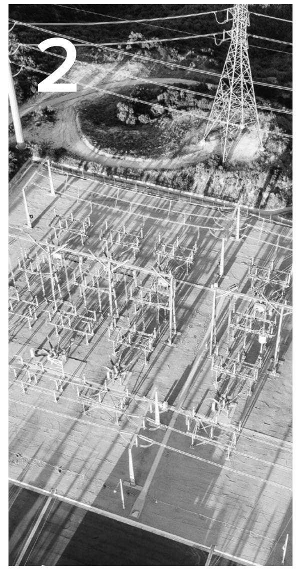

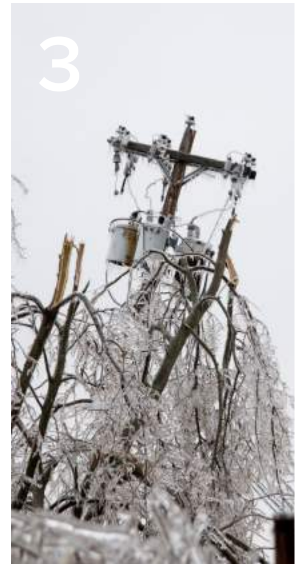


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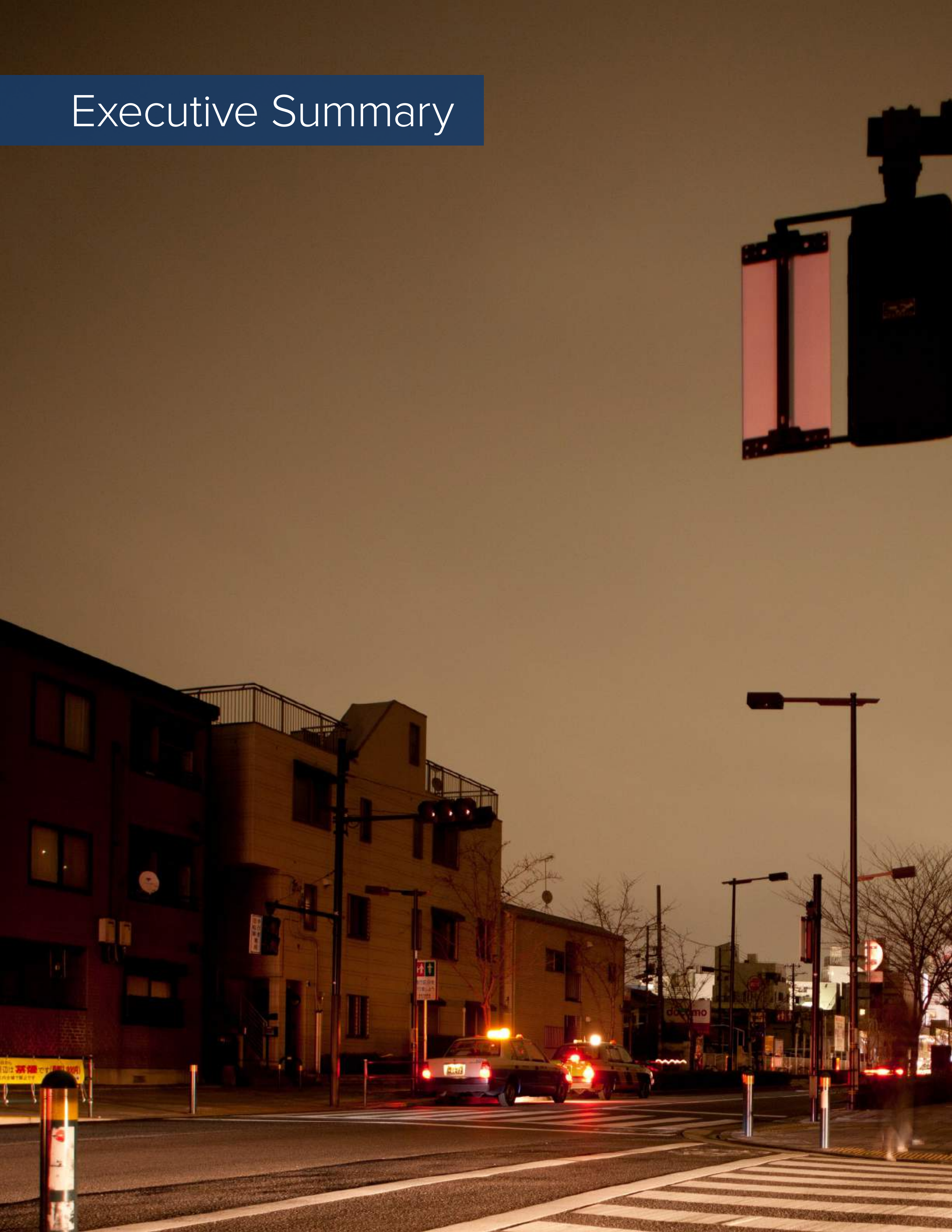


Executive Summary

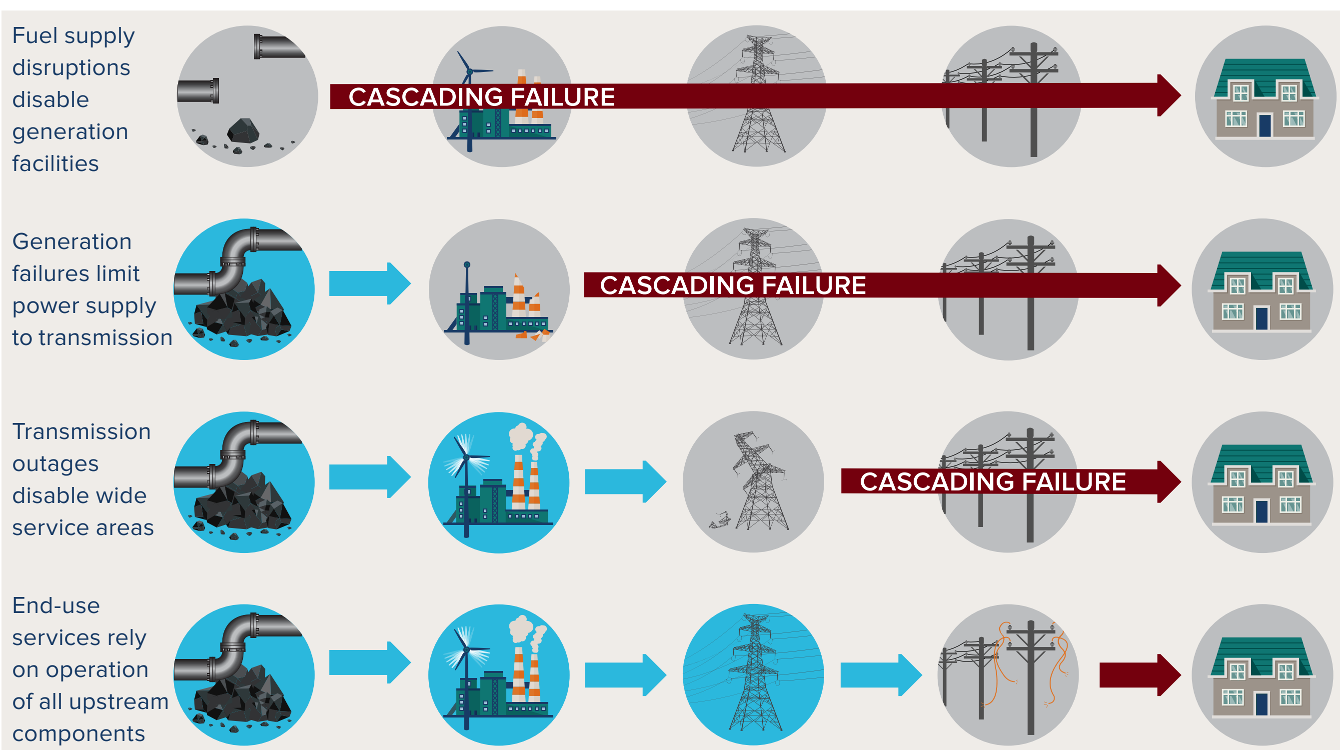
Since its origins at the beginning of the last century, the electricity system has been a critical driver of US economic growth and prosperity. Today, its importance has grown exponentially, with the increasing prevalence and importance of internet-based services within all sectors of the economy, and growing momentum to electrify vehicle and building heating energy use. But what happens when the grid goes down? A grid outage can mean not being able to access critical health services, water supply, communications, and more, negatively affecting people's well-being and our country's economic growth.

Unfortunately, the US grid, generally defined by a linear, one-way flow of electricity and economic value from central-station generators to end-use customers, was developed in an era dominated by economies of scale of fossil-fuel power plants. It is now increasingly at risk from rapidly evolving threats from both malicious attacks and natural disasters. Long-term, large-area grid outages driven by severe weather alone now cause tens of billions of dollars in damage to the US economy each year, and this threat is only one of many that are growing in impact and likelihood.

Grid planners and operators have long managed this inherent vulnerability through redundancy and hardening of critical equipment but are unable to completely avoid outage risks. Exhibit ES1 illustrates the components of the grid value chain, and in particular the dependence of electricity access to end-use customers on the continued operation of each component of the chain, from fuel supplies, to central-station generation, to transmission and distribution. If any of these components within the grid is disrupted, end-users face outages.

EXHIBIT ES1

Grid Architecture and Vulnerabilities Associated with Each Component of the Grid Value Chain



And the number of outages is growing. Emerging human-made threats and natural disasters are compounding the risk of catastrophic, long-term outages across the power grid and the economy it supports. In recent years, malicious actors have demonstrated the potential for physical attacks as well as cyberattacks on grid infrastructure to wreak havoc on human safety, economic activity, and political stability. Natural disasters including solar storms and climate change-driven extreme weather have caused long-duration outages for millions of customers across wide swaths of North America.

Exhibit ES2 summarizes four categories of catastrophic threats to the power grid. They vary in the extent to which they are understood by industry practitioners and policymakers, but each has the potential to disrupt access to electricity across wide regions, for days to months at a time (potentially longer), with severe consequences for the US economy.

Importantly, there are other categories of threats not specifically covered in this study, but which have largely similar effects on the ability of grid infrastructure to deliver electricity to end-use

EXHIBIT ES2

Summary of Catastrophic Threats to Grid Security

	 Extreme Weather and Natural Disasters	 Physical Attacks	 Cyberattacks	 Electromagnetic Pulse Attacks and Geomagnetic Disturbances
Examples/Definition	Hurricanes, superstorms, cold spells, high winds, wildfires, earthquakes.	Bombings, shootings, wire cutting, arson.	Deliberate exploitation of computer systems in order to gain control of or damage the grid.	An electromagnetic pulse (EMP) is caused by high-altitude detonation of a nuclear device. A geomagnetic disturbance (GMD) is caused by a severe solar storm.
Scope of Potential Damage	Damage or destroy infrastructure; cause precautionary power outages to avoid wildfires.	Most attack effects would be limited to local grid; coordinated attack potentially catastrophic.	Disable or limit access to grid control systems, resulting in outages and/ or infrastructure damage, potentially widespread and long-lasting.	Wide-area damage to transmission and distribution infrastructure. In the case of EMP, indiscriminate damage to unhardened electronic equipment.
What is Being Done?	Emergency response plans for critical facilities; grid hardening.	Physical security standards; spare transformers.	Cybersecurity standards and processes.	Reliability standards; scenario simulation.

customers. Notably, pandemics such as COVID-19 can affect electricity supply security by limiting the availability of healthy personnel to maintain and operate the grid. Such threats, even though not specifically addressed in this study, can be assessed in the same framework introduced here.

Even as the risks posed by these and other catastrophic threats are becoming apparent, the technologies and underlying architectures that define the US electricity grid are changing at a faster pace than ever before. New electricity supply resources, including natural gas extracted from shale formations, solar photovoltaic (PV) arrays, and wind turbines, are rapidly gaining market share and displacing legacy coal- and nuclear-fired generation facilities. For example, 72% of 2019 global net additions of generating capacity came from renewables.[1] Internet-enabled monitoring and control technologies, both within the transmission and distribution networks and increasingly behind customer meters, are enabling a far more flexible and dynamic grid than was envisioned throughout most of the 20th Century.

Each of these technologies, with adoption being driven largely by market forces, has implications—some positive, some negative—for grid security. Exhibit ES3 summarizes the impacts of emerging technologies in the context of risks affecting different components of the grid.

EXHIBIT ES3

Summary of Technologies Reshaping the Power System at Each Stage of the Value Chain

Fuel | **Generation** | **Transmission** | **Distribution** | **End-Users**

Fuel / Generation: An ongoing shift from coal to natural gas, utility-scale renewables, and storage tends to reinforce the grid's linear value chain and associated vulnerabilities.

Transmission / Distribution: Grid hardening and modernization can mitigate physical risks, improve visibility and flexibility of the system, and support integration of distributed energy resources (DERs).

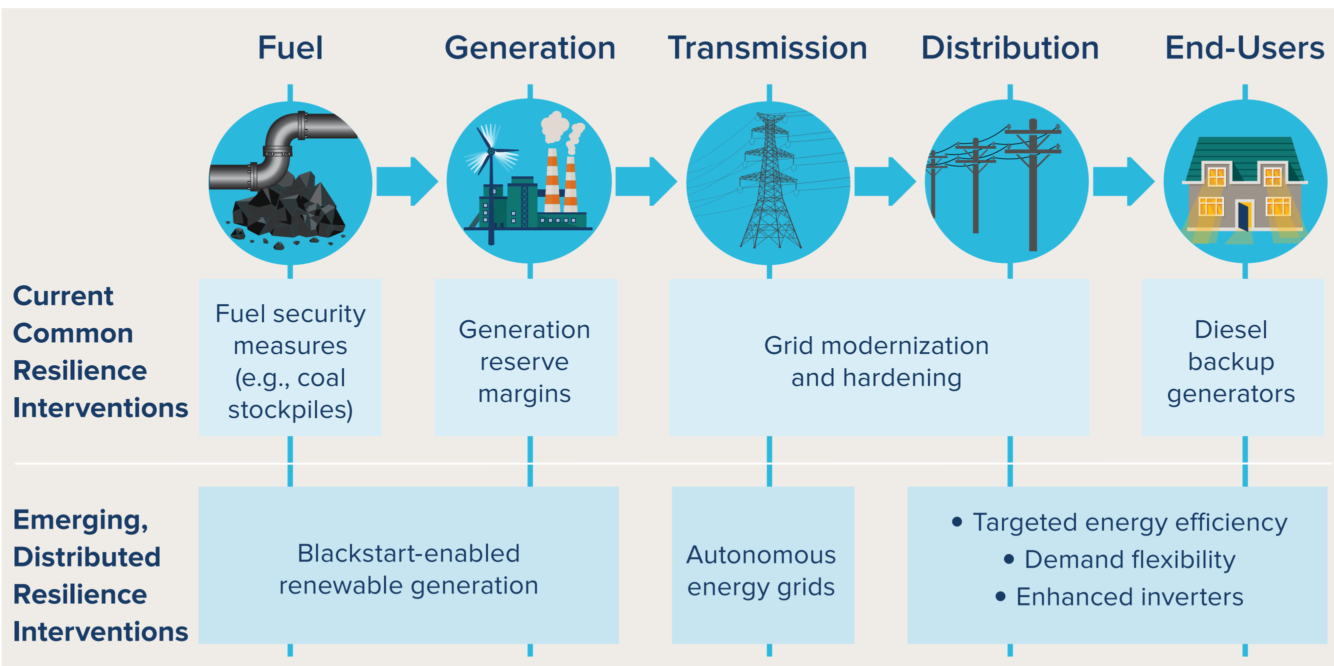
End-Users: Market-share growth of DERs, including generation as well as demand-side resources, allows for end-user-focused strategies to mitigate upstream risks.

While the US electricity industry has over a century of practical experience in mitigating routine outages and developing restoration plans for major disruptions, there is a pressing need to reevaluate the efficacy of current approaches. The confluence of emerging catastrophic outage risks and market-driven adoption of disruptive technologies suggest an updated approach to planning for resilience is both timely and of critical importance to mitigate the economic risks associated with even a single large-scale outage event.[i]

This study first assesses the suitability of current approaches to manage and improve grid security and resilience within the current context of emerging catastrophic threats and rapidly-changing technologies. It then introduces elements of a framework to better evaluate resilience strategies in the changing grid landscape, and introduces a set of resilience interventions that are aligned with market trends and can complement existing approaches. Exhibit ES4 describes both current and emerging resilience strategies considered in this study.

EXHIBIT ES4

Overview of Current and Emerging Resilience Approaches



[i] In this study, "resilience" is used to describe the overall ability of the electricity system to prevent, mitigate, and recover from wide-area, long-duration outages. This conforms to official definitions. RMI's 1981–2 DoD synthesis *Brittle Power: Energy Strategy for National Security* (**https://rmi.org/insight/brittle-power/**) also usefully included an active-learning element akin to that of ecosystems, so recovery includes adaptations that make the disrupted system more resilient against future shocks.

Based on qualitative and quantitative analysis of different resilience strategies listed in Exhibit ES4, we develop a set of principles for evaluating and promoting resilience. We find that, in general, legacy strategies are not ideally suited to providing resilience benefits at scale in the context of catastrophic threats and changing technology adoption. In contrast, emerging resilience interventions, generally located closer to end-use customers and better-aligned with market-driven investment trends, provide larger resilience benefits and greater economic value, and can complement or supplant current approaches rooted in legacy technologies.

Exhibit ES5 summarizes the recommended principles and associated findings for both current resilience strategies and emerging interventions.

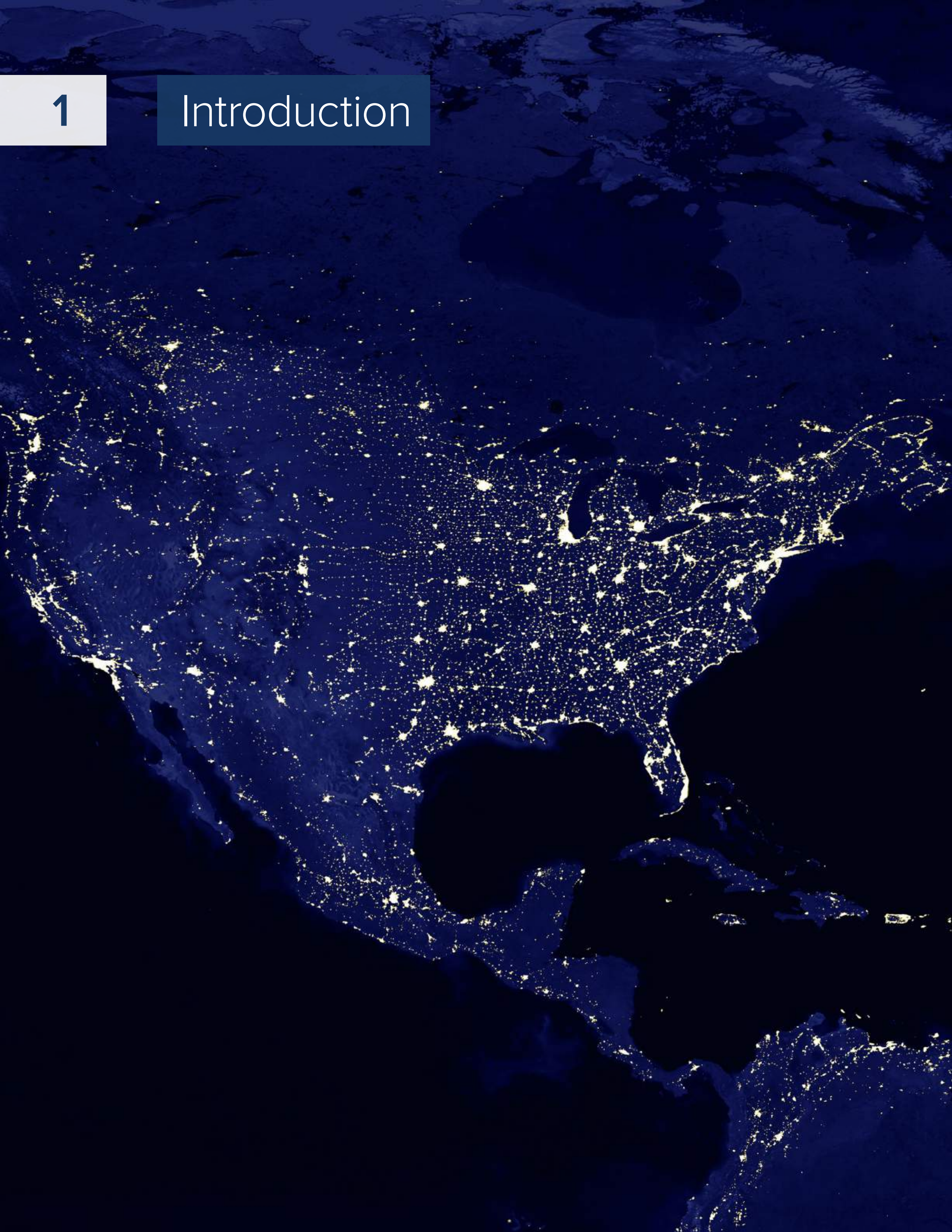
Electric utilities will probably invest approximately $1 trillion in the US power grid between 2020 and 2030. Given the magnitude of long-lived assets under consideration, there is an economic and national security imperative to invest in our grid in a way that promotes resilience by design, economically and from the bottom up, and not as a cost-adding afterthought years later. The principles laid out in this study can serve as guideposts for investors, regulators, policymakers, and other stakeholders as the United States mobilizes this capital to reorient its power grid and economy in response to both the emerging catastrophic threats and the market-winning technologies of this decade and beyond.

EXHIBIT ES5

Proposed Principles for Grid Resilience and Associated Evaluation of Different Strategies

Principles for Maximizing the Benefits of Resilience Strategies	1. Address, Don't Ignore, Linear Dependence	2. Leverage the Market, Don't Fight it	3. Prioritize Critical Loads	4. Maximize Economic Value from Resilience Investments
Current Common Resilience Interventions	Generally limited to addressing risks within single grid components.	Return declining resilience benefit as the market drives grid evolution.	Limited potential to prioritize critical loads in the event of widespread outage.	Limited economic value outside of contingency events.
Emerging, Distributed Resilience Interventions	Generally have higher value across multiple outage scenarios.	Complement one another and reinforce resilience benefits associated with the ongoing evolution of grid technologies.	Can directly support prioritization of critical loads.	Can provide economic value, especially as grid technology mix evolves.

1 Introduction



Introduction

The electric power system has long been recognized as critical to the success and growth of the US economy. The power grid is poised to play an increasing role in economic growth for decades to come. A 2011 report from the Brookings Institution Energy Security Initiative stated, “The US power system is the backbone of the country’s economy.”[2] This “backbone” is becoming more relevant each year as the nation’s economy relies ever more on reliable, cost-effective access to electricity. Increasing availability of internet-enabled information services and internet-connected devices—all of which rely on constant power access—across all economic sectors has helped drive global economic growth for several decades.[3] More recently, momentum toward electric vehicles and focused attention on electrifying buildings and industry,[4] driven by both economics and broader decarbonization efforts,[5] have reinforced the importance of reliable electricity access across an increasing share of the US economy.

However, the electricity grid that underpins the US economy is aging, and has become increasingly vulnerable to disruption by accident or malice. The average thermal power plant in the United States is now over 30 years old,[6] and a 2013 US Department of Energy (DOE) report found that more than 70% of transmission lines and transformers were over 25 years old.[7] Moreover, the design paradigms governing the power grid, including large-scale, central-station, fuel-driven generating equipment interconnected via long-distance transmission lines, remain largely unchanged from the grid of the 1900s, even as the scale of the grid itself and individual components (e.g., generator sizes) grew significantly. Aging generators, connected via long-distance ties to aging local distribution systems, expose our economy to massive risks; for example, the DOE reported in 2013 that weather-related outages alone cost Americans $18–$33 billion each year between 2003 and 2012.

Severe weather is perhaps the most immediately observable and salient risk to the grid on the minds of most Americans, but there is increasing recognition of a broader set of catastrophic threats to the US power system that could lead to blackouts across large geographic regions lasting from days to months if not longer. The industry has long recognized such threats as physical attacks on grid infrastructure,[8] geomagnetic disturbances (GMD) caused by solar flares,[9] and electromagnetic pulses (EMP) caused by high-altitude detonation of nuclear weapons.[10] An emerging set of threats, including extreme weather driven by climate change and cyberattacks,[11] similarly imposes risks of long-duration, widespread power outages across many regions of the United States. Since a Defense Science Board report featured these threats in 2008,[12] they have received greater, though still inadequate, policy attention, both public and classified.

At the same time as the threat landscape evolves and exposes the grid to new and greater blackout risks, a set of emerging technologies are rapidly gaining market share and reshaping the grid, with significant implications for resilience. New natural gas-fired power plants have claimed virtually all recent investment in new thermal generating capacity in the United States, driven by advances in turbine technology and the availability of abundant gas extracted from shale formations.[13] Renewable energy resources, most notably utility-scale solar photovoltaics (PV) and wind turbines, are increasingly the least-cost option for new grid investment,[14] and as of early 2019 produced more energy than the US coal-fired generator fleet,[15] which is rapidly retiring. Battery energy storage technologies are already cost-effective for several use cases on the grid,[16] and will become more so as technology continues improving rapidly.[17] Internet-connected load control technologies can create significant value for customers and the grid,[18] and are gaining market share across the United States.[19] As explored in this study, all of these technologies have significant implications—both positive and negative—for system resilience.

The electricity industry, policymakers, and other energy sector and national security stakeholders are already taking steps to update our nation's understanding and treatment of grid resilience in the context of this rapid change. There are many existing efforts and resources within industry, government, and research institutions that lay the groundwork for this improved approach to resilience:

- **Definition and Metrics of Resilience**
  To complement the longstanding and well-understood practices of electric utilities around maintaining service reliability under the threat of commonplace disruptions (e.g., equipment failure, animal-caused disruption),[20] there is an emerging focus in the industry on resilience as a distinct characteristic of power systems. The National Academy of Sciences, for example, discussed resilience in the context of "events that can cause large-area, long-duration outages: blackouts that extend over multiple service areas and last several days or longer."[21] To benchmark the resilience of power grids in the context of these events, US Department of Energy-funded research labs are working with regulators to establish a common understanding of resilience metrics.[22]

- **Assessment and Valuation of Resilience**
  Industry stakeholders are expanding on current analytical tools to assess system resilience and the monetary value of resilience in a changing risk and technology environment. For example, US Department of Energy-funded research labs perform analyses of grid security threats and their potential impact in different US regions using probabilistic approaches.[23] State-level energy regulators are considering their role in prioritizing resilience investments by utilities,[24] and evaluating various methodologies of assessing the value of resilience in the context of regulatory decisions affecting state-jurisdictional grid investments, especially DERs.[25]

- **Non-Technological Resilience Risk Assessment and Solutions**
  The industry is looking beyond the changing technological landscape in assessing resilience risks and opportunities to mitigate them. For example, there is increasing recognition of the importance of human factors in outage prevention and response: a joint US and Canadian government report following the 2003 blackout in the Eastern United States and Canada affecting 50 million people found that human error contributed significantly to the outage, and the National Academy of Sciences in its 2017 report on grid resilience explored recommendations for "how the human–computer interface and visualization could improve reliability and resilience."[26]

These and other existing efforts and resources around grid resilience provide a critical starting point, but there are important gaps that will hinder further progress on improving grid security in the current rapidly changing landscape. This study focuses on complementing existing efforts by addressing these gaps in our analysis and recommendations. Accordingly, this report focuses on catastrophic threats, emerging technologies, and solutions.

- **Catastrophic Threats**
  Many existing efforts largely focus on "routine" disruptions to electricity service, up to and including the effects of severe weather, while little direct attention is paid to mitigating the potential long-duration outages caused by concerted attacks or very large-scale natural disasters (including climate change-driven extreme weather). This study focuses on high-impact, low-probability events with the potential to cause catastrophic outages lasting from days to months or longer.

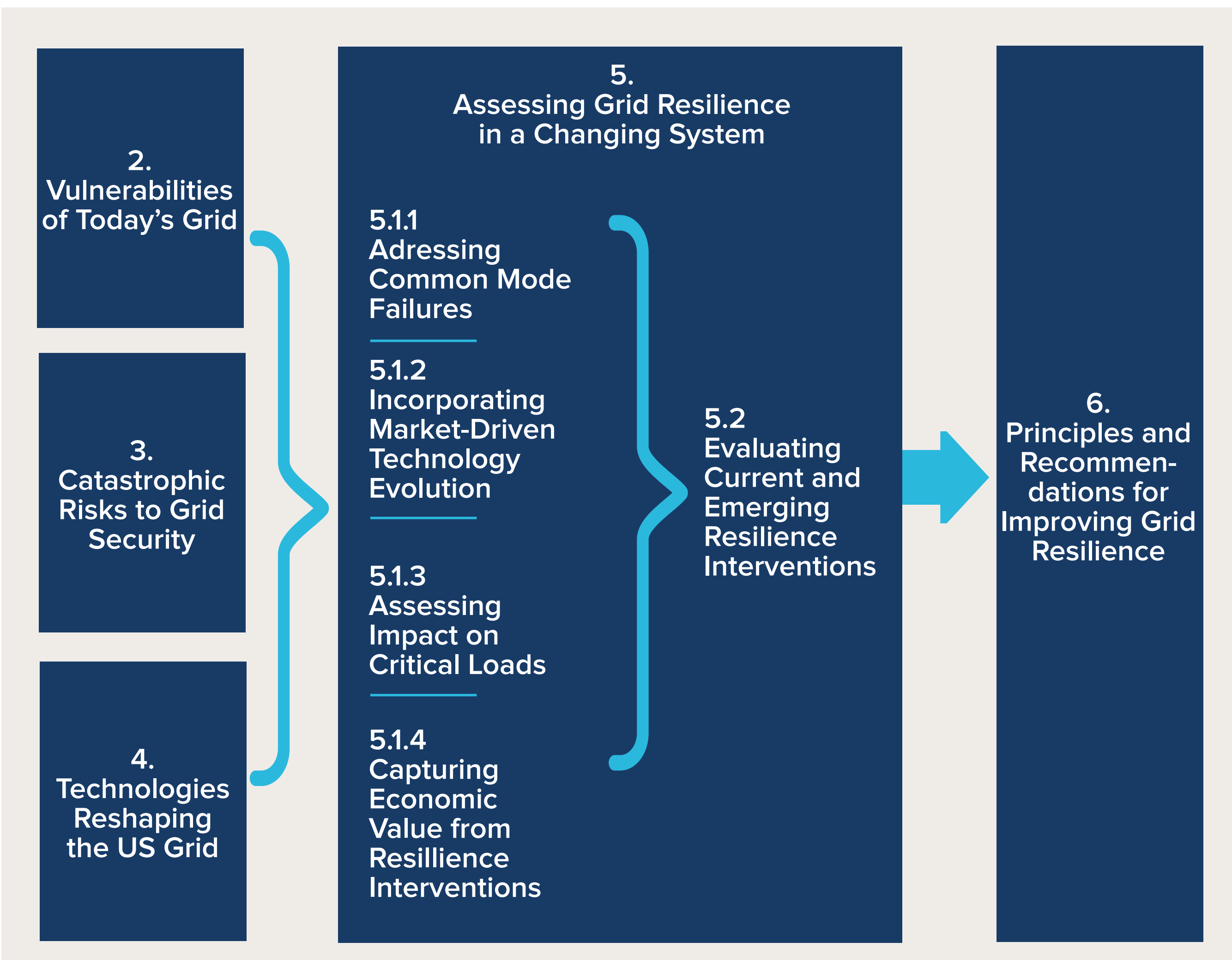
- **Emerging Technologies**
  Most current efforts and resources discuss response to resilience risks primarily in the context of the existing grid and supply portfolio. This study focuses

on the dramatically different set of technologies currently gaining market share that will reshape the grid over the coming decades in order to provide longer-term guidance to industry stakeholders in the context of a changing grid.

- **Evaluation of Solutions**
  Even when current efforts assess resilience solutions relevant to catastrophic threats and a changing grid technology mix, they generally do not systematically characterize the effects of available solutions. This study introduces a framework for assessing the benefits of and criteria for successful interventions to improve grid resilience in the context of catastrophic technologies and emerging threats.

Exhibit 1 outlines the contents of this report and the overall framework we use to characterize and assess grid resilience in this period of rapid change within the US power system.

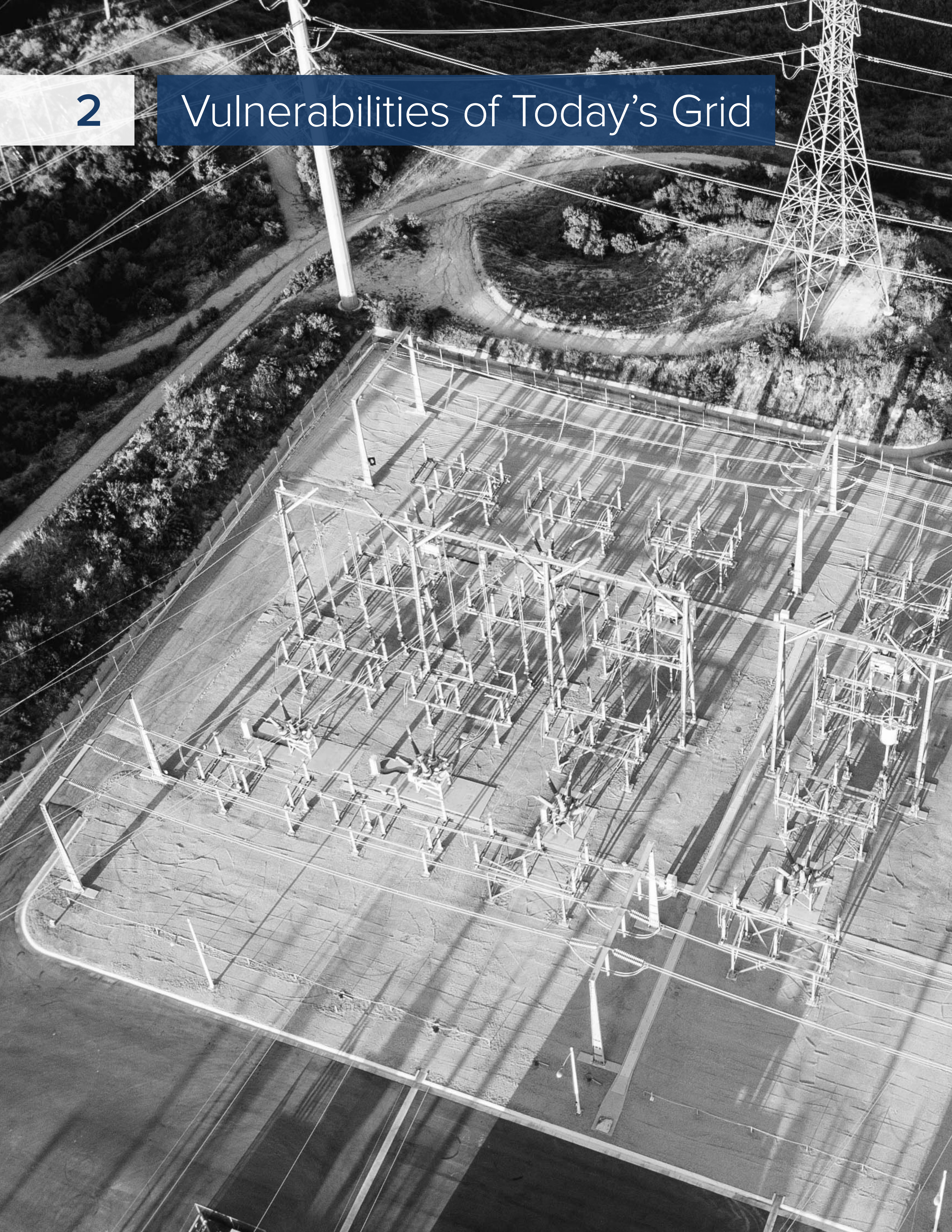
EXHIBIT 1
Study Overview and Framework



Following the framework laid out above, this report addresses the following questions in subsequent sections:

- How is the current grid vulnerable to resilience risks, and what existing efforts are underway to address these risks? (Chapter 2)
- What are catastrophic risks to the grid, and how would they affect different components of grid infrastructure? (Chapter 3)
- How are emerging "market-winning" technologies reshaping the grid, and what impacts might they have on resilience in the face of catastrophic risks? (Chapter 4)
- How can we begin to assess the impacts of market-winning technologies and highest-value interventions to mitigate catastrophic threats? (Chapter 5)
- What steps can regulators, policymakers, and other stakeholders take in the near term to address risks and improve resilience? (Chapter 6)

2 Vulnerabilities of Today's Grid



Vulnerabilities of Today's Grid

Summary of Key Points

- The evolution of the US grid as a one-way value chain from primary fuel to end-use consumer has reinforced a "top-down" resilience paradigm that reinforces cascading vulnerabilities within the power system.
- As a consequence of this design paradigm, a failure of any component of the grid can result in disruption of service to end-users.
- Current approaches to mitigate grid security risks generally focus on addressing threats within, not across, each component, and thus reinforce cascading vulnerabilities within the grid.
- In short, some proposed mitigations could worsen the problem by focusing on parts rather than wholes and on hardware rather than the architecture of how its pieces interact.

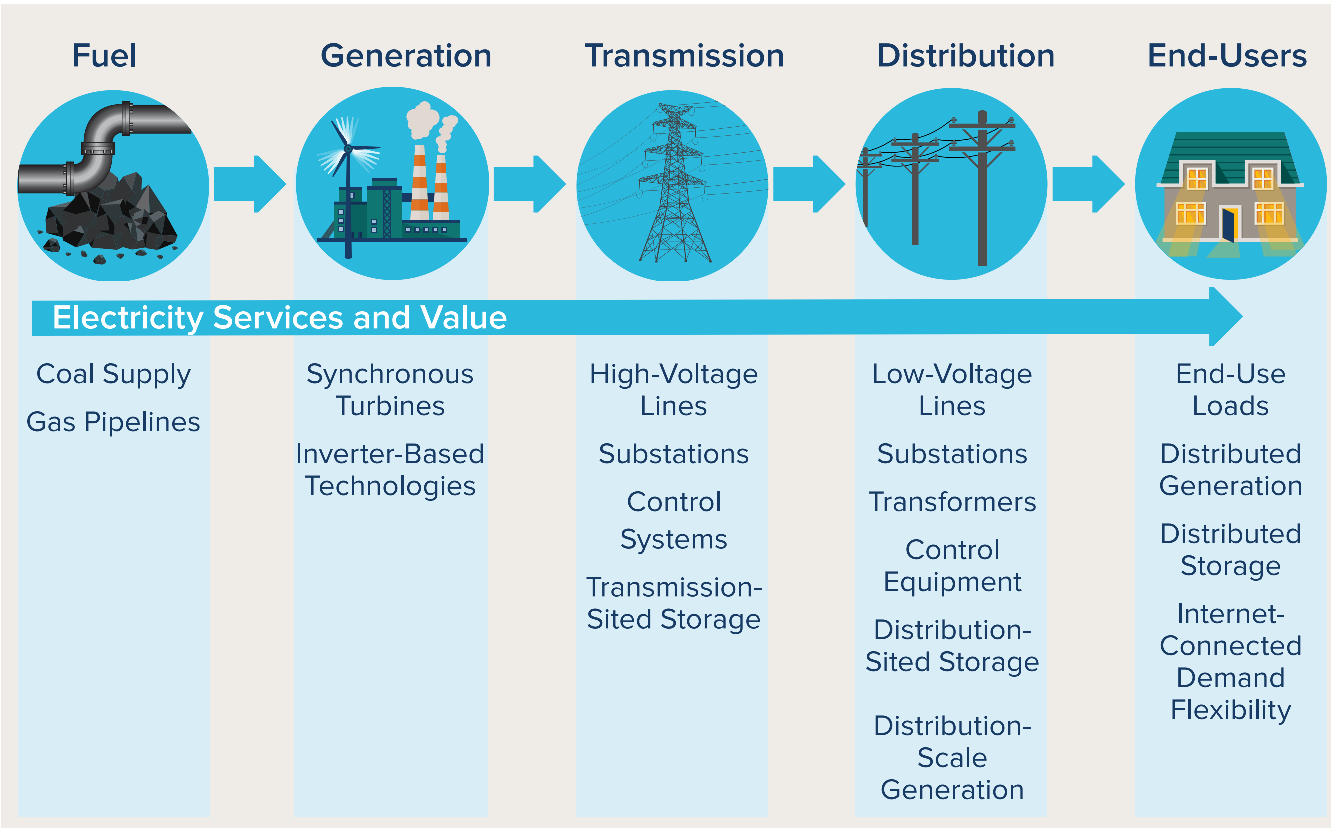
Power System Value Chain and Resilience Interdependencies

The US grid has evolved as essentially a one-way value chain from generation to consumers. Exhibit 2 illustrates the way in which value flows from primary energy sources to end-use consumers within the electricity system:

- Fuel supplies, including coal, gas, and uranium, provide stocks of primary energy to thermal generation technologies. Non-fuel resources, including hydroelectric potential, wind, and solar radiation, also provide natural flows of primary energy to renewable generation technologies.
- Centralized generation technologies convert primary energy to electricity and transmit it over high-voltage transmission lines.
- Transmission substations step down voltage, then lower-voltage distribution networks transmit electricity to communities and businesses.
- End-use technologies (e.g., electric lights, air conditioners, Wi-Fi routers) convert electricity into value-added services (e.g., illumination, comfort, connectivity).

EXHIBIT 2

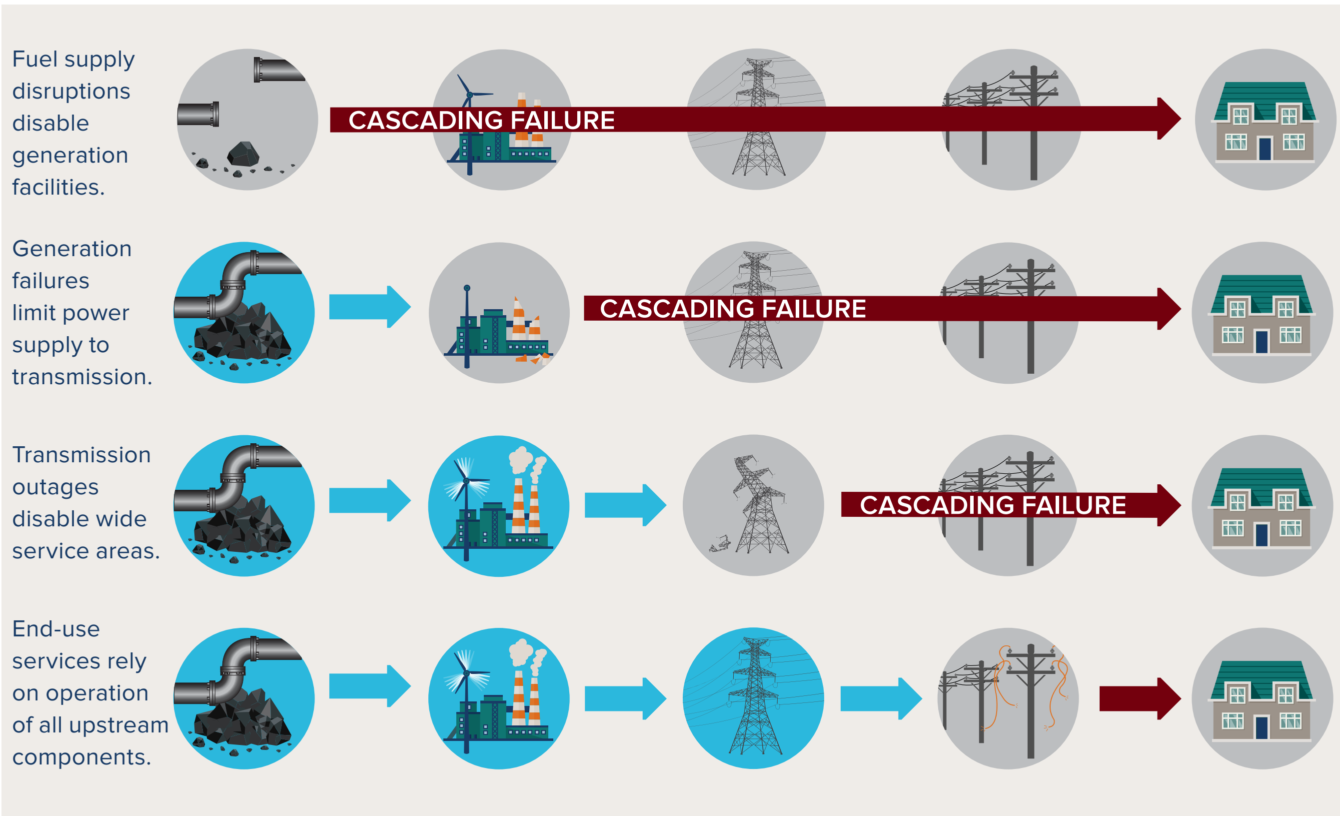
Overview of Grid Architecture and Associated Components



This one-way value chain, a product of historical economies of scale and network economics present over the past century, has also reinforced a "top-down" resilience paradigm that enforces interdependencies within the grid. Specifically, it is only possible for consumers and businesses to receive value from the electricity system if all of the components of the power system and the connections between them function properly. Disruption of any one component of the power system, or any single critical connection between components, precludes the ability of end-use consumers to use electricity to deliver valuable services. In other words, the grid value chain developed over the 20th century has set up a system designed for resilience from the top down, but that system relies on multiple critical failure points, and delivers value to consumers only if none of those failure points are disrupted. Exhibit 3 illustrates the reliance of end-users upon all upstream components within the power system. The synchronous grid—dependent on thousands of large, costly, and precise machines rotating in exact synchrony across half a continent—heightens interdependencies and vulnerabilities.

EXHIBIT 3

Cascading Vulnerabilities of the Grid



Existing Approaches to Ensuring Grid Security

Current practices by the US government and the electricity industry generally seek to maintain grid security and resilience by reinforcing each element of the value chain. This is done by independently assessing risks associated with each component within the grid, and pursuing mitigation strategies that reinforce the linear dependence and cascading vulnerabilities. Exhibit 4 summarizes the risks present and mitigation approaches commonly taken for each component of the grid value chain, and the following sections provide further detail for each grid infrastructure component.

EXHIBIT 4

Summary of Current Risks to Grid Components and Associated Mitigation Strategies

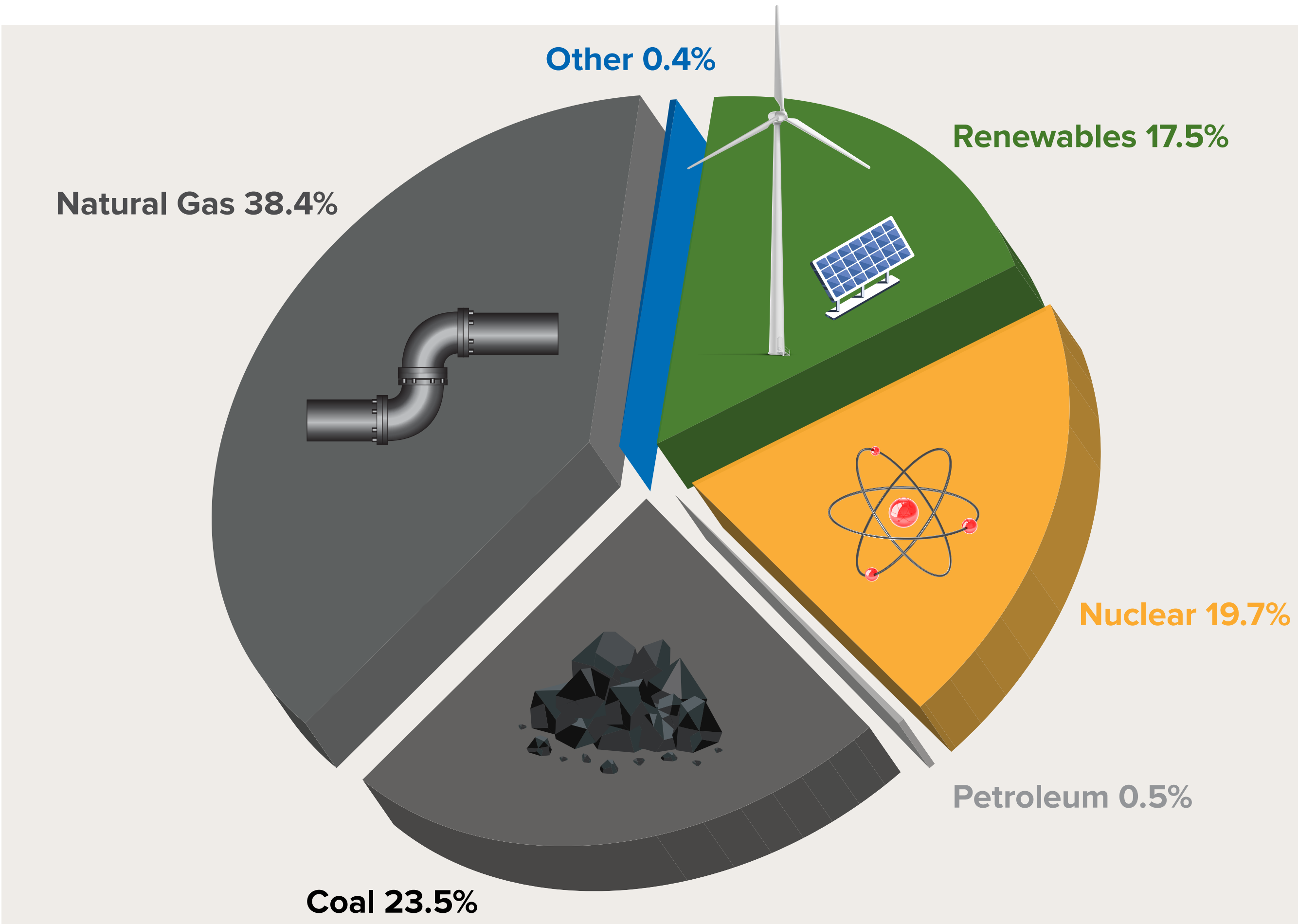
	Fuel	Generation	Transmission	Distribution	End-Users
Risks	Coal and natural gas supply chains can be susceptible to extreme weather and natural disasters. Natural gas transmission and distribution networks can add interdependent complexity.	Severe weather or other forced outages can disable equipment within generators. Renewable energy resource availability depends on weather.	Transmission hardware infrastructure (lines, poles, towers, transformers, switchgear) can be susceptible to severe weather and other natural disasters. Substation equipment and control centers can be targets for physical attacks and cyberattacks.	Distribution infrastructure can be susceptible to severe weather and other natural disasters.	All upstream threats can have cascading effects.
Current Mitigation Approaches	Redundant and/ or stored fuel supply. Diversity in generation mix to reduce dependency on single fuels.	Generation reserve margin. Improved renewable forecast accuracy.	Grid hardening and modernization. Contingency analysis and planning (e.g., alternate power flow paths).	Grid hardening and modernization.	Diesel backup generators. Behind-the-meter solar and/or storage.

Fuel Security

The majority of US electricity is produced by generators reliant on fossil fuel supply chains of varying length and complexity, each with its associated vulnerabilities. In 2019, 63% of the power generation in the United States came from fossil fuel-based plants, primarily coal and natural gas.[27] Exhibit 5 illustrates the reliance of US power generation on transported fuels.

EXHIBIT 5

Share of Utility-Scale Electricity Generation by Source in the United States in 2019



Coal Supply Chain Risks

Coal supply chains have common vulnerabilities associated with the geographic concentration of their key infrastructure. Coal is normally transported through railroad, barge, truck, or intermodally (e.g., barge-to-rail). In 2013, 67% of the coal produced in the United States was shipped by rail.[28] The railroad network used for coal transportation is most heavily concentrated in the Powder River Basin (PRB) that spans Northeastern Wyoming and Southeastern Montana, which in 2015 provided 40% of the coal in the United States.[29] Those railroad lines can be affected by extreme weather; in 2005, two trains derailed in Wyoming due to heavy snow, causing the curtailment of coal production in the PRB for several months and doubling the spot price.[30]

Fuel supply to coal-fired generators is also at risk from extreme weather even after coal is successfully delivered to generating stations. Coal piles can freeze in cold weather, which makes it impossible to unload from railcars or move on conveyor belt between supply piles and generating equipment. In 2011, 50 fossil-fueled power plants in Texas, totaling 7 GW, shut down due to burst pipes and frozen coal piles.[31]

Natural Gas Supply Risks

Natural gas-fired generators rely on pipeline capacity to deliver gas from production regions within the United States to generation facilities. As natural gas is used for both heating and power generation, there is competition for both fuel and supply pipeline capacity during periods of peak demand. During cold weather, heating is commonly prioritized over power generation use, diverting natural gas to buildings from electric generators, which at times cannot procure enough fuel to keep running. In the 2014 polar vortex, the Northeastern United States experienced a peak of over 8,000 MW of generator outages,[32] with curtailments and interruptions of natural gas delivery directly causing over 3,000 MW of outages. This happened again in the polar vortex in January 2019, when 2,930 MW of gas generation was idled because of a lack of fuel in the PJM power pool.[33] The natural gas system also depends on the electricity system, which uses electric motor-driven compressors, meaning power outages can also disrupt pipeline delivery capabilities. Loss of distribution pressure (which depends on transmission pressure) can extinguish numerous end-use devices' pilot lights, requiring retail gas service to be suspended across large areas to prevent explosions, then reestablished by tedious door-to-door visits.

Approaches to Mitigate Fuel Supply Risks

Approaches to mitigate fuel supply chain and deliverability risks center on the idea of requiring or incentivizing "fuel security" for generating facilities. At the federal level, the US DOE released a report in August 2017,[34] followed by a Notice of Proposed Rulemaking (NOPR)in September 2017,[35] ordering the Federal Energy Regulatory Commission (FERC) to "accurately price generation resources necessary to maintain reliability and resiliency" and design rules for "recovery of costs of fuel-secure generation units frequently relied upon to make our grid reliable and resilient." This rule would have guaranteed cost recovery for power plants capable of maintaining a 90-day supply of fuel on site, but was unanimously rejected by FERC in January 2018 due to a lack of evidence showing that "existing RTO/ISO tariffs are unjust, unreasonable, unduly discriminatory or preferential." FERC's decision echoed the filed comments of numerous analysts that argued that subsidizing "fuel-secure" resources would fail to address more significant risks, especially within the transmission and distribution system, that cause several orders of magnitude more service outages than fuel security-related disruptions.[ii]

Meanwhile, FERC initiated a proceeding that asked regional grid operators to evaluate the resilience of the bulk power system,[36] which expanded the discussion beyond just fuel security. Individual market operators all responded. ISO-NE stated in its response that fuel security is the most significant resilience challenge in New England, especially against the backdrop of coal, oil, and nuclear unit retirements; constrained fuel infrastructure; and the difficulty in permitting and operating dual-fuel generating capability.[37] ISO-NE conducted an operational fuel-security analysis in 2018 showing that fuel-security risk, particularly in winter, is the foremost challenge to a reliable power grid in New England.[38] The study proposed a number of measures that could help improve system reliability, including:

- Improving generators' advance arrangements for timely winter deliveries of liquefied natural gas (LNG);
- Adding more dual-fuel capability, which would increase the inventory of stored oil available to generate electricity; and
- Increasing adoption of renewable resources, which could reduce dependence on coal- and oil-fired plants.

[ii] See, for example, the filed comments of Amory Lovins that summarize many issues associated with subsidizing fuel-secure resources: **https://rmi.org/wp-content/uploads/2017/06/RMI_FERC_Memo_2017.pdf**.

Generation Adequacy

Conventional generators, such as coal, natural gas, and nuclear, made up 76% of US installed capacity in 2019.[39] Renewable generators, including distributed energy resources, are rapidly gaining market share, and generation from renewables is projected to surpass nuclear and coal by 2021, and to surpass natural gas in 2045.[40]

Generator Mechanical Failures

Most generation capacity in the United States relies on rotating machines that can be disabled by routine outages or during emergencies. Extreme weather events, in particular, can cause breakage/shutdown in the energy conversion equipment, and this effect can be magnified when combined with fuel supply issues. During the January 2019 polar vortex, PJM experienced forced outages in 10.6% of total generating capacity.[41] This was due to a combination of natural gas supply shortage, coal and natural gas plant outages, as well as a nuclear plant shutdown due to frozen water-cooling equipment.[42]

Renewable Variability

Renewably powered generators, such as hydro, wind, and solar, do not require transported fuel supply or water-cooling equipment like coal, nuclear, and gas generators.

At the same time, renewably powered generators have the risk of not being able to generate power during peak demand periods, due to resource variability. For example, the ISO-NE fuel security analysis stated that solar PV systems can help reduce summer peak demand in the region, but not winter,[43] as the winter peak arrived after sunset. Wind power can help with evening load, but variations in wind speed as well as outages caused by extreme wind speeds and/or blade icing can complicate planning and operation. Hydro generation, especially in regions with common droughts like California, might create reliability and resilience concerns, especially under the forecast increases in extreme heat waves, droughts and water supply stress.[44]

Approaches to Mitigate Generation Shortage Risks

Reserve margin is the most commonly used way to mitigate generation shortage risks, and it has been widely adopted by regional grid operators. The DOE 2017 Staff Report concluded that all regions have reserve margins above resource adequacy targets, which in most regions are set at 15% above predicted peak load.[45]

Improving renewable forecast accuracy can effectively mitigate the renewable intermittency risks. Several efforts from national labs and regional grid operators have significantly improved wind forecasts over the past decade, enabling wind resources to contribute more effectively to reliable system operations.[46]

Transmission Network Security

The US electric transmission network consists of approximately 700,000 circuit miles of lines,[47] of which 70% (including their transformers) are over 30 years old,[48] and some are more than a century old.

Transmission System Risks

There are risks associated with various components along the transmission network. Large power transformers are easily identified and difficult to protect from physical attack. They have long lead times for replacement (5–20 months) due to their specialization and reliance on third parties and/or offshore manufacturers. Transmission towers and lines are also vulnerable, due to their accessibility and lack of surveillance, but most can be restored quickly. Transmission system control centers and/or control equipment can also be targets for cyberattacks. A FERC study concluded that a coordinated attack on nine critical substations across US interconnections could lead to a national blackout that could last for at least 18 months.[49] The attackers could presumably then try again, by physical or cyber means or both.

Approaches to mitigate transmission network risks

Transmission grid hardening is often considered most effective in preventing the outage and minimizing the impact of the outage. This includes hardening the hardware (lines, transformers) as well as smart grid and grid modernization technologies, such as using line sensors and smart relays to detect outages and island the system.[50]

A comprehensive contingency plan can help enhance the response speed and improve recovery efficiency. Regional grid operators, such as NYISO and CAISO,[51] conduct regular single (N–1) or multiple (N–1–1) contingency analyses for the bulk power system and implement associated plans.

Distribution System Hardening

There are more than 6 million miles of distribution lines across the country,[52] and more than 60% of the distribution transformers and distribution poles are 30–50 years old.[53] Meanwhile, 90% of electric power interruptions are attributed to distribution systems,[54] underscoring the urgency to upgrade the network to improve system resilience.

Distribution System Risks

Distribution system infrastructure is in general vulnerable to severe weather, natural disasters, and fire. Underground portions of the distribution system are more resilient to those threats than overhead systems, but are still at risk from earthquakes and flood, and are less prevalent in the United States than overhead systems due to significantly higher costs.

Another major category of distribution system-related risk stems from the widespread nature of distribution systems, and the associated difficulty of gathering information in a timely manner. In many areas of the country lacking advanced metering infrastructure (AMI) and other related technologies, utilities still need to send out a truck with technicians manually detecting faults.[55] This adds complexity to distribution system operations, and slows utility response when outages occur.

Approaches to Mitigate Distribution System Risks

Across the country, utilities are proposing distribution grid modernization projects that can enhance monitoring, control, and optimization capabilities of the distribution systems.[56] A federal effort led by the Department of Energy and that includes national labs, utilities, researchers, and local stakeholders is exploring innovative approaches to enhance resilience of the distribution systems,[57] including projects ranging from software platforms helping with outage response and recovery, to developing flexible architecture coordinating centralized and decentralized assets in the distribution system, to designing blackstart solutions from DER feeders, which will be discussed in more detail in Chapter 5.

Backup Power for Critical End-Use Services

At the downstream end of the power grid, any risks and outages from the upstream transmission and subtransmission grids could have cascading effects on the power delivery to end-use customers. During outages, industrial, commercial, and residential customers do not have access to power unless they have a backup source, such as diesel generators or "islandable" solar PV systems.

Diesel Fuel Security Risks

Diesel backup generators have the same fuel supply issue as central-scale generators, in that they are limited to fuel on-hand or deliverable during emergencies. Those generators usually maintain a 72-hour fuel reserve,[58] after which the generators would rely on a functional diesel fuel supply chain to sustain operation. Diesel distribution systems are susceptible to extreme weather that can affect pipelines or transportation (if diesel is distributed by rail, barges, or tankers). After Hurricane Maria in Puerto Rico, 2,500 gallons of diesel were needed every day to power generators to sustain food and medicine supply, yet there was a severe lack of fuel for trucks to deliver those supplies across the rugged island.[59]

Solar PV Associated Hardware and Software Risks

Behind-the-meter solar PV systems can be installed at critical customer sites and can potentially provide power during outages, but currently the majority of them cannot "island" (i.e., they are unable to operate unless their inverter is connected to an energized grid). This guaranteed inoperability of PV resources otherwise available during daytime is due to older inverter standards or, in some jurisdictions, utility interconnection rules not yet updated for IEEE Standard 1547 amendments that now allow auto-islanding in ways that keep line workers safe. Solar PV systems are also susceptible to weather that destroys the physical panels and cyberattacks or EMPs that could disable inverters and control systems (such as PV maximum power point trackers).

Approaches to Mitigate Backup Power Risks

Currently the most prevalent approach to enhance resilience against outages from the customer side, regardless of the fuel shortage risks, is installing on-site diesel backup generators. Behind-the-meter solar installers, including Sunrun and Tesla,[60] also sell solar-plus-storage systems that can provide backup power to individual residential customers. Overall, the market for solar and solar-plus-storage as a backup power resource for residential customers is still nascent, and there are economic and technical challenges that need to be considered (see Chapter 5) before it can fully scale. These challenges are greater for larger customers with higher power demands and commensurately limited ability to provide backup power with on-site renewable resources.

3 Catastrophic Risks to Grid Security

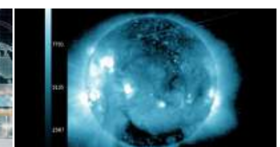
Catastrophic Risks to Grid Security

Summary of Key Points

- A set of high-impact, low-probability events poses catastrophic risks of long-term power outages, with corresponding risks to US economic activity and national security.
- Both natural events (e.g., extreme weather, geomagnetic storms) and malicious attacks (e.g., physical sabotage, cyberattacks, and electromagnetic pulses) are increasingly likely to occur and increasingly serious for the grid and economic activity.
- Each of these threats has the potential to disrupt multiple components of the power system's value chain, with risks amplified by the cascading vulnerabilities present in current grid infrastructure.

EXHIBIT 6

Summary of Catastrophic Risks, Grid Impacts, and Current Mitigation Activities

	 Extreme Weather and Natural Disasters	 Physical Attacks	 Cyberattacks	 Electromagnetic Pulse Attacks and Geomagnetic Disturbance
Examples/Definition	Hurricanes, superstorms, cold spells, high winds, wildfires, earthquakes.	Bombings, shootings, wire cutting, arson.	Deliberate exploitation of computer systems in order to gain control of or damage the grid.	An electromagnetic pulse (EMP) is caused by high-altitude detonation of a nuclear device. A geomagnetic disturbance (GMD) is caused by a severe solar storm.
Scope of Potential Damage	Damage or destroy infrastructure; cause precautionary power outages to avoid wildfires.	Most attack effects would be limited to local grid; coordinated attack potentially catastrophic.	Disable or limit access to grid control systems, resulting in outages and/ or infrastructure damage, potentially widespread and long-lasting.	Wide-area damage to transmission and distribution infrastructure. In the case of EMP, indiscriminate damage to unhardened electronic equipment.
What is Being Done?	Emergency response plans for critical facilities; grid hardening.	Physical security standards; spare transformers.	Cybersecurity standards and processes.	Reliability standards; scenario simulation.

This chapter provides an overview of high-impact, low-probability threats and their potential impacts on the electric grid. For each catastrophic risk, we also review current mitigation strategies. Exhibit 6 provides a summary of risks and impacts, with details explored in subsequent sections. This study does not address every risk to grid security; in particular, we omit here any direct discussion of pandemics or other human-related threat vectors (e.g., insider attacks). However, we will discuss in this and other chapters how the risks posed by human-related threats share many of the same failure modes and mitigation opportunities as the catastrophic threats discussed here.

Extreme Weather and Natural Disasters

Extreme weather events, including hurricanes, superstorms, cold snaps, flooding, and particularly heat waves that have led to wildfires across the globe, are likely to increase in intensity and frequency due to continued climate change.[61] In addition, certain regions of the country are vulnerable to longstanding natural disasters including earthquakes, coastal and inland flooding, high winds, and extreme heat.

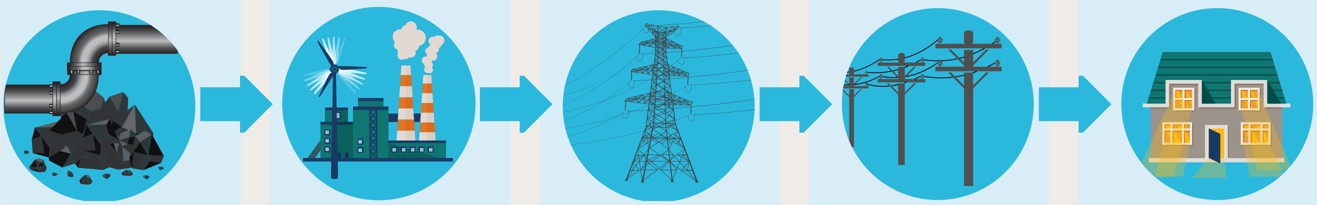
In the past two decades, most major power outages in North America were caused by extreme weather and natural disasters.[62] Hurricanes have caused several large outages. The 2017 Hurricane Maria in Puerto Rico caused major economic loss, and the power supply was not fully restored until 18 months after the hurricane,[63] while a 6.4 magnitude earthquake in January 2020 led to another blackout across the island.[64] It is estimated to take a decade to reconstruct and modernize the island's grid to be a truly resilient system,[65] assuming that currently inadequate or held-up funding is actually provided and governance/structural issues are overcome—the two often being interrelated.

Extreme weather events can cause widespread damage beyond the electricity system. They can displace people and damage transportation and communications infrastructure, compounding the effects of an electricity service outage. The Camp Fire in California in November 2018 became the deadliest and most destructive fire in state history, leveling nearly 14,000 homes,[66] and power lines were reported to be both the cause of the fire and the main compounding factor when fallen power lines blocked the streets for evacuation.[67]

Even when extreme weather does not directly cause a power outage, it can contribute to conditions where utilities must proactively de-energize power lines and cause customer blackouts in order to minimize broader risks. In California in 2019, in part as a response to the fires caused by utility equipment in 2018, utilities executed "public safety power shutoff" (PSPS) events in an attempt to avoid catastrophic fires caused by energized power lines arcing to the ground or trees during extreme wind events. Those PSPS events led to significant economic loss to the communities and utilities, and should only be adopted expediently until more resilient solutions are urgently implemented. Chapter 7 discusses the impact of PSPS in more detail.

EXHIBIT 7

What Is Susceptible to Extreme Weather and Natural Disasters



Fuel	Generation	Transmission	Distribution	End-Users
Natural disasters affecting transportation systems can disrupt diesel and coal supply chains. Persistent cold weather can cause freeze-off of natural gas pipelines.	PV systems and wind turbines can be physically damaged or rendered unable to generate electricity due to inadequate conditions. Thermal plants cannot function if there isn't enough cooling water supply due to the rising temperature of surrounding rivers, lakes, and coastal waters.[68]	Transmission lines and towers are susceptible to extreme weather (e.g., high winds, wildfires, and other natural disasters). Their impacts can cascade, as when heat plus wind cause or worsen wildfires.	Distribution lines and poles are highly susceptible to damage from natural disasters as they are the most geographically distributed components of the electricity system.	Natural disasters and extreme weather can displace end-users, reducing load to serve but also creating a need to meet customers' basic needs through community centers or other places of refuge.

What is Being Done to Address Threats from Extreme Weather and Natural Disasters?

Utilities in regions prone to extreme weather and natural disasters have incorporated disaster planning into their operation. For example, Florida Power & Light Company (FPL) has a comprehensive storm plan,[69] which includes an annual week-long storm drill as part of the year-long employee training, as well as emergency response plans for critical facilities, including hospitals, police and fire stations, communication facilities, water treatment plants, and transportation providers. FPL also has ongoing investment plans in infrastructure hardening, including tree-trimming, pole inspection and upgrading, and smart grid technology installation.

After several severe wildfires in the past two years, PG&E in California is implementing a safety plan to mitigate the risks from wildfire, earthquakes, and other climate-driven extreme weather and natural disasters, including such measures as adding weather stations in the high fire-risk areas, upgrading more reclosers and circuit breakers with remote control capabilities, partnering with additional communities in high fire-threat areas to create new resilience zones that can power central community resources, and more.[70] The PSPS events described above are part of the safety plan, but those events also create their own risks and negative impacts. Chapter 7 discusses in more detail what alternative solutions could offer.

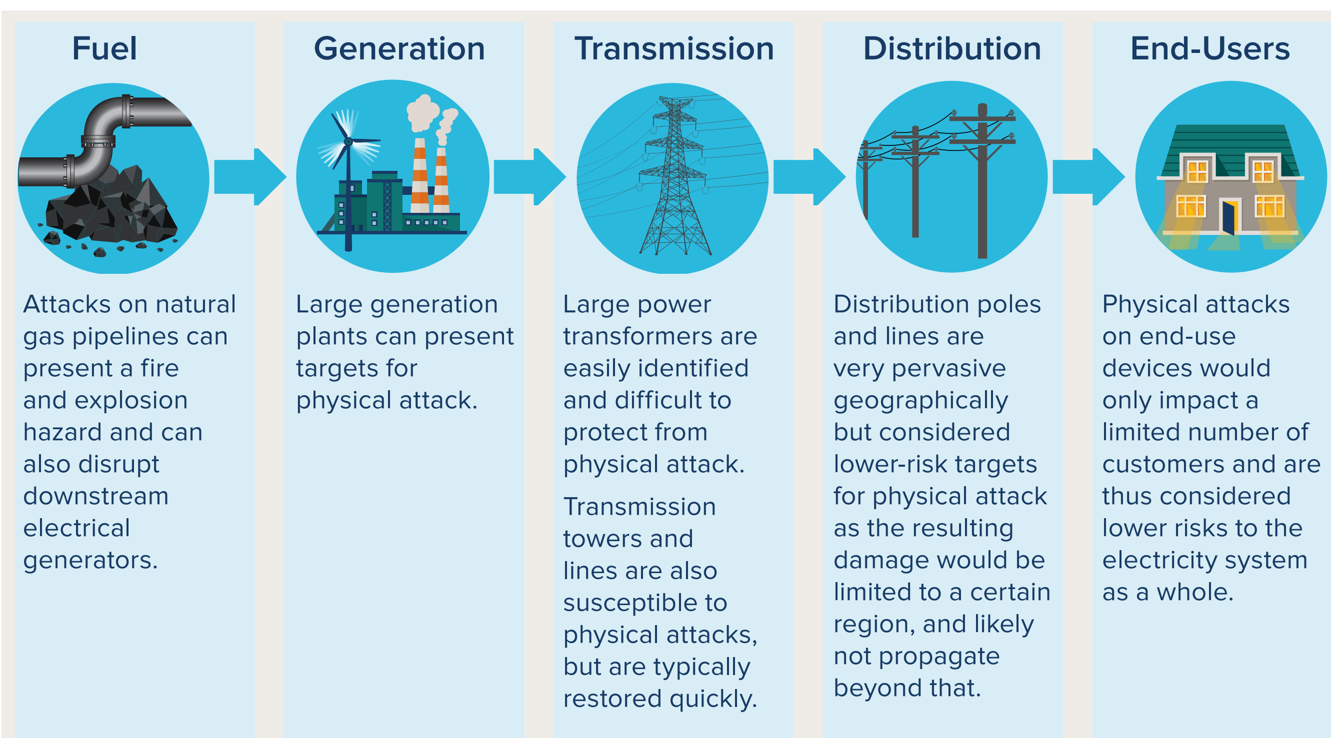
Utilities serving communities in rural areas face unique challenges in mitigating the risks of outages caused by extreme weather, and some are pursuing novel approaches to address these challenges directly. For example, Holy Cross Energy, an electric cooperative in the Roaring Fork Valley in western Colorado, is partnering with community organizations including health and emergency services, city and county governments, school districts, transportation providers, and private businesses to understand priorities and identify opportunities for resilience improvements that leverage both utility- and community- or customer-owned resources.[71]

Physical Attacks

Physical attacks on grid infrastructure can include bombings, shootings, wire or fiber-optic cable cutting, and arson. Potential attacks range from large, coordinated attacks by nation-states to small guerilla-style or covert attacks by individuals. In 2013, PG&E's Metcalf substation was attacked by highly trained snipers, resulting in the shutdown of 17 large transformers.[72] Fortuitous interruption of the attack before it knocked out the largest transformers (and a modification of the adjacent power plant's switchyard wiring, reportedly not on as-built drawings) meant that this attack had little impact on the customer power supply, but the repair cost was over $15 million. But without those two mitigating factors, a deep and prolonged interruption to Silicon Valley's main power supply could have occurred, with potential economic and political effects that would

EXHIBIT 8

What Is Susceptible to Physical Attacks



make it tantamount to an act of war if the attackers were known. Attacks by individuals, for example the series of attacks on transmission lines and substations in Arkansas in 2013,[73] can also cause major impacts to local service territories.

What is Being Done to Address Threats from Physical Attack?

Utilities are investing in better security systems and barriers to protect critical infrastructure, such as large power transformers.[74] Mutual assistance programs, like SpareConnect and Spare Transformer Equipment Program (STEP),[83] allow bulk power system operators to share transmission transformers and other equipment in the event of a physical attack.[iii] The STEP program also maintains an inventory of spare transformers. Some spares are single-phase, combinable into three-phase installations using smaller, lighter, more transportable, and readily installable modules. The North American Electric Reliability Corporation (NERC) has developed standard to deter, inhibit, moderate, or prevent physical attacks to the bulk power system, including workforce training, information sharing, and restoration planning.[76] However, the vulnerable assets are so widespread that defense is difficult. For example, making chain-link barriers opaque could obstruct rifle attacks but would not prevent attacks with easily portable and available mortars or even rocket-propelled grenades.

Cyberattacks

Cyberattacks are deliberate exploitations of computer systems in order to gain control of or damage the grid. Cyberattacks can be carried out by a single individual or by groups, with or without nation-state backing. The scale of the attack is proportional to the sophistication of the attackers. The 2015 Ukraine cyberattack is considered to be one of the first known successful cyberattacks on a power grid.[77] Russian hackers took 60 substations offline by gaining control of computers in three control centers, leaving 230,000 residents without power on Christmas day. Simultaneously, call centers were overwhelmed with a denial-of-service attack to prevent reporting of outages.

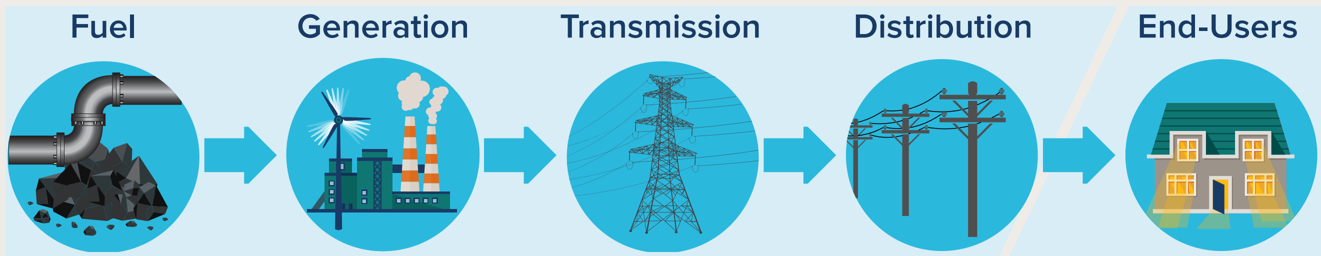
Cyber systems can be infiltrated with attacks going undetected for a long period of time, allowing the intruders to study the system, identify interdependencies, and then carry out a combined attack at a time of their choosing to maximize cascading failures. Following a cyberattack, the intruder may still have access to the system and carry out subsequent attacks. Some kinds of cyberattacks could cause catastrophic damage to large numbers of billion-dollar rotating machines over a wide area. These are typically custom-built machines, often made only overseas, with manufacturing lead times of one to several years.

To date, there has not been a reported cyberattack that has caused major outages in the United States. The Department of Homeland Security has reported attempts to insert malware in electric power control systems,[78] although none have yet caused significant disruption in service. Duke Energy was fined $10 million by NERC for cybersecurity violations,[79] including critical cyber assets, between 2015 and 2018, although it was not clear if hackers ever gained access to the utility's system. Privately, many utilities report tens to hundreds of probing attacks per day.

[iii] However, many large transformers have custom specifications that limit interchangeability, and the extent of this issue is not publicly reported.

EXHIBIT 9

What Is Susceptible to Cyberattack



Much of the critical electrical infrastructure is controlled by legacy Supervisory Control and Data Acquisition (SCADA)/Industrial Control Systems (ICS), which were designed decades before internet connectivity. Such systems often lack basic security measures such as authentication and encryption,[80] making them insecure by design. The Defense Science Board's 2008 panel study found that utilities often set simple passwords all the same or left them set to the factory default.[81]

SCADA systems control generation plants, transmission and distribution control centers, and natural gas delivery system and oil supply chains.[82]

Distributed devices can present common-mode failures,[83] which allow a vulnerability to be exploited across thousands or millions of nearly identical, geographically dispersed devices. These devices include distributed generators (wind, PV) and inverters, storage (batteries, EVs), demand response devices (e.g., thermostats), smart meters (AMI), and smart appliances (e.g., washers/dryers).

Despite the absence to date in the United States, cyber-related major outages have drawn increasingly significant attention given widespread Internet of Things (IoT) development. Each IoT device needs its own connection point to the grid, which inherently introduces many more points of entry for cyberattacks than traditional centralized assets. Furthermore, security researchers have identified the potential for networks of IoT devices to launch denial of service and other attacks on grid-connection information technology and operations technology, with an associated risk of major blackouts.[84]

What is Being Done to Address Threats from Cyberattack?

NERC provides clear cybersecurity standards for bulk power system through its Critical Infrastructure Protection (CIP) standards.[85] Most distribution systems, however, are not required to comply with NERC CIP standards,[86] even though distribution-level events are more frequent than transmission-level events.[87]

Cybersecurity receives close attention from US government agencies given the potentially critical consequence of cyberattacks. President Obama released Executive Order 13691 in 2015,[88] encouraging the sharing of cybersecurity threat information between the private sector, public sector, and government, though information-sharing continues to be slowed or blocked by classification rules and clearance procedures. The DOE has also created a platform, the Cybersecurity Risk Information Sharing Program (CRISP),[89] to promote the sharing of classified and unclassified threat information between utilities and national laboratories. The Defense Advanced Research Projects Agency (DARPA) runs the Rapid Attack Detection, Isolation, and Characterization Systems (RADICS) program for power engineers, cybersecurity personnel, and first responders to accelerate restoration of cyber-impacted electrical systems.[90] The effectiveness of these measures against sophisticated state actors, several of which are widely believed to have pursued longstanding exploration and even preparation for potential grid cyberattacks, is not publicly reported.

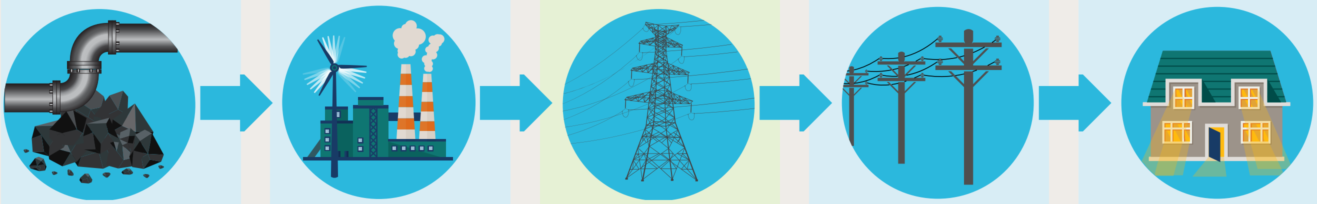
Geomagnetic Disturbance and Electromagnetic Pulse Attacks

Wide-area electromagnetic effects can be triggered by either an electromagnetic pulse (EMP), high-altitude detonation of a nuclear device, or a geomagnetic disturbance (GMD) caused by a severe solar storm. In both cases, the electromagnetic event induces large currents through long-distance wires in the electrical grid. In 1989, a magnetic storm caused the collapse of the Canadian Hydro-Québec power system,[91] leaving 6 million people without power for nine hours. In 2003, a smaller GMD led to short blackouts in Scotland and Sweden.[92] Historically, impressive examples have occurred when the power grid was small or not yet invented; such an event today could destroy many of the most critical high-voltage transformers.

Compared to GMD, EMP produces a broader band of effects, and thus has the potential to damage a wider variety of electronic equipment. However, there are very limited examples of EMP effects to draw from, and very little unclassified understanding across the industry of the likely impacts of an attack. EPRI's study in 2019 concluded that a 1 megaton nuclear weapon detonated at 200 km (174 miles) above the Earth's atmosphere can affect a circular area of about 3 million square miles.[93] But not all areas included within those 3 million square miles would experience the maximum impact of an EMP. Those high-altitude detonations that could produce strong EMPs over subcontinental areas would need little guidance and no reentry technology to be highly effective, so it appears it is within current attack capabilities.

EXHIBIT 10

What Is Susceptible to EMP and GMD[iv]



Fuel

Electronics and control systems in transportation infrastructure can be damaged, disrupting the supply chains of diesel, coal, and natural gas.

Generation

Electronics and control systems can be damaged by an EMP, affecting the operation of both thermal generators and renewable systems.

Transmission

Long-distance transmission lines are most susceptible as current induced by an electromagnetic event is proportional to the length of the wire.[94] Resulting damage will likely be at transformers and protective relays. Communication systems will also be affected.

Distribution

Power lines, tower structures, and relays can be affected.

Damage to the grid in affected areas may cause cascading failures in unaffected areas.

End-Users

It remains unclear to what extent smaller electrical devices (cell phones, vehicle electronics) will be affected. With increasing digitalization, more devices can be susceptible to EMP. It would be prudent to assume widespread damage.

EMP only

EMP and GMD

What is Being Done to Address Threats From EMP and GMD?

NERC has convened industry and government experts to better understand the impact of electromagnetic events on the bulk power system and has offered a set of considerations and recommendations. Generally, NERC recommends[95] sharing plans with neighboring jurisdictions and government agencies to coordinate restoration efforts in the event that interdependent systems, such as telecommunications, are shut down. To better characterize GMDs, US Geological Survey (USGS) is mapping scenarios of potential electromagnetic storms,[96] and the National Science and Technology Council has released reports on GMD strategy and an action plan.[97] The 2006–2008 Defense Science Board panel was told that protecting a large and critical transformer from GMD would cost only tens of thousands of dollars (for a diode shunt to ground, discharging powerlines' induced direct current that would otherwise saturate the transformer iron, leaving the transformer unable to handle its alternating-current load too). However, many utilities have not taken this precaution over the dozen years since that report, because of a lack of immediately available funding and/or cost-recovery mechanisms for the required expense.

[iv]GMDs are comparable to the E3 wave form of EMP, which affects long lines. Only E1 and E2, which are unique to EMPs, can affect smaller electronics. Therefore, all those risks are associated with EMP only, except transmission lines that are susceptible to both EMP and GMD.

EMP research activities are mostly at the federal level. The Congressional EMP Commission has released a series of declassified reports that assess the risk of EMP attack from potential national threats,[98] prioritize critical infrastructure for protection,[99] and establish reliability standards for a GMD event.[100] Weapons causing EMP effects could only be launched by a small number of state actors with sophisticated nuclear weapons and intercontinental ballistic missile technology,[101] so the US military, rather than NERC and FERC, are considered responsible for preparation and deterrence of the attack. Military electronic devices are commonly required by specification to be EMP-hardened. Civilian devices may be able to achieve similar EMP resistance at lower cost; EPRI's 2019 study estimated a small incremental cost for an EMP-hardened utility control center.[102]

Common Trends Across Catastrophic Risks

Though each threat is distinct, they share a number of common impacts in the context of the existing power system:

- **Broadly Similar Consequences Across Risks**
  Although catastrophic risks have different causes and specific mechanisms of disrupting grid components, the consequences to the grid are likely to be fairly similar. Human-made attacks also tend to be combined (e.g., coordinated cyber/physical attacks). As such, it is not often necessary or useful to assess threat-specific risks and mitigation opportunities.

- **The Value of an "All-Hazards" Approach**
  An "all-hazards" approach to resilience can help integrate resources available and develop plans against a wider range of outage scenarios. This approach has been suggested by government agencies as well as national labs,[103] and the labs specifically pointed out that "measures that are threat-agnostic, providing system-wide resilience against a wide range of known and unpredictable threats, may be much more cost-effective than measures that only address a single threat." In the following chapters, we take such an all-hazards approach in evaluating the technologies and measures that would help enhance resilience across the grid.

- **Multiple Points of Failure Reinforce Vulnerabilities**
  Each catastrophic risk described above can disable multiple components of the grid. Since current grid architecture requires all components of the fuel-to-customer value chain to remain operational in order to avoid outages, when these risks break any of the components, the whole grid would be disrupted, and end-use customers would not have access to power at all.

4 Technologies Reshaping the US Grid

Technologies Reshaping the US Grid

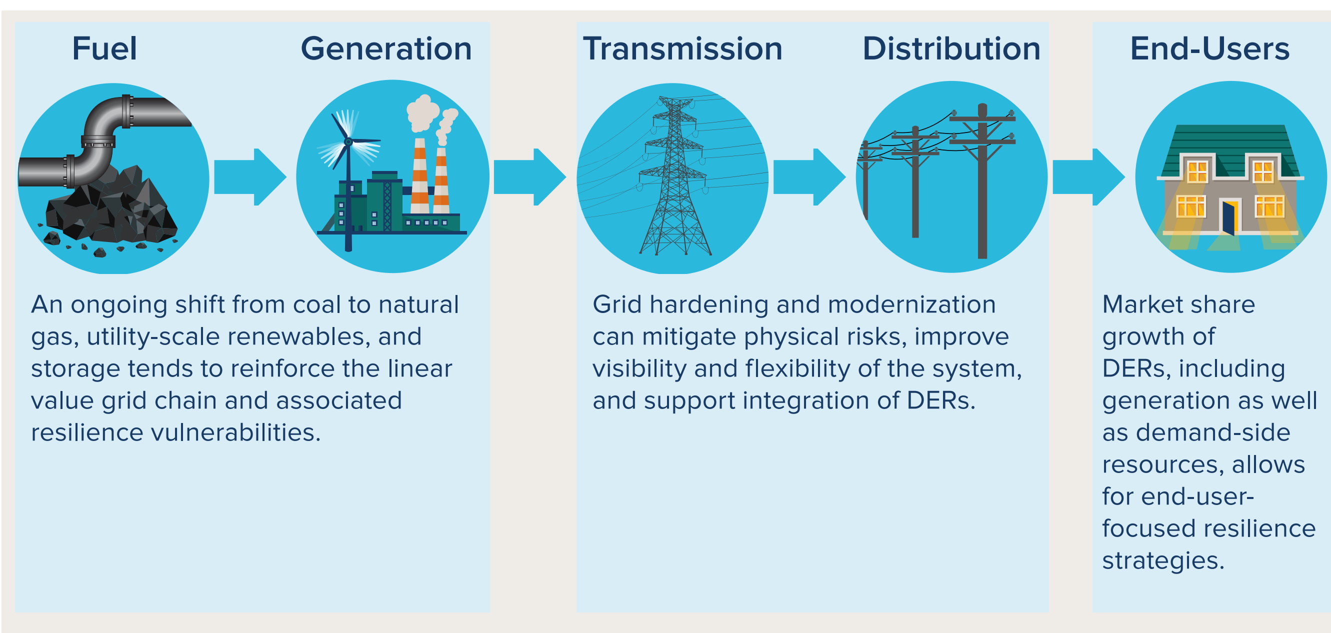
Summary of Key Points

- A set of both existing and emerging technologies is rapidly gaining market share in the US electricity system, reshaping the infrastructure that powers our economy.
- Primarily driven by economics, new generation technologies including natural gas, utility-scale wind farms, utility-scale and distributed solar, battery energy storage, and internet-enhanced demand-side management tools are taking a larger role in investment and future resource plans.
- Each of these "market-winning" technologies has implications—some positive, some negative—for power system resilience.

This chapter provides an overview of a set of grid technologies gaining market share across the United States, affecting both the power supply mix as well as grid architecture. For each category of technology, we also summarize resilience impacts. Exhibit 11 provides a summary of technology trends and impacts, with details explored in subsequent sections.

EXHIBIT 11

Summary of Key Technological Trends in Power Sector Transition



Fuel and Generation

Large-scale, centralized generation has long provided a sizable majority of power in the United States, and that remains true today, but the fuel mix of central-station supply is changing rapidly. The percentage of coal generation in the total supply decreased from 48% in 2008 to 27% in 2018, while natural gas generation increased from 21% to 35%, and renewables from 9% to 17%.[104] In 2019, coal continued falling to 24%.[105] This rapid transition has been driven by, among other factors, the increasingly competitive economics of natural gas and renewable generation. In many locations throughout the United States, it is less expensive to build natural gas or renewable generation than to maintain and operate existing coal plants.[106] The result has been a dramatic increase in utility-scale natural gas, wind, and solar generation. Among the 31.3 GW of generating capacity added in the United States in 2018, 60% is natural gas and 37% is wind and solar; in 2019, over 60% of new capacity added came from wind and solar.[107] In the meantime, approximately 13 GW of US coal capacity was retired in each of 2018 and 2019.

Looking forward, it is increasingly the case across much of the United States that new gas-fired generators are no longer the least-cost choice for new additions to the grid. Rather, the falling costs of wind, solar, and storage, coupled with advances in demand-side management approaches, have made "clean energy portfolios," which combine these resources, a lower-cost investment than new gas plants, while providing the same level of energy and other grid reliability services.[108] As of 2019, a growing number of US utilities have prioritized investment in clean energy portfolios,[109] and have minimized or abandoned new gas plants, as these economic trends become clearer.

EXHIBIT 12

Resilience Implications of a Shifting Power Supply Mix

Potential Values	Potential Risks
Wind and solar generators are not dependent on fuel, and are typically spread out across a wide geographic region. This removes dependence on a fuel supply chain common to coal-fired generators, and limits the ability of any geographically constrained natural disaster or attack to disable a significant fraction of renewable production. Coupled with storage, renewable generators have the potential to help with system blackstart (see Chapter 5 for more details).	All utility-scale generation relies heavily on the downstream transmission and distribution systems, reinforcing the grid's linear dependencies. Increasing reliance on natural gas generation introduces additional risks associated with natural gas fuel delivery. In addition to reliability risks during peak load events in wintertime when demand for gas in residential and commercial buildings is also high, additional resilience risks emerge to the extent that gas delivery infrastructure can be disabled by attack or natural disaster for long time periods.

Transmission and Distribution

Across the United States, utilities are increasingly prioritizing “grid modernization” investments to, among other things, improve the resilience of the networks that deliver electricity from generators to customers.[110] One major category of this investment is spent on hardening the transmission and distribution grid, including targeted undergrounding, tree-trimming, pole replacement, and other physical upgrades. Those investments can make the grid more resilient to the threats discussed in the earlier chapters, as well as speed recovery when they occur. Meanwhile, an increasing amount of investment is spent on smart grid technologies that can enhance the grid’s flexibility to limit the scale of grid failures, while enhancing the ability to accommodate higher levels of DERs. Distribution-level battery storage has started participating in wholesale electricity markets to provide grid services (e.g., voltage stabilization, frequency stabilization, and ramping), and has the potential to support portions of the distribution system to operate independently (see Chapter 5).

EXHIBIT 13

Resilience Implications of Grid Modernization Investments

Potential Values	Potential Risks
Modernized transmission systems can potentially be blackstarted through utility-scale renewables,[111] reducing reliance on upstream fuel supply chains and thermal generators. **Distribution systems connecting resources equipped with advanced controls can also be partially energized through DERs, enabling portions of the grid to operate and to serve prioritized local loads even if centralized systems are disabled by attack or disaster.**	**Physical upgrades to the grid (e.g., hardening) primarily address short-duration reliability risks (e.g., severe weather), often without directly addressing catastrophic outage risks described in Chapter 3.** **Continued reliance on aging transmission systems compounds risks associated with extreme weather (e.g., intentional outages driven by fire risk from transmission lines in California in 2019; see Chapter 7).** **Grid modernization technologies rely heavily on internet-based control and communication systems, which are prone to cyberattacks.[112]**

Customer-Sited Technologies

Distributed energy resources already constitute a fairly large share in the generation mix in some regions, and continue to gain market share with compelling economics.[113] In many locations, behind-the-meter (BTM) PV systems are cost-competitive with retail rates under common net-metering rate structures.[114] Many new PV systems are connected to the distribution network (MW-sized systems) or behind-the-meter (kW-sized). BTM battery storage is increasingly sited together with PV systems, and the solar-plus-storage system can be cost-effective for shifting generation—storing electricity when it is cheap and discharging it when it is valuable—as well as providing resilience value during outages.

Other customer-sited technologies are also gaining market share rapidly. Electrification of vehicles and buildings, driven both by economics and decarbonization policies, may add significant new load to the electricity grid, potentially offsetting savings from more-efficient end use. New electricity demand from building heating, water heating, and vehicle charging is flexible on an hourly basis,[115] allowing these loads to efficiently utilize variable renewable energy resources. These and other emerging demand flexibility and energy efficiency technologies often rely on internet-connected controls and monitoring services, creating both more visibility and control as well as new entry points for cyberattacks.

EXHIBIT 14

Resilience Implications of Emerging Customer-Sited Technologies

Potential Values	Potential Risks
Behind-the-meter PV systems with appropriate inverter technologies and/or storage can fully or partially power individual homes and businesses when the broader grid is de-energized. **Flexibility resources like battery storage and internet-connected demand flexibility devices can help maximize the use of any available electricity supply resources during long-duration outages on the broader electricity grid.**	**BTM devices depending on internet-connected control and communication systems are vulnerable to cyberattacks that potentially can affect a large number of devices simultaneously.**

5 Assessing Grid Resilience in a Changing System

Assessing Grid Resilience in a Changing System

Summary of Key Points

- Current approaches used to mitigate resilience risks have significant drawbacks in the context of catastrophic risks and the increasing prevalence of “market-winning” technologies.
- This chapter summarizes an updated framework to evaluate risk mitigation options in the context of rapid system change, focused on reducing linear dependencies, leveraging market forces, prioritizing critical loads served, and capitalizing on economic value to scale resilience solutions.
- We apply this updated framework to evaluate five interventions associated with market-winning technologies, and summarize insights common across interventions and risk scenarios.

A New Framework For Addressing Resilience Risks

The current approach used to mitigate grid resilience risks, as discussed in Chapters 2 and 3, has significant drawbacks in the context of emerging risks and technologies. Continued prioritization of existing methods to mitigate catastrophic risks to the grid is likely to fall short of improving resilience, impose unnecessary costs on customers, or both. This chapter introduces an updated framework to evaluate the risk mitigation options, addressing the drawbacks of the current approach.

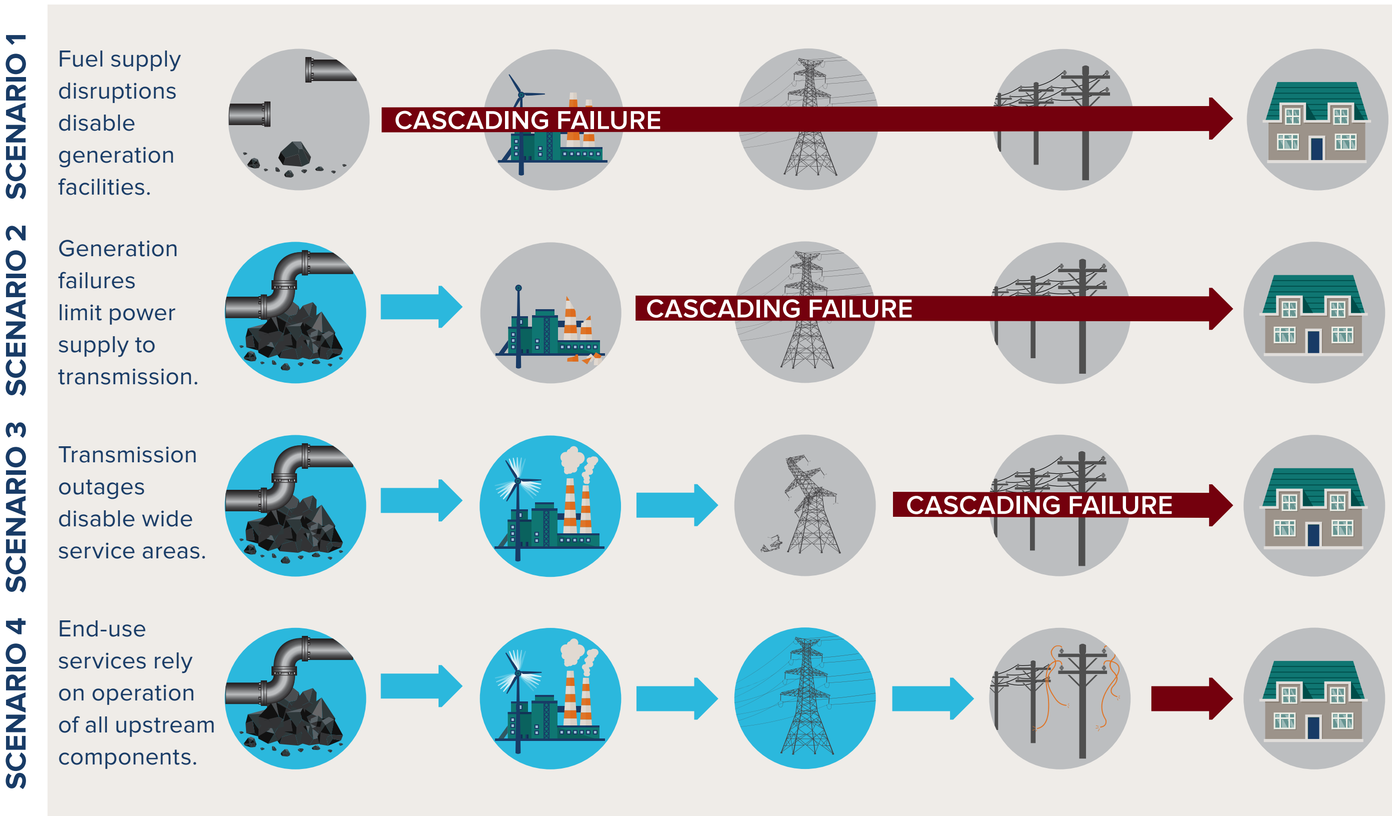
Addressing Common-Mode Failures

Current approaches to improve resilience typically fail to address the linear dependencies inherent in today’s grid. For example, efforts to improve fuel security have no effect on customer blackouts caused by transmission and distribution system outages, and typical grid modernization proposals do not prioritize the ability for customer-sited generation to work during such an outage. Current processes for restoration after an outage also explicitly rely on the linear dependencies of today’s grid,[116] by proceeding with system energization along the same one-way value chain that defines the vulnerability of the system.

As discussed in Chapter 3, a threat-agnostic, all-hazards approach can be more effective than looking at single threats in isolation, as it focuses on the common points of failure and the similar consequences led by various catastrophic risks. Here, we introduce four generic outage scenarios that correspond to the linear dependencies in the current grid. Exhibit 15 illustrates the linear dependencies of the grid, and the cascading impacts of the outage scenarios where parts of the system are disabled.

EXHIBIT 15

Four Outage Scenarios; Cascading Vulnerabilities of the Grid



The four outage scenarios are described below, and build on the threats identified in Chapters 2 and 3. These threat scenarios are not meant to be exhaustive or comprehensive; rather, they represent an illustrative set of failure modes characteristic of catastrophic resilience risks, with a particular focus on interactions with the technologies reshaping the grid technology mix. For example, the effect of a pandemic affecting the US population, including the electricity industry workforce, can be thought of in the same terms as other catastrophic threats that disrupt elements of the linear value chain (e.g., an inability of utility workers to effectively staff grid operations centers or maintain critical infrastructure).[117]

SCENARIO 1 Fuel Supply Partly Down

This scenario models the impact of an inability to deliver fuel (coal and natural gas) to thermal power plants, for example due to a cyber or physical attack or natural disasters.

SCENARIO 2 Dispatchable Generation Down

This scenario models the impact of a portion of dispatchable generators within the grid (i.e., coal, natural gas, reservoir hydro) being disabled, for example due to cyberattack, coordinated physical attack, or extreme weather (e.g., frozen or too hot cooling water).

SCENARIO 3 Transmission Partly Down
This scenario models the impact of the transmission system being disabled, for example due to an EMP attack, GMD event, cyber or physical attack, or extreme weather (e.g., proactive disabling of the system to lower wildfire risk).

SCENARIO 4 Distribution Partly Down
This scenario models the impact of a portion of the distribution system being disabled, for example due to a cyber or physical attack or extreme weather (e.g., overhead lines and towers destroyed).

Incorporating Market-Driven Technology Evolution

Current approaches to improve resilience typically either fight the market or ignore it. For example, efforts to subsidize uneconomic coal generation in the name of resilience run headlong into the prevailing market forces of inexpensive gas and renewable generation, increasing costs to customers. In addition, current approaches to resilience typically don't take into account the ability of emerging resources (e.g., behind-the-meter solar-plus-storage) to provide resilience services to customers and the broader grid. This static view limits the compatibility of current approaches to resilience with a grid resource mix that is being rapidly reshaped by market forces.

In this study, we take a dynamic view of market evolution by introducing three future grid mix scenarios that illustrate a range of possible market shares for emerging technologies, with different associated vulnerabilities, opportunities, and priority solutions for improving resilience. Exhibits 16 and 17 summarize each grid mix scenario, along with associated, illustrative impacts of building and vehicle electrification in each that would grow the scale of total electricity demand.

EXHIBIT 16
Three Grid Mix Scenarios (percentage of total generation)

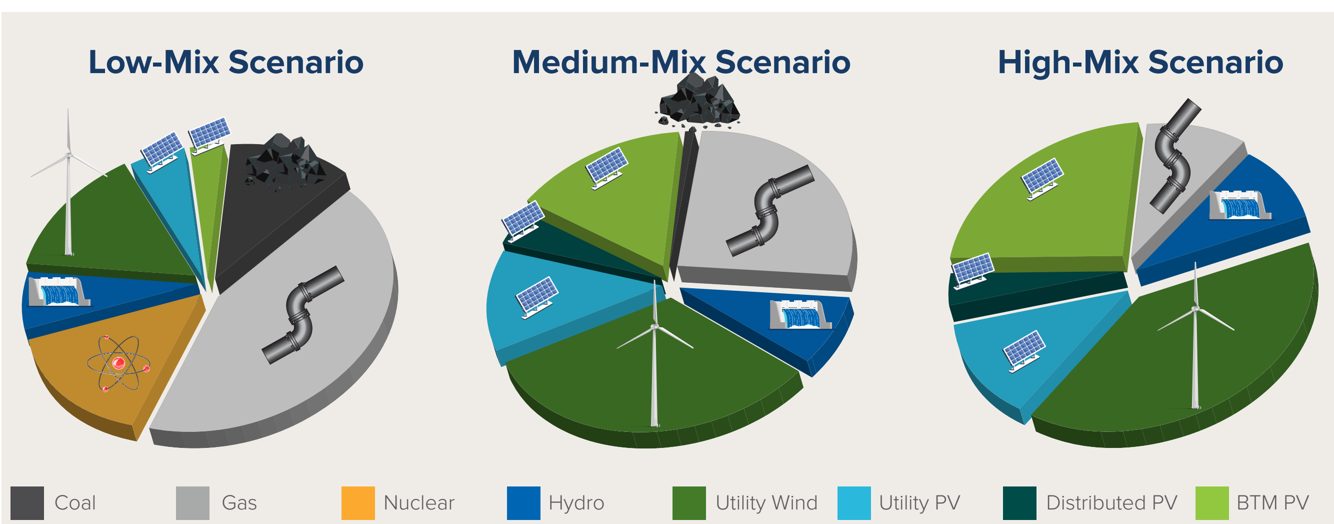


EXHIBIT 17

Future Grid Mix Description

Scenario	Description	Example Timing/ Geography	References
Low-Mix Scenario	30% RE, mostly utility-scale (3% DERs). Minimal transport and building electrification.	Similar to leading markets (e.g., Hawaii, California) today. Potential for average US grid mix in 10–20 years under "business as usual."	BNEF 2030 Scenario[118]
Medium-Mix Scenario	70% RE, 20% DERs. Moderate electrification (+20% load).	Leading markets in 5–10 years, or US average in 20 years under moderate carbon policy and/or technology advances.	Average BNEF 2050 Scenario;[119] RMI Reinventing Fire Transform Scenario.[120]
High-Mix Scenario	90% RE, 30% DERs. Significant electrification (+50% load).	Leading markets in 20 years, or US average by 2050 under CO_2 policy and/ or technology advances.	DER adoption consistent with RMI Reinventing Fire Transform Scenario;[121] electrification consistent with Evolved Energy Research 350 PPM scenarios[122]

Assessing Impact on Critical Loads

The current resilience approach often focuses on functionality of specific segments of the grid value chain, without guaranteeing the delivery of energy services to end-use customers. For example, proposals to enhance resilience by subsidizing resources with "fuel on hand" may succeed in guaranteeing a supply of coal ready to be burned to produce electricity, but do nothing to ensure the deliverability of produced power to end customers.[123] Further, the current approach doesn't actively differentiate high-value or critical loads from loads with little economic, health, and safety value. That homogenization makes it hard to assess impact and prioritize restoration activities according to the highest societal value.

To address this gap, we apply a generic load prioritization strategy (Exhibit 18) to characterize the ability of different interventions to provide critical loads with power. In this framework, we focus on two steps of load prioritization:

- Prioritize critical customers whose power consumption is most economically valuable and/or of high societal value (e.g., first responders, hospitals, water treatment).

- Prioritize critical loads for noncritical customers to maintain a basic level of service (e.g., life-safety and critical medical systems for all, light and heat for residential customers).

Such a pre-determined prioritization strategy, supported by emerging technologies, can help expedite the restoration process after outages (see callout box on page 48).

EXHIBIT 18

Load Prioritization Strategy

Before the Outage

1. Identify Critical Customers

Examples of Critical Customers: hospitals, military bases, cellular networks, first responders

Key Assumption
100% of the load for critical customers is critical load

2. Identify Critical Load for Non-Critical Customers

Examples Of Critical Load for Non-Critical Customers

Residential: heat and hot water in the winter season, home essential medical device

C&I: AC for pharmacies; fuel pumps for gas stations

Immediatly After Outage

1. Prioritize Critical Customers

Ensure uninterrupted power supply to critical customers, through bulk power and backup generation

2. Prioritize Critical Load for Non-Critical Customers

Rotate power supply or provide centralized power through refugee centers

During Power Restoration

Restore Power Based on the Load Priority

Noncritical loads will be powered only when all critical loads are met

Existing Restoration Process

In response to a major prolonged blackout, there are several routes to post-outage recovery and restoration.

1) Individual Power Restoration

Overview—This approach aims to island individual customers during an outage and bring individual power supply back up. It has minimal impact to the grid and doesn't require coordination across customers, utilities, and grid operators.
Current Practice—Solar-plus-storage service providers and inverter manufacturers are working together and have developed products to install backup systems at individual customer homes.

- Prior to the outage, service providers would work with customers to choose four to eight circuits in homes that are most important, for example garage doors, fridge, microwave oven, WIFI router, key lights, bathroom, etc., depending on the customer's preference.

- When an outage occurs, the backup system would be able to disconnect from the load center and power its own devices, and integrated circuit breakers would be able to monitor and control the power flow to power only critical loads.

- In the future, those systems could include smart breakers that can make optimized decisions and turn off certain appliances in real-time to conserve battery capacity. Already, wireless plug-through switches can route power in fully distributed fashion rather than by circuit. This may permit multiple levels of priority, and even automatic in-building dispatch that continuously limits total load.

- The communication system is currently using cellular protocol. If the cellular system and the data/telecoms systems behind it are kept powered (by on-site renewables and storage not needing fuel logistics), those systems would continue to get data in a blackout even without internet.

2) Community Power Restoration

Overview—This approach aims to restore power to as many feeders/customers as possible, which could lead to uninformed and indiscriminate load rationing. It requires either utilities communicating with customers in advance to identify critical loads, or individuals perhaps working with appliance manufacturers to decide which loads are most 'critical' to them. It also requires technical capability to dynamically isolate and reconnect portions of the distribution system.
Current Practice—Utilities are working with national labs to develop pilot programs on testing the self-driving grid, which we discuss in more detail in Chapters 5 and 6. So far, utilities are only able to control the load prioritization at the meter level, while appliance manufacturers are looking at appliance-level controls (e.g., cycled refrigeration) and working with customers to help ration their power.

3) Refuge Centers

Overview—This approach aims to provide shelter space for large numbers of people (normally one refuge center can hold 100–1,000 people) during outages that displace residents. Refuge centers can be designed with sufficient generation to meet load requirements for critical resources: medical equipment, water, sanitation, lighting, phone charging, etc. It requires prior planning and generally more centralized control. It's similar to the military bases and critical infrastructures discussed above.
Current Practice—This is already done in many places, normally led by local government agencies. Compared to other restoration approaches, this one is more "centralized" and to some extent still susceptible to disasters, either the ones like natural disasters that would indiscriminately destroy all infrastructure, or human-made attacks that target centralized key facilities.

Capturing Economic Value from Resilience Interventions

Current approaches to improve grid resilience typically prioritize only the ability to provide power during an extended outage, and fail to prioritize or capture any economic value outside of outage scenarios. In other words, common resilience interventions focus only on system performance during "black sky" days—the ability to avoid or recover from large-scale outages—without assessing the economic value (or lack thereof) associated with resilience-related investments on "blue sky" days when the grid is functioning normally.

For example, resilience approaches that rely on stock-piled fuel (e.g., coal at power plants or diesel to power backup generators) add both capital and operating costs for generator owners and customers. These costs must be recovered through revenues during normal grid operations. In contrast, emerging resilience interventions can avoid other sources of grid costs; for example, solar-plus-storage systems can provide backup power to customers on "black sky" days, while producing power and lowering peak demand during "blue sky" grid operation. This reduces fuel burn, system losses, and incremental generation capacity investment needs.

While the primary motivation for investment in resilience solutions is to avoid and speed recovery from large-scale outage scenarios, any secondary economic value can help increase the pace and scale of investment in such solutions and bring resilience benefits to more end-users. In this study, we qualitatively assess the economic value of resilience interventions, in addition to their value in mitigating outage scenarios.

Evaluating Current Resilience Interventions

Exhibit 19 summarizes key elements of the high-level framework discussed above. In the following sections, we apply this framework to evaluate the resilience impact of key interventions. We used a variety of methods in applying this framework, including tabletop exercises with utility partners and other industry experts, as well as structural modeling of system behavior under different outage and grid mix scenarios.

No Intervention (Business as Usual): Impact of Common-Mode Failures

We first evaluated the impact of common-mode failures without any additional resilience interventions, and summarize the results in Exhibit 20.

EXHIBIT 19

Impact Evaluation Framework

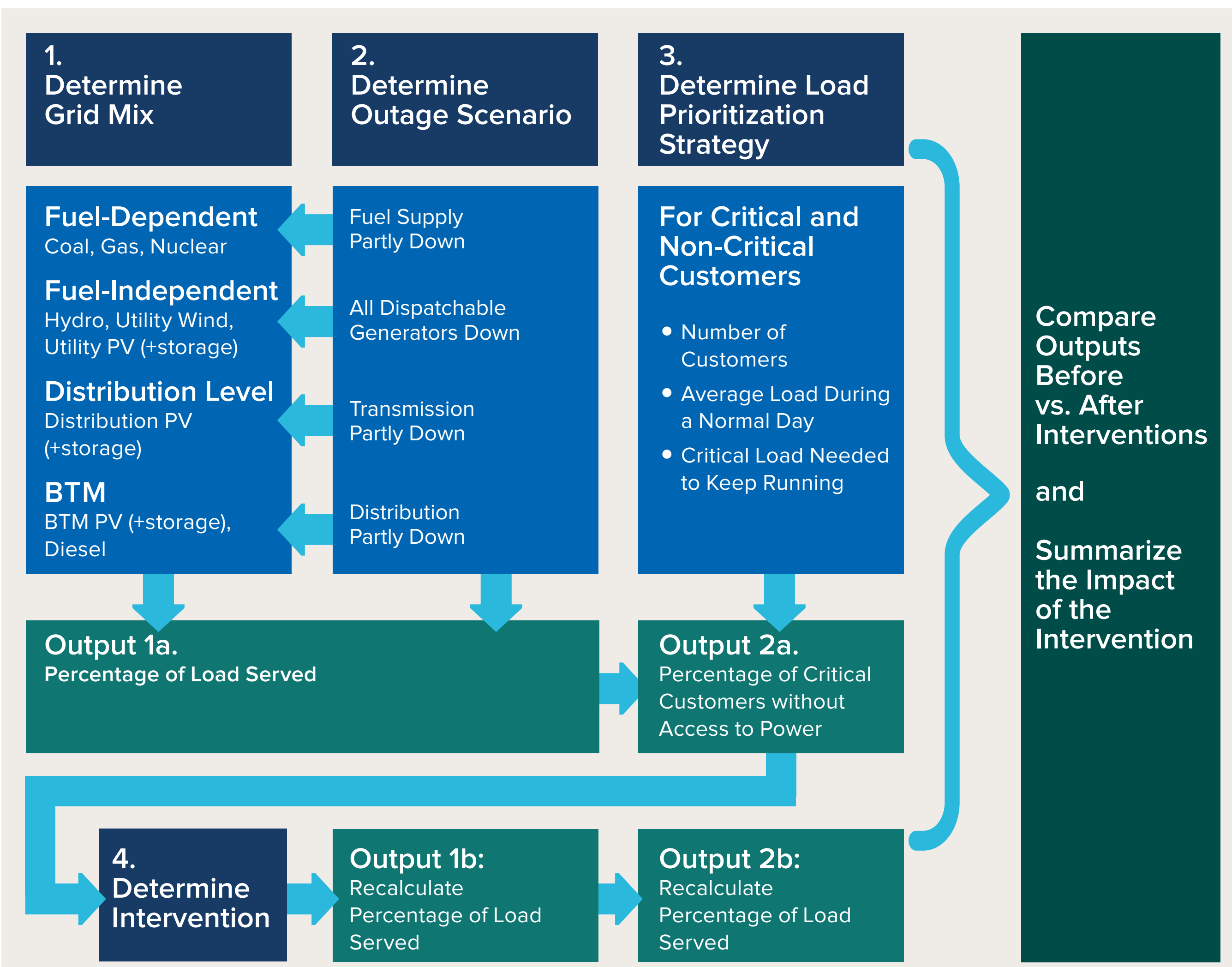
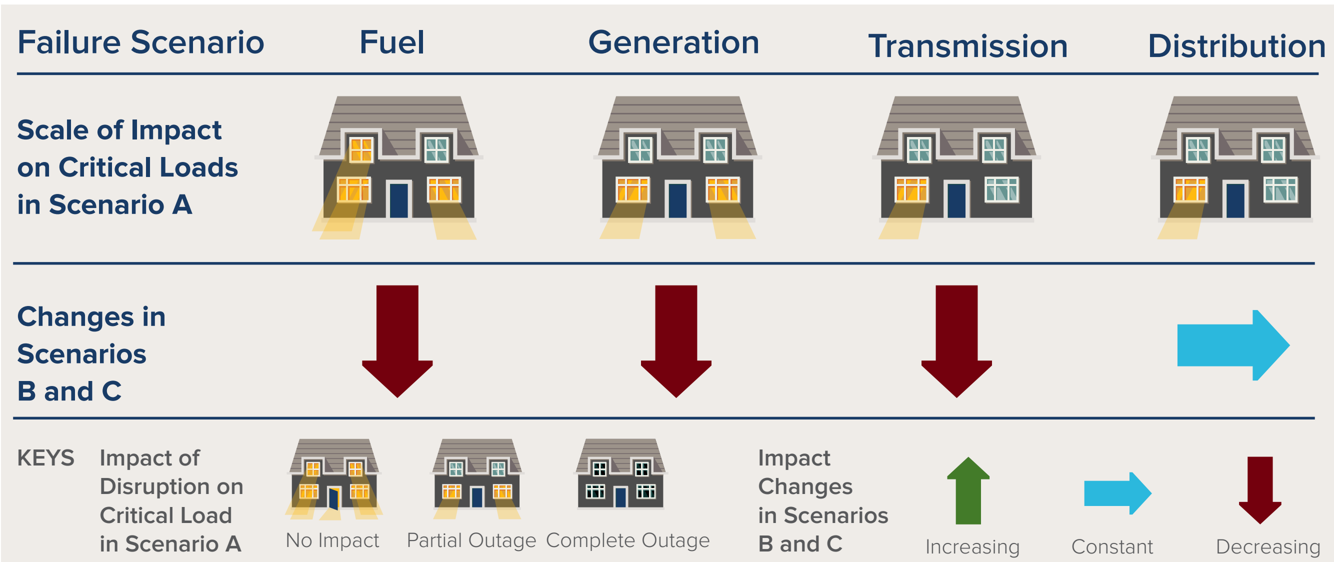


EXHIBIT 20

Impact of Common-Mode Failures on Ability to Serve Critical Loads



Applying an updated resilience framework reveals that disruptions closer to the customer generally have higher impact than disruptions further upstream. Upstream disruptions (i.e., in fuel and generation) can have cascading effects and limit power delivery to customers downstream, but since these disruptions are further from customers, there are opportunities for resources at all levels to mitigate the outage impact. For example, if fuel supply shortages limit coal and gas generation, system operators are able to use generators otherwise held in reserve to provide power. If a failure occurs closer to the customer, for example within the distribution system, there are fewer resources available "downstream" of the point of disruption that can be used to mitigate the outage.

As the grid transitions into a more decentralized system from Scenario A to C, disruptions generally decrease or at worst remain at constant impact. Generator fuel supply disruptions become less important as more renewable generation comes online, and disruptions to generator availability and transmission affect fewer critical loads as DER technologies increase market share. However, disruptions to the distribution system continue to affect downstream customers, including those who adopt DERs (unless those DERs are connected resiliently as described below).

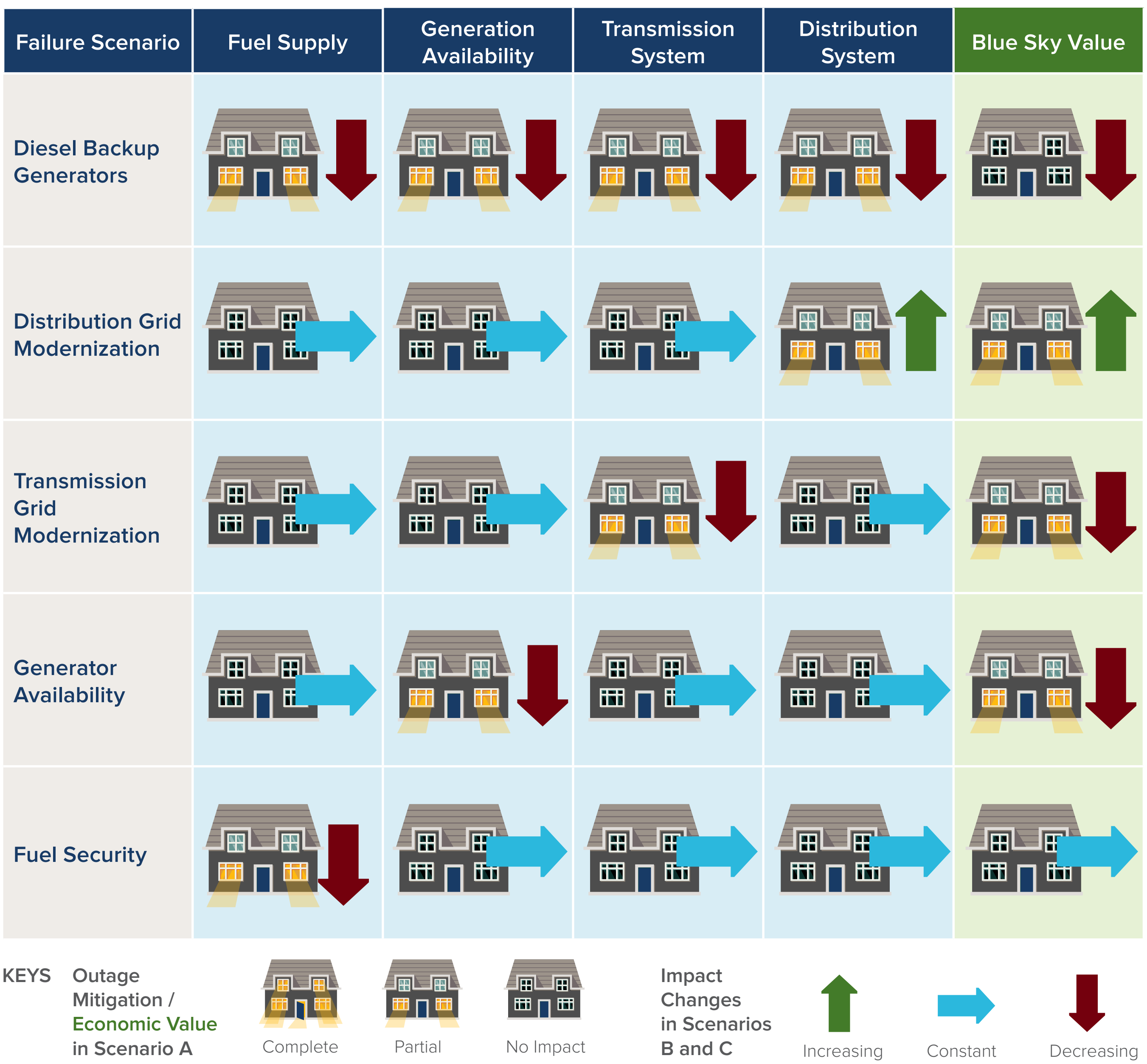
Importantly, this assessment does not quantify the likelihood of large-scale disruptions within each component of the grid, or the changes in likelihood as grid technology evolves. For example, disabling the transmission and distribution system serving a significant number of customers would require an attack (e.g., exploiting common software flaws across many devices) or a natural disaster (e.g., a GMD/EMP event or extreme wildfire) affecting a wide geographic area. Growth in DER and other internet-connected grid technology may increase the possibility of such a widespread attack unless offset by correspondingly greater care with cybersecurity and EMP hardening. On the other hand, targeted attacks or single disasters, which may be more salient threats in the near term, can disrupt fuel supplies or central generating stations that serve an equivalent number of customers.

Impact of Existing Interventions

We then evaluated the impact of existing interventions introduced in Exhibit 4 by comparing the reduction of outage impacts before and after certain interventions. Exhibit 21 summarizes the results.

EXHIBIT 21

Impacts of Existing Interventions under Different Failure Scenarios, and Changes in Impact with Shifts in Grid Technology Mix



INSIGHT 1 Each Intervention Is Limited To Addressing Risks Focused On Specific Segments.
With the exception of backup generators, current resilience interventions typically only mitigate the impact of a failure within a single component of the grid value chain. For example, distribution grid modernization approaches do not currently provide resilience value in the case of an upstream disruption, as the distribution grid requires power delivery from the transmission system to provide service to end-use customer loads. Interventions are thus limited in their ability to address risks across the system; for example, if a coordinated attack or disaster disables multiple components across the grid value chain, no single intervention can effectively address the systemic issue.

INSIGHT 2 Resilience Benefits Decline With Current Interventions As The Market Drives Grid Evolution.
As we move from Scenario A through C, the relative outage mitigation impact of each intervention decreases, mainly because the decentralized system reduces the need for upstream interventions. For example, fuel security and thermal generator availability interventions provide declining resilience value as additional fuel-free and/or distributed resources gain market share and can provide power during an outage. In general, the evolution of grid technology through each scenario already breaks down linear dependence, so segment-specific interventions have lower marginal value as the grid evolves.

INSIGHT 3 Each Intervention Has Limited Potential To Prioritize Critical Loads In The Event Of Widespread Outage.
Interventions shown in Exhibit 21, with the exception of diesel backup generators deployed at critical customer sites, typically provide a blanket solution to maintaining functionality within each component of the grid, without an ability to prioritize delivery of power to the highest-value services during an outage. For example, fuel security interventions are designed to enable continued operation of coal and gas generators, but have no means to prioritize delivery of coal- and gas-generated power to the most economically or societally valuable customers and loads (e.g., critical medical equipment) at the expense of discretionary or deferrable loads.

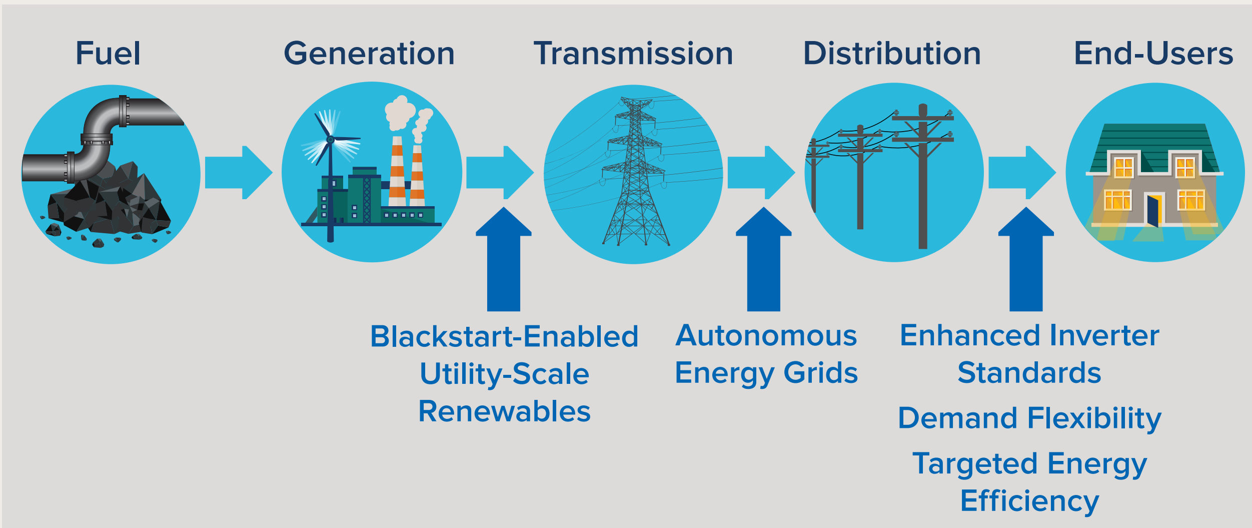
INSIGHT 4 Current Interventions Have Limited "Blue Sky" Value.
Among the interventions shown in Exhibit 21, only grid modernization investments provide the opportunity to capture meaningful value from resilience investments outside of outages. If designed appropriately, grid modernization investments can improve operating efficiency (e.g., reduce line losses), reliability (e.g., minimize short-duration outages), and capital efficiency (e.g., enhance DER integration) within the current grid, with benefits increasing in Scenarios B and C as renewable and DER technologies gain market share. Other interventions, including fuel security for central and backup generation, tend to only add cost for asset owners and customers during normal grid operations.

Emerging Interventions: Overview

In this section we explore interventions enabled by market-winning technologies and their impacts in the context of catastrophic threats. Exhibit 22 shows where these interventions sit in the energy system value chain, and the sections below define and characterize each approach.

EXHIBIT 22

Role of Emerging Resilience Interventions in the Grid Value Chain



Targeted Energy Efficiency

Overview of the Intervention

Improving passive efficiency for critical loads reduces the energy and capacity required to serve them during a long-duration outage. For example, improved building envelopes and high-efficiency equipment (e.g., LED lighting) for hospitals, emergency responder buildings, centers of refuge, and other similar facilities require less electricity to maintain safe internal temperatures. Targeted energy efficiency is considered “passive” as it doesn’t require changes in behavior after the emergency in order to minimize the power requirements for critical loads. As described in RMI’s *Brittle Power* study in 1981, end-use efficiency provides “the most bounce per buck,” both by stretching surviving supplies and by buying precious time to fix what’s broken.

Summary of Effects

Targeted energy efficiency reduces power needed for critical customer loads, allowing more loads to be served, and enabling more critical services to be delivered. Targeted energy efficiency is most impactful when there is insufficient power to supply full load and the distribution systems are intact. In this case, load prioritization coupled with efficiency would help increase the number of customers and end-use tasks that can be served.

Key Requirements

Once the energy efficient devices are installed, no particular change is required. However, an operating power distribution system is necessary for the excess power enabled by targeted energy efficiency to serve more customers.

Demand Flexibility

Overview of the Intervention

Demand flexibility interventions change the customers' load shapes through various levers, such as timed heating of water in water heaters, timed cycling of air conditioning compressors, and timed or grid-responsive charging of electric vehicles. Demand flexibility allows demand to match the production from available power sources, and therefore maximize the utilization of any power generated and delivered during an outage.

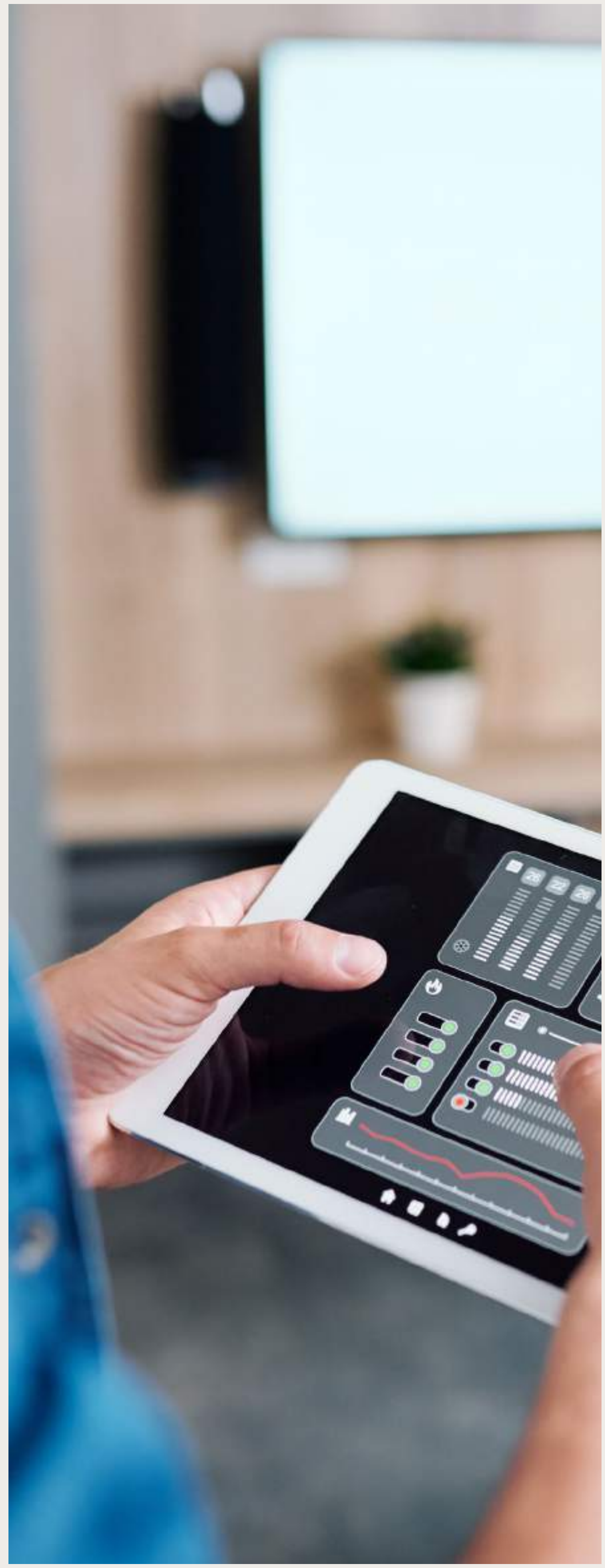
Summary of Effects

Demand flexibility shifts loads across time (on the scale of seconds to hours), reducing the instantaneous peak load when there's limited power supply and improving the delivery of critical services in periods of low generation availability. Demand flexibility potential is maximized when coupled with behind-the-meter generation, especially fuel-free solar-plus-storage systems. During an outage, generation from PV panels in excess of load or available storage capacity cannot be exported to the grid. Demand flexibility can shape the load curve to match PV production, reducing curtailment (e.g., by 40% in an RMI case study[124]) and ensuring utilization of as much available power as possible.

Demand flexibility would be most impactful when the entire system is not energized, and power generated from BTM PV systems is curtailed. In this case, demand flexibility would help maximize the utilization and improve system efficiency.

Key Requirements

Control and communication systems need to be in place to enable flexible control of loads. Systems that rely on off-site, internet-enabled services are at risk of failure due to broader communications disruptions during a large-scale outage unless, consistent with the internet's historical purpose, its key elements have resilient power supplies.



Enhanced Inverter Standards for BTM Generation

Overview of the Intervention

Different from conventional synchronous generators that rely on spinning turbines to create and maintain a steady frequency on the grid, variable renewable energy (VRE) such as wind and solar PV systems rely heavily on digital control protocols to determine how the machines would respond physically to the grid.[125] The IEEE 1547 standard is a set of requirements for interconnecting DER with the grid that dictates how such inverter-based technologies interact with the broader grid, including requirements for voltage and frequency ride-through, voltage regulation, islanding, and other operating modes.[126]

An older version of the standard, IEEE 1547-2003, which has been widely adopted in the inverters that are installed as part of behind-the-meter PV systems, have strict anti-islanding rules, and require inverters to trip offline when the voltage/frequency deviates from certain ranges.[127] This was mainly due to safety concerns to avoid the risk of unintentional islanding and potential damage, but can also make PV inverters quite sensitive to outages and disturbance on the grid. This anti-islanding feature could cause a huge loss of solar PV systems during voltage disturbance, which could then destabilize the grid.[128] The more recent version of the standard, IEEE 1547-2018, specifies both the electrical and interoperability/communication requirements for islanding solar PV systems.[129] Inverters that comply with this enhanced standard are able to communicate better with the bulk power system to coordinate on disturbance ride-through, and safely island from the broader grid to allow customers to use power from behind-the-meter PV systems during an outage.

Summary of Effects

IEEE 1547-2018 standard compliance enables solar PV systems with compatible inverters to remain online and serve loads behind the meter even when connected to a de-energized distribution system. Enhanced inverter standards can help increase the power available from "islandable" PV systems. Those PV systems, if coupled with the critical load identification features, can control the power flow to power critical loads only, thus automatically implementing the predetermined load prioritization strategy.

Enhanced inverter standards would be most impactful when the transmission system shutdown blocks bulk power delivery. In this case, enhanced inverter standards would help BTM PV systems ride through the disturbance and provide enough power for individual customers as well as neighbors.

Key Requirements

IEEE 1547-2018 allows inverters to safely island in an outage, but still hasn't been widely adopted. It is unlikely that existing inverters will be updated to comply with this new standard until the equipment is replaced at the end of life.

Importantly, even when PV systems are equipped with inverters capable of safely islanding during a distribution outage, many US utilities do not permit their interconnection due to outdated business practices that do not reflect the new inverters' capabilities. Thus, in addition to deployment of the updated standard, it is also necessary for utilities to adjust interconnection practices to fully leverage the islanding and grid support functions that the standard enables. The National Association of Utility Regulatory Commissioners has recommended that state commissioners pursue adoption of the updated standard in the interconnection processes of their regulated utilities.[130]

Autonomous Energy Grids

Overview of the Intervention

As defined by NREL, autonomous energy grids (AEGs) can "self-organize and control themselves using advanced machine learning and simulation to create resilient, reliable, and affordable optimized energy systems."[131] AEGs are a broader concept than individual solar-plus-storage systems or microgrids; rather, they are a set of control and optimization tools that can integrate various DER resources to operate "without operators." At this time, AEGs remains in the research space, but under active development.

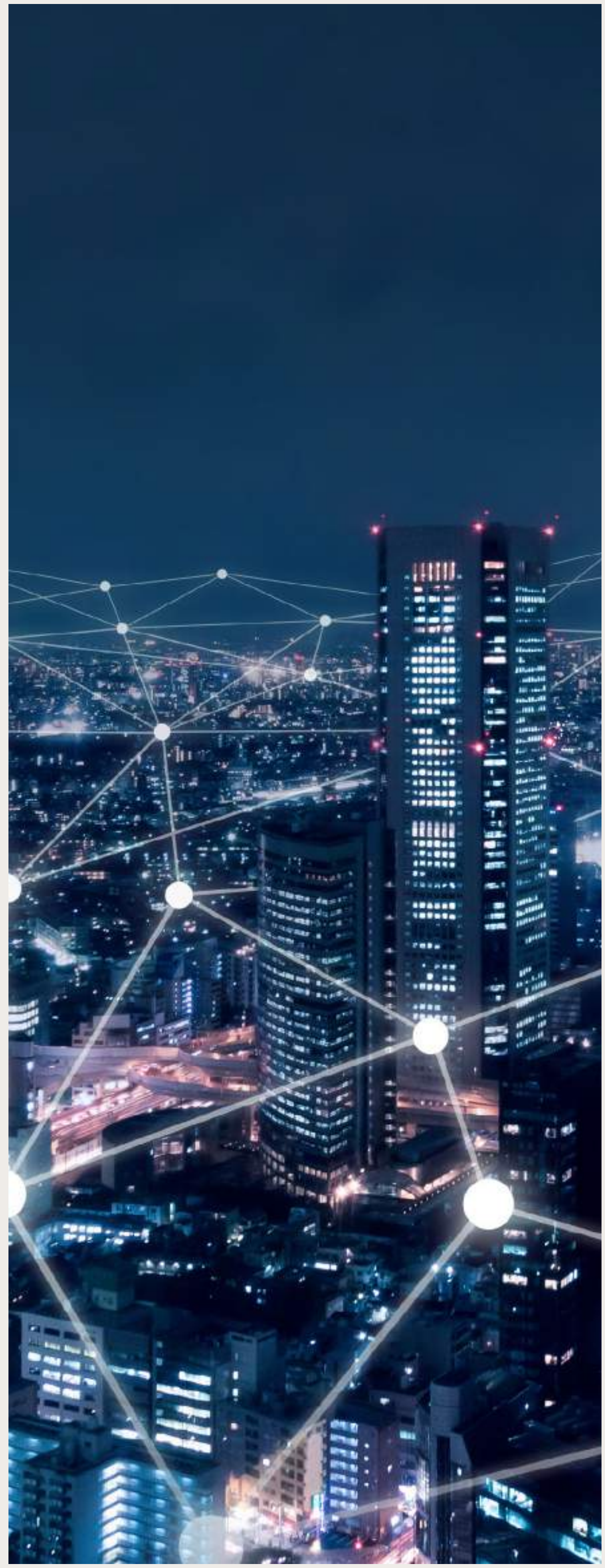
Summary of Effects

When the transmission system is de-energized, AEGs can allow for operation of portions of the grid in islanded or grid-connected mode, enabling portions of the distribution system, and connected DERs, to energize using available distributed generation and provide power to end-use loads. AEGs can allow people to share available power from DERs across physically intact, but otherwise de-energized, portions of the grid, enabling power delivery from distribution-scale resources during an outage.

Autonomous energy grids would be most impactful when the outage affects the ability to deliver power from the transmission system to the distribution system.

Key Requirements

Autonomous operation of distribution-connected resources would require inverter configuration to remain connected within the autonomous grid systems while isolating the energized system from the rest of the network. Similar to demand flexibility, communication systems need to be online in order to coordinate community-level restoration.



Blackstart-Enabled Utility-Scale Renewables

Overview of the Intervention

Blackstart refers to the process of reenergizing portions of the grid after an outage. The process normally includes coal and gas-fired steam units, gas combustion turbines, and hydroelectric units, and activates each according to a "cranking path" that energizes portions of the transmission system in sequence. Wind and solar generators usually operate in grid-following mode, and when an outage occurs, they would be disconnected until a stable frequency from restarted synchronous generators is available to support their operation. No grid operators currently employ wind or solar resources for blackstart services.[132] FERC and NERC studied blackstart availability following the 2014 blackout,[133] and recommended that grid operators mitigate the risk of relying on a single fuel for blackstart, suggesting they either diversify or obtain additional fuel security assurance.

With advanced inverter technology and battery storage to provide power balancing, it is possible to switch renewable energy resources into grid-forming mode to perform blackstart, with the potential to offer more resilient options during a blackstart event that do not rely on fuel supply chains.

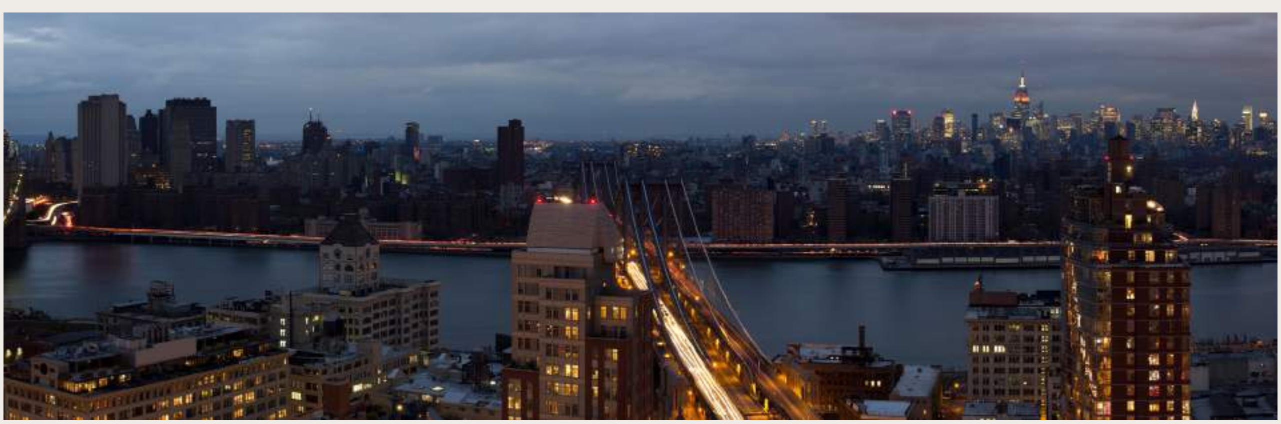
Summary of Effects

When transmission is down, utility-scale renewables could blackstart the transmission and distribution system, therefore powering the load. Blackstart from renewables would be most impactful when the transmission is not energized but is still physically intact.

Key Requirements

Both hardware and software requirements must be met before blackstart from solar and wind can be realized. Similar to the AEG requirements, the inverters must be capable of operating on a dynamic grid with dynamic loads and less inertial, spinning thermal generation. This would require modifications in both software and hardware. IEEE 2800 is the equivalent of IEEE 1547 on the transmission side that can enable inverters to initiate blackstart.

Power balancing is another key requirement for blackstart. Power supply and load need to be balanced all the time, and sufficient starting current needs to be provided to start electrical equipment, such as transformers and motors, or the loads must be segregated in such a manner as to enable controlled repowering of the grid.[134] This requires standardization from reliability organizations such as NERC.

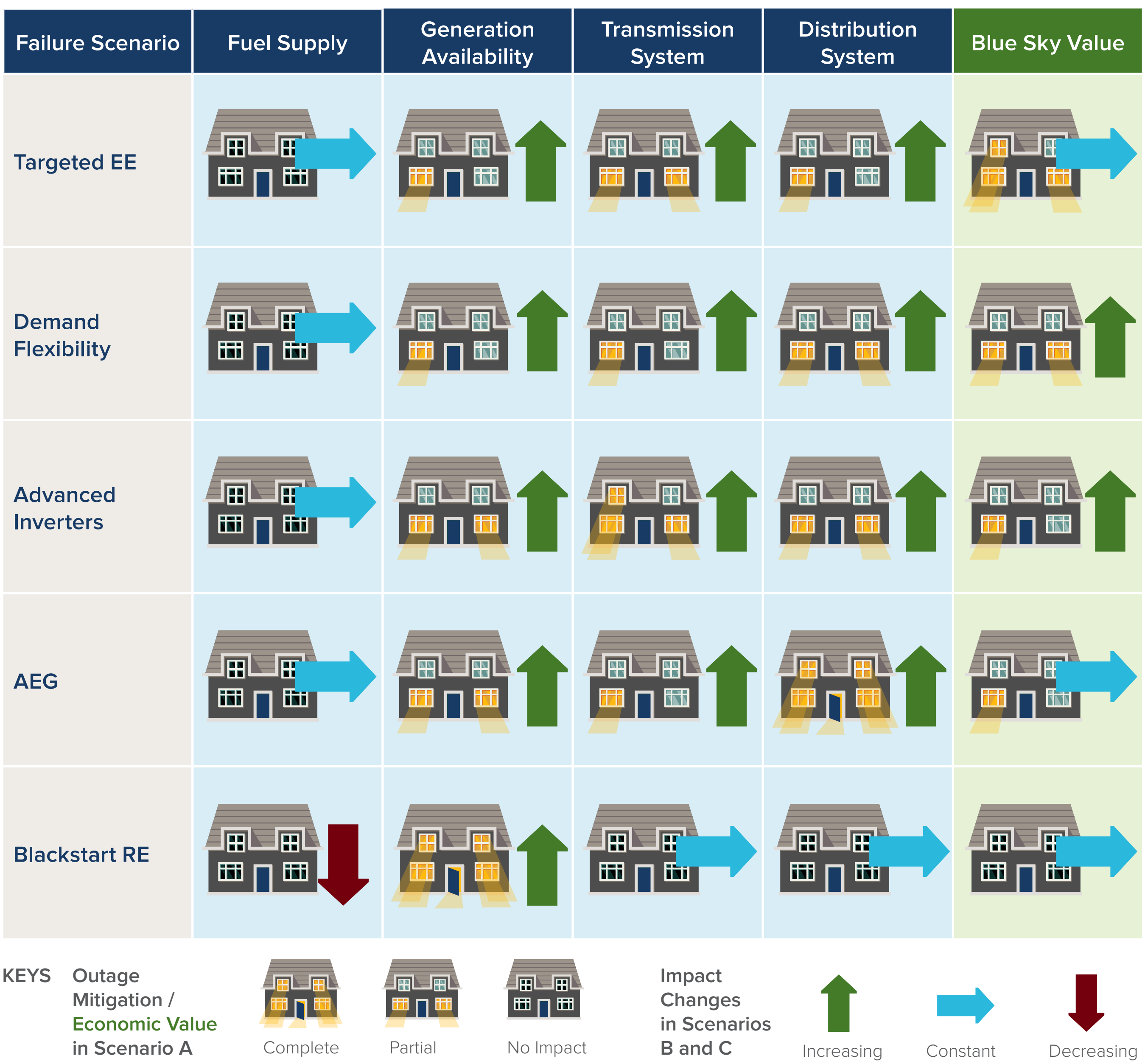


Impact of Emerging Interventions

We evaluate the impact of each emerging intervention by comparing the reduction of outage impact before and after the intervention. We also assess how outage mitigation changes as the grid mix scenario evolves. Exhibit 23 summarizes the results.

EXHIBIT 23

Impacts of Emerging Interventions under Different Failure Scenarios, and Changes in Impact with Shifts in Grid Technology Mix



INSIGHT 1 Distributed Resilience Interventions Have Value Across Outage Scenarios.

Only one intervention examined here—blackstart from renewables—is significantly upstream of customer loads. The other four interventions are at the distribution or customer level, and are able to mitigate failures that occur in all components of the grid value chain. Compared to the mostly upstream impact of existing interventions shown in Exhibit 21, the interventions closer to customers have higher impact across more modes of failure.

INSIGHT 2 Distributed Resilience Interventions Complement Each Other and Reinforce the Resilience Benefits Associated with the Ongoing Evolution of Grid Technologies.

Distributed resilience interventions tend to have higher value, relative to a case with no intervention, as the grid evolves toward higher shares of renewable and distributed energy resources. This is consistent with declining benefits from upstream interventions noted in the previous section. For example, the three customer-sited interventions in Exhibit 23 all have increasing resilience value with a higher share of renewable and distributed resources:

- **Targeted energy efficiency:** As more generation resources are located closer to customers in Scenarios B and C, efficiency for critical customers and loads enables a higher level of generation from distributed resources to be available to more customers and loads, both critical and noncritical.

- **Demand flexibility:** As the generating portfolio moves toward variable and/or distributed supply, demand flexibility enables loads (both critical and noncritical) to take advantage of available power and maintain service levels during a disruption.

- **Advanced inverters:** As the share of behind-the-meter generation grows, the ability to island and balance on-site generation allows a higher share of loads to remain online during a disruption.

Certain combinations of distributed resilience interventions also complement one another and enhance system-wide resilience benefits. For example:

- **Targeted energy efficiency + AEG/Blackstart:** By reducing the load for critical services, targeted energy efficiency can enable a higher level of generation from renewable and/or distributed energy resources. In tandem with grid-side interventions (e.g., AEG and Blackstart) that can take advantage of available generation resources to energize portions of the transmission and distribution system, this combination of interventions can enable a larger number of customers to share any amount of deliverable generation capacity.

- **Demand Flexibility + Inverter Standard, AEG, and/or Blackstart:** Similar to targeted energy efficiency, demand flexibility can allow customers to leverage more fully all available energy and power generation capacity from any deliverable resource. Combined with islandable inverters, demand flexibility can thus allow more loads to be served from behind-the-meter PV. Combined with upstream interventions (e.g., AEG or blackstart-enabled renewables), demand flexibility can help balance available supply and allow a larger portion of the grid to remain energized after a disruption.

INSIGHT 3: Distributed Resilience Interventions Can Directly Support Prioritization of Critical Loads.
In contrast to typical approaches to system-wide resilience discussed in the previous section, each of the four customer- and distribution-system-sited resilience interventions discussed here can directly support prioritization of critical services during a broader disruption. For example:

- Targeted energy efficiency reduces the critical load required for individual critical customers and loads, thus increasing the total number of critical customers served.
- Demand flexibility approaches can prioritize load-shifting activities so that time-dependent critical services are available even during a broader disruption.
- Advanced inverters and AEG deployment can be targeted and/or configured to preferentially support critical customers and/or services, for example by ensuring those loads are equipped with resilient supply and/or are first in line for power recovery after a disruption.

INSIGHT 4: Distributed Approaches to Increase Resilience Can Also Provide Economic Value, Especially as the Grid Evolves Toward Higher Shares of Renewable and Distributed Resources.
Each of the distributed resilience interventions evaluated here also has the potential to provide value during "blue sky" days, in addition to increasing resilience during contingency events. For example, targeted energy efficiency reduces energy use for critical loads, and thereby reduces electricity supply costs at the facility level. Other interventions provide increasing value as the grid technology mix evolves; for example, advanced inverters can help regulate distribution system voltage and mitigate voltage fluctuations driven by increasing rooftop PV deployment, and thus reduce investment in grid infrastructure that would otherwise be required to integrate distribution generation resources.

6 Principles and Recommendations for Improving Grid Resilience

Principles and Recommendations for Improving Grid Resilience

Even as the US economy relies increasingly on uninterrupted access to affordable electricity, transformative changes are rapidly reshaping both the threat and investment landscapes that govern the option space for improving system resilience. This study finds that continued prioritization of a 20th century approach to grid resilience risks reinforcing and perpetuating vulnerabilities already present in our grid infrastructure, while missing opportunities to leverage architectural changes within the electricity system to prioritize resilience by design. To aid investors, policymakers, and other practitioners in navigating this complex landscape, we summarize four principles and associated recommendations that follow from this study's findings and that can be immediately applied in utility planning and regulatory activities across the United States.

PRINCIPLE 1

Address, Don't Ignore, Linear Dependence

In a changing risk environment and amid the technological shift reshaping the US grid, effective resilience approaches should acknowledge and address the linear dependencies that lead to common points of failure, seek to remove the dependencies by creating redundancy below common points of failure, or both. Continued prioritization of hardening individual components or subsections of grid infrastructure risks reinforcing the system's vulnerability to attacks or disasters spanning the entire grid value chain across wide areas.

Recommendations on Principle 1

- Rethink investment in upstream resilience interventions (e.g., fuel security) that provide resilience value only if the rest of the grid value chain is intact.
- Focus outage prevention and restoration investments as far downstream as practical, and prioritize scalable resilience solutions that can serve critical loads and services under a wide range of outage scenarios.

PRINCIPLE 2

Leverage The Market, Don't Fight It

Effective resilience solutions consider the dynamic, market-driven evolution of grid technologies. Technology and market evolution have been and will continue changing the resource mix on the grid, and in turn affect how customers and grid operators respond to catastrophic threats. Accounting for technological change, in contrast to planning for a static resource mix, can provide a more comprehensive foundation for decision makers as they create strategies to improve resilience.

Recommendations on Principle 2

- Carefully assess any incremental investment in legacy assets to support resilience outcomes, to mitigate the risk that these assets (e.g., coal plants) might become uneconomic sooner than expected as technology evolves, creating stranded costs for resilience investments.
- Consider a range of market-driven outcomes for the grid technology mix when assessing value of resilience investments, and assess the changing value of resilience investments as generation technologies and grid infrastructure evolve.
- Where markets are helping drive deployment of assets that could improve customer resilience, such as DERs, never prohibit, always allow, and preferably encourage their installation to deliver their potential resilience. Specifically, make IEEE 1547-compliant auto-islanding the default design for inverter-driven DERs, so rooftop solar and similar resources can safely work with or without the grid.

PRINCIPLE 3

Prioritize Critical Loads

Effective resilience solutions should consider load prioritization to enable targeted restoration plans. Rather than focusing on maintaining functionality within each segment of the grid, the key factor guiding resilience planning should be how much power is available to customers to meet electricity demand according to the highest societal value. All other related outcomes, upstream of the customer, are secondary considerations.

Recommendations on Principle 3

- Acknowledge that "black sky" events may not be entirely preventable. Focus on resilience of critical loads (economic, health, and safety) to disruption, and avoid a blanket approach that could be costly and less effective.

- Ensure that any new stock of devices with important resilience potential, such as DER inverters and controllers, are inherently resistant to known "black sky" threats such as EMP, so their resilience value is not defeated by built-in but unresolved vulnerabilities.

- Consider a broader definition of "critical load." It could be types of loads for individual customers, types of customers, or a community-defined list of shared services across customers provided by community centers in the neighborhood.

- Pay particular attention to loads that may be critical during a broader emergency that can accompany a grid outage. For example, prioritizing resilient access to electricity for pumps at fueling stations (e.g., through solar-plus-storage systems with direct connection to fuel pump circuits) can prevent a situation where first responders are unable to access fuel for emergency vehicles during a broader grid outage that would otherwise disable fuel pumps.

PRINCIPLE 4

Maximize Economic Value from Resilience Investments

Resilience investments are not generally justified by cost-effectiveness (because blackouts are costly but historically rare), but there is still societal value in achieving a balance between resilience for as many customers as possible and maintaining bearable costs. It follows that the lower the net cost of a resilience-enabling investment, the more scalable it is in a world with limited capital available for grid investment.
Our analysis has shown that a growing range of technologies and approaches can provide net benefits during normal operations, lowering or offsetting the net cost of scaling resilience solutions.

Recommendations on Principle 4

- Integrate resilience planning into other, economics-oriented planning exercises within utility and grid operator jurisdictions, to maximize the opportunity to co-optimize investments.

- Take advantage of market-driven grid evolution to buy down the cost of resilience from newly adopted technologies. Incremental costs of resilience-enabling features (e.g., advanced inverters, targeted energy efficiency) can be negligible in the context of ongoing investment in the grid totaling $100 billion per year or more.

An Opportunity to Reimagine Grid Resilience

The principles laid out before can serve as guideposts as we reorient our power grid and our economy in response to both the emerging catastrophic threats and market-winning technologies of this decade and beyond.

Current trends suggest that the US utility industry will invest on the order of $1 trillion in the electricity system between 2020 and 2030,[135] and possibly more under a range of transformative scenarios of clean energy adoption.[136] Given the magnitude of long-lived assets under consideration, there is an economic and national security imperative to invest in our grid in a way that promotes resilience by design, economically and from the bottom up, and not as a cost-adding afterthought or redo years later.

We are now at a crossroads where the changing economics of grid technologies can be recognized, understood, and leveraged for their ability to promote an evolved and scalable approach to improving grid resilience. In an era of ever-increasing investment in rapidly-changing technologies, investors, regulators, policymakers, and others have a unique opportunity to prioritize resilience approaches best suited to the technologies that will underpin our grid for the next decade and beyond, and reassess past approaches developed alongside the declining technologies of the past century.

7 Case Study: Resilience Options for Public Safety Power Shutoffs

Case Study: Resilience Options for Public Safety Power Shutoffs

Insights in Brief

- Driven by wildfire risks, public safety power shutoff (PSPS) events affected more than 1 million customers in California in 2019, with an estimated economic loss of $2 billion.
- We analyzed the resilience value and expected economics of behind-the-meter, solar-plus-storage (PV+S) systems to mitigate the impacts of PSPS events for different customer classes.
- We found that commercial customers in fire-prone areas could install PV+S systems to provide backup power during the PSPS events to support critical loads, and recoup investment costs both by minimizing outages and providing grid services to the California bulk power system.
- Residential customers have a less economic case due to lower expected outage costs, but could potentially leverage existing Self-Generation Incentive Program funding to justify focused implementation in low-income and/or vulnerable communities.
- Solar-plus-storage systems can provide energy, capacity, and carbon reduction value during normal operation to justify project economics.

Context

The three investor-owned utilities in California have been authorized to perform public safety power shutoffs (PSPS) in fire-prone areas to prevent wildfires caused by energized transmission/distribution lines and to prevent the fire from spreading out. CPUC reported that more than 1 million customers were affected by PSPS in California in 2019, with an average outage duration of 35 hours per event.[137]

Though it could be much worse if another deadly fire occurs, those PSPS events, with the intention to avoid social and economic loss from fires, also caused significant economic damage to utility customers across the state of California, which is now the fifth-largest economy in the world.

Different options are on the table for addressing those problems and replacing PSPS with better solutions. This analysis provides the cost-effectiveness evaluation for one proposed solution: behind-the-meter solar-plus-storage systems that can provide power during PSPS events, while also adding daily value to the electric grid system.

Approach

We assessed both the costs and benefits of prioritizing distributed PV+S systems in California to mitigate PSPS impacts. The major steps of estimating the system cost include:

- **Estimate the optimal system size** by optimizing a PV+S system to provide power to critical loads during PSPS events. We assume 20% of the total load is critical for all customers. We use the resilience module of the NREL REopt Lite model to run the optimization and get the initial result of the solar and battery size.[138]

- **Adjust system sizing** to match commercially available products. For residential and small commercial customers, the system size recommended from REopt is comparable to the Tesla PowerWall module, so we used the PowerWall specification as a reference to adjust the battery configuration.[139] For large commercial customers, we used the Tesla PowerPack specification as a reference.[140]

To estimate the economic value of PV+S systems during PSPS outage ("black sky") events, we calculated the avoided lost load and associated monetary value. The major steps of estimating the "black sky" value include:

1. **Estimate the total lost load** during the outage events. We estimated based on the CPUC report that 89% of the customer groups affected by PSPS events are residential and 11% are commercial and industrial (C&I).[141] Then we used the California state average consumption for residential and C&I customers to get the total kWh lost for each event, which by CPUC's definition is the power shutoff at a single distribution circuit.[142] Finally, by multiplying the consumption by the average number of customers within one circuit, we got the total lost load.

2. **Estimate the unit value of lost load** (VOLL). We used the Interruption Cost Estimates (ICE) tool developed by the US Department of Energy and took the average outage cost for residential and C&I customers.[143] We excluded large industrial customers because the fire-prone areas in California are mostly rural without a significant heavy industrial presence.

3. **Estimate the annual VOLL** across all customers. We multiplied the VOLL by the critical load, assuming that the solar-plus-storage would provide only this portion of the lost load.

4. **Estimate the net present value of VOLL** for multiple years. As we discuss in Chapter 3, extreme weather is expected to be more frequent and severe, thus we assumed for the purpose of this analysis that a PSPS event comparable to 2019's events will happen once each year in the next 25 years (same as the generation asset life).

We also estimated the value that PV+S systems provide to the grid system during normal operation days ("blue sky"). The major steps of estimating the "blue sky" value include:

- **Estimate the energy value.** We calculated the energy production assuming 90% roundtrip efficiency of the solar-plus-storage system. Then we multiplied the hourly production by the minimum hourly clearing price from the CAISO energy market to get the total energy value.

- **Estimate the capacity value.** We used recent national data on capacity contract prices of $43/kW-year as a conservative proxy for the value of incremental resource adequacy in California.

We then multiplied that number by the firm peak capacity credit from the solar-plus-storage systems, which we define as total storage capacity.

- **Estimate the carbon reduction value.** We assumed that the solar-plus-storage systems replace generation from natural gas combined-cycle (NGCC) plants. We then used the standard heat rate and carbon intensity numbers for the NGCC plants and calculated the total avoided carbon cost by multiplying the carbon emissions by $50/ton.

Findings

We modeled the economics of solar-plus-storage systems for the approximately 1 million customers affected by PSPS in 2019, totaling 10 GW of solar PV and 5.5 GW of battery storage. Residential customers in our simulation would account for 44% of solar and 80% of the battery capacity, with the remainder for commercial customers. We estimated the net present costs for this level of deployment would total $34 billion, with residential systems accounting for 50% of that total.

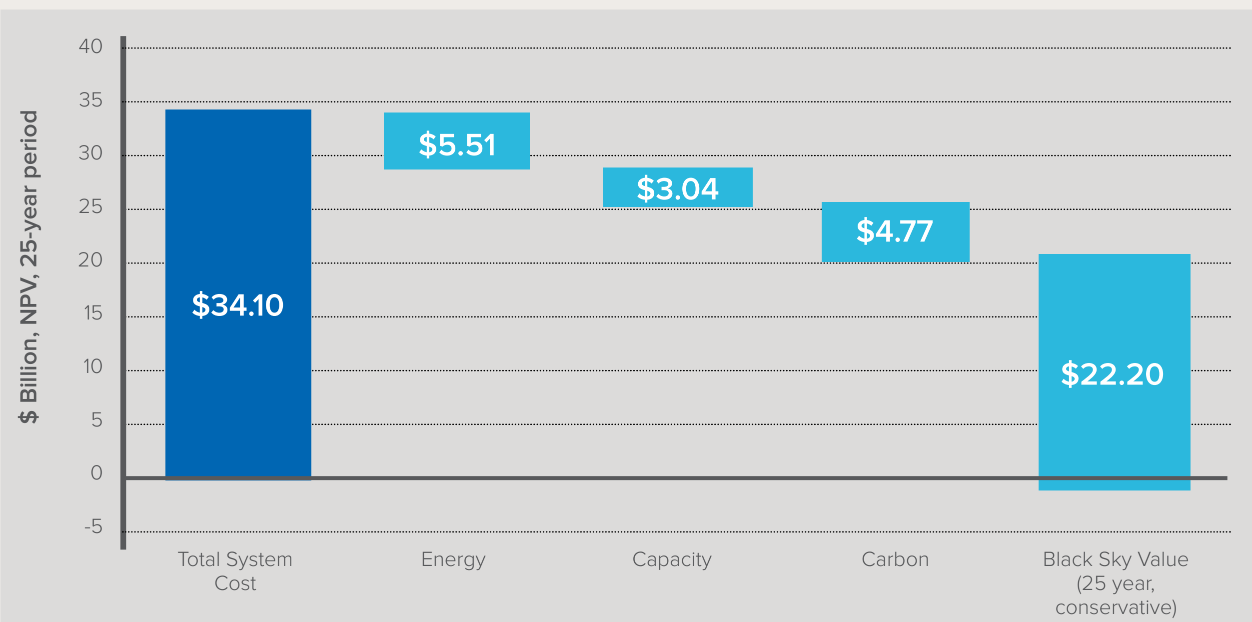
Together, these PV+S systems would provide $2 billion of value per year in avoided lost load ($22 billion net present value [NPV]). However, only 1% of that total value is provided by the residential systems, given the lower estimate of value of lost load for residential customers. These PV+S systems would also provide $13 billion (NPV) in value to the grid, including:

- $5.5 billion in energy value,
- $3 billion in capacity value, and
- $4.8 billion in value associated with reduced carbon emissions.

Combined, the PV+S systems would provide $1.4 billion (NPV) in net benefits. Exhibit 24 illustrates the costs and benefits.

EXHIBIT 24

Costs and Benefits of PV+S Systems to Mitigate PSPS Risks



The findings depend on several key assumptions, each of which has a large band of uncertainty:

- **Value of lost load (VOLL).** We used the average VOLL for typical customers from the ICE tool, but recognize that the true value might vary between customers, and that costs may grow nonlinearly depending on the duration of the outage. In particular, we excluded VOLL estimates for customers with in-home medical devices due to data limitations, but recognize that the value of lost loads for such customers could be significantly higher than regular residential and commercial customers.

- **Percentage of load as critical load.** Similar to VOLL, the assumption of what percentage of load is deemed "critical" and thus covered by the PV+S systems can significantly change the valuation of customer loss. A higher assumed percentage would increase the resilience value of the system and improve overall economics.

- **Projection of PSPS frequency.** Our analysis assumes that PSPS events will continue for the next 25 years. If we anticipate that alternative approaches will make PSPS unnecessary at an earlier year, the lifetime "black sky" value could be lower.

- **Incremental cost of solar-plus-storage systems.** This analysis assumes all solar-plus-storage needs to be newly built to support ride-through and islanding during the PSPS event. However, it is likely that certain existing solar systems can use inverter upgrades to enable coupling with battery storage modules, providing the same value at much lower cost.

- **Customer subsidies.** Inclusion of these incentives, particularly the "resiliency adder" for the low-income residents in the fire-risk zones through the Self-Generation Incentive Program,[144] would improve the private economics for eligible customers.

Implications

The analysis presented here provides a case study of emerging resilience solutions in the changing technology and threat landscape facing the US electricity system, and reinforces the four principles for improving grid resilience explored in the rest of this study:

PRINCIPLE 1

Address, Don't Ignore, Linear Dependence

Locating resources near customers reduces their dependence on an upstream grid value chain that is vulnerable to common-mode failures; in this case, wildfires and associated PSPS strategies.

To maximize effectiveness of the strategy explored here, California stakeholders should address other elements of linear dependence, in particular ensuring that inverters allow PV+S systems to safely island during broader outage events.

PRINCIPLE 2

Leverage the Market, Don't Fight It

Deploying PV+S systems strategically to minimize economic damage during PSPS events takes advantage of the ongoing market-driven adoption of PV+S, and maximizes an additional benefit (i.e., resilience) that otherwise might be lost.

To maximize effectiveness of the strategy explored here, California stakeholders should incorporate resilience into permitting, interconnection, siting, and any applicable incentive programs affecting PV+S deployment, so that resilience is built in by design as systems are deployed, and not sought later as a costly afterthought.

PRINCIPLE 3

Prioritize Critical Loads

Our analysis shows that prioritizing critical loads is a key driver of any net benefits available from PV+S system deployment. Customers with a higher value of lost loads (e.g., commercial customers in our analysis, and/or customers with critical medical equipment at home) will see the highest benefits from PV+S systems deployed to cover their critical needs, with larger systems providing diminishing returns.

To maximize effectiveness of the strategy explored here, California stakeholders should ensure that any PV+S deployment meant to support resilience is not only targeted to customers with high VOLL, but also that for those customers, PV+S systems are sized and interconnected in a way to preferentially support the highest-value loads within customer premises.

PRINCIPLE 4

Maximize Economic Value from Resilience Investments

Our analysis illustrates that resilience value alone does not justify investment in PV+S systems for the customers affected by PSPS events. Rather, a significant fraction of the benefits accrue from energy, capacity, and climate benefits generated during daily operation of PV+S systems.

To ensure that any PV+S systems deployed are able to provide their highest value to customers and the electricity system as a whole, California stakeholders should continue implementation of programs that incentivize participation of behind-the-meter PV+S systems in the CAISO wholesale electricity market.

This case study is specific to California, but illustrative of the threats and technologies emerging in other markets. PSPS events are but one example of a common-mode failure that creates risk for the electricity value chain upstream of customers; and distributed, resiliently interconnected PV+S systems are only one example of a distributed resilience intervention that can mitigate such risks. The principles implied by this case study can be interpreted and tailored according to specific grid conditions across the United States and globally, and support policymakers, regulators, and industry in maximizing resilience in a changing environment.

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Endnotes

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