EPRI

PERSPECTIVES ON TRANSFORMING UTILITY BUSINESS MODELS

Paper 11 – Business Models for Resilience

September 2024

INTRODUCTION

The energy system is in the early stages of a profound transformation. This transformation brings many opportunities, but there are also new risks that must be addressed if the right outcomes are to be delivered confidently. These risks include those arising from increased dependency on weather, convergence of many sectors on electrification as a primary energy source, and cybersecurity threats, among others. Some of these risks can be addressed by using data to give better visibility of system operation, others through infrastructure hardening interventions; all require effort to understand, plan, and act in an environment characterized by uncertainty and a need for pace.

Resilience is being redefined; ensuring that energy supply is resilient is more complex and critical than ever before. There are a number of factors contributing to this spanning environmental, technical, operational, commercial, economic, social, and geo-political considerations. A systems perspective—one that looks at the energy system holistically—will help to build understanding of the interactions and trade-offs between these factors and enable good decision making. Business models[1] have an important role to play in helping utilities respond to related emerging challenges and opportunities. They will complement other measures and support utilities and consumers in recognizing and realizing the value of resilience.

This paper explores resilience in the future energy system and considers ways in which business models might contribute to ensuring that people, communities, and businesses have the benefit of a safe, secure, and resilient energy supply. The paper does not provide a comprehensive treatment of resilience; other work by the Electric Power Research Institute (EPRI) looks more deeply into key aspects of this important subject.[2]

RESILIENCE IN AN ENERGY SYSTEM

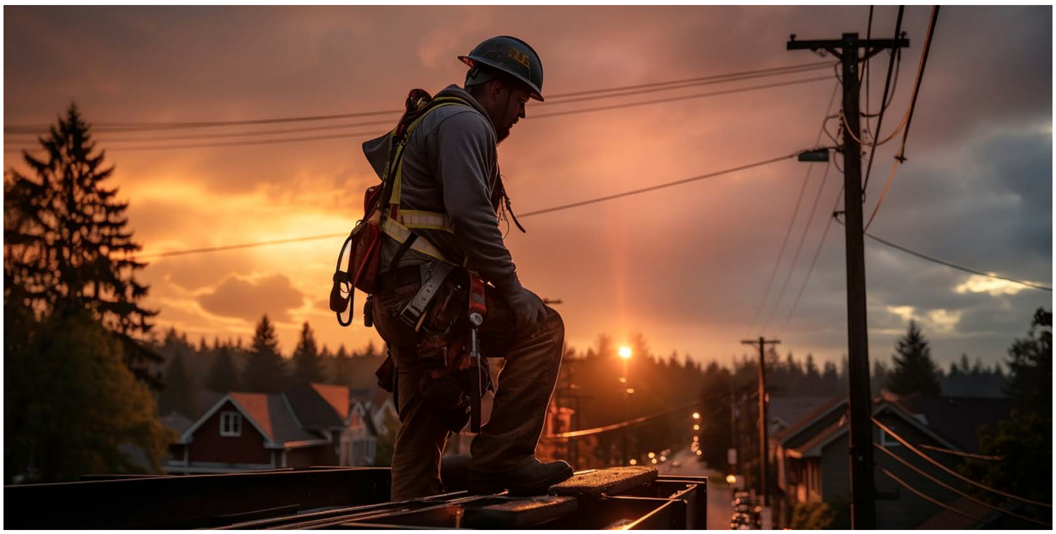
Energy system resilience refers to the ability to withstand, contain, adapt to, and recover from various disruptive events and stresses while maintaining the provision of essential energy services to customers. Resilience is distinct from reliability. *Reliability* focuses on the prevention of events and on lowering the chances of failures occurring. *Resilience* focuses on minimizing the consequences of an event, including events that are very unlikely to occur or cannot be foreseen.

Examining resilience reveals there are several aspects relating to the delivery of service:

1 Utility business models are explored in the EPRI portfolio, including in *Towards Net Zero: The Evolving Utility Business Model and Possible Future Scenarios* (epri.com)

2 *Value of Resilience Research Roadmap*. EPRI, Palo Alto, CA: 2023. 3002027407.

- **Physical resilience** refers to the ability of the energy infrastructure to withstand and recover from physical disruptions, such as weather events, earthquakes, or equipment failures. This requires robustness across all critical infrastructure. Hurricane Katrina (2005), the Fukushima Nuclear Disaster (2011), and the California Wildfires (in 2018 and other years) are striking examples of events where physical resilience was challenged.
- **Operational resilience** describes the capacity of the energy system to maintain essential functions and services during disruptions. This includes strategies for managing energy supply and demand, optimizing system operations, and implementing emergency response measures to minimize disruptions and restore service as quickly as possible. Examples that illustrate the demands on operational resilience are the Texas Winter Storm (2021) and Storm Arwen (2021).
- **Cyber resilience** focuses on protecting the energy system against cyber threats, including cyber attacks, malware, hacking, and other cybersecurity risks. This involves implementing robust cybersecurity measures, such as network monitoring, threat detection, encryption, access controls, and incident response protocols, to safeguard critical energy infrastructure and data systems. Attacks on the Ukraine Power Grid (2015 and 2016) and the Colonial Pipeline Ransomware Attack (2021) are notable examples where resilience was severely tested.



Resiliency events highlight the evolving need to include system resiliency in resource planning

2011 Japanese earthquake and tsunami resulted in meltdown of reactors at the Fukushima nuclear plant, led to the closure of all other nuclear reactors in Japan, and caused policy changes governing nuclear generation going forward.

2011 tornados in the southeastern United States damaged approximately 200 high voltage transmission lines across the TVA and Southern Company systems.

2012 Hurricane Sandy devastated parts of New York and other portions of the northeastern United States.

2013 rifle attack on PG&E's Metcalf substation damaged 17 power transformers.

2014 Polar Vortex resulted in very low temperatures across a large cross section of the eastern United States driving very high demand for power and natural gas and resulted in extremely high forced outage rates for many generators.

2015-2016 leak at the Aliso Canyon natural gas storage facility dramatically limited natural gas supplies to Southern California.

2017 series of hurricanes in the United States and Caribbean led to massive damage to power systems and months of recovery as highlighted by the ongoing recovery from Hurricane Maria in Puerto Rico.

3 *Developing a Framework for Integrated Energy Network Planning (IEN-P)*. EPRI, Palo Alto, CA: 2018. 3002010821.

The experience of Lancaster in the United Kingdom illustrates clearly how resilience is a systems issue with energy at its core.

"The loss of power affected services many take for granted. Mobile coverage was lost, as was the internet and television. Electronic payment systems could not work, and people could not access cash from ATMs. Petrol stations had to close as the pumps need electricity. Food retailers had to throw away large amounts of stock when the fridges and freezers went off, schools and universities had to close and care homes lost lights, heat and water."[4]

A report was prepared highlighting the issues and calling for action, and the subject received significant attention.

There are further aspects of resilience that relate to the context in which the system is designed, built, and operated and may be considered as addressing strategic resilience:

- **Supply chain resilience** is concerned with the energy supply chain, encompassing sourcing, production, transportation, and distribution of energy resources (including fuels) and components used to develop and maintain the system. This involves diversifying supply sources, building redundancy into supply chains, and developing contingency plans to mitigate risks associated with supply chain disruptions such as geopolitical instability, trade disruptions, or natural disasters. The war in Ukraine and the resulting impact on gas supplies is a powerful example where events have significant and enduring consequences, requiring substantial interventions from governments.
- **Social resilience**, sometimes termed community resilience, refers to the ability of communities and stakeholders to withstand and recover from energy-related disruptions. This will draw on encouraging community engagement, building social networks and support systems, and addressing social vulnerabilities to ensure that affected people have access to essential energy services during emergencies.[7]
- **Economic resilience** refers to the capability of the energy system and its stakeholders to absorb and recover from financial shocks and disruptions. This includes strategies for managing financial risks, diversifying revenue streams, securing investments, and ensuring the financial viability of energy infrastructure and operations. An interruption can lead to both direct and indirect impacts; for example, some could affect the energy supply chain itself, while others could affect manufacturing operations because they cannot obtain materials from an affected source.
- **Regulatory and policy resilience** focuses on the effectiveness of regulatory frameworks, policies, and governance structures in facilitating resilience planning, coordination, and response. This encompasses developing adaptive regulatory frameworks, establishing clear roles and responsibilities, and building collaborations across government agencies, regulatory bodies, industry stakeholders, and other actors involved in energy resilience.

Utilities should consider all these strategic and service delivery perspectives on resilience if they are to place themselves in the strongest possible position to respond to a broad spectrum of potentially disruptive events. The decisions they make should be balanced across these factors and reflect the particular circumstances in which they operate and the ambitions they have regarding delivering service to people and the communities in which they live and work.

4 *Learning from Lancaster's power cuts*, Lancaster University blog, 2016.

5 *Living Without Electricity*. Royal Academy of Engineering, London, England: 2016.

6 *Living Without Electricity*. Professor Roger Kemp, Gresham College, 2017. https://www.youtube.com/watch?v=_pehBTjB38o

7 Southern California Edison has done work with Sandia on community resilience metrics. See *Equity in Resiliency Evaluation and Planning* and recording from Nov 2023 at https://youtu.be/e0ZXqXuCLyg.

HOW ENERGY SYSTEM RESILIENCE IS CHANGING

Traditionally resilience focused on networks and the effects of physical and operational issues such as weather, failing equipment including aging equipment, and excess demand. Effort was directed to trying to reduce the likelihood of long-duration outages over large service areas, limit the scope and impact of outages when they occurred, and rapidly restore service after an outage. Energy infrastructure was constructed to withstand and recover quickly from disruptions.

The Texas freeze of February 2021 serves as an illustration of the need for energy resilience in the face of extreme weather events. The storm exposed significant vulnerabilities in Texas's energy infrastructure, leading to widespread power outages that affected millions due to equipment failure across various energy sources from the prolonged sub-freezing temperatures. This case study provides an example of the need for robust resilience planning and better preparedness in energy supply and infrastructure and the importance of robust emergency response protocols and enhanced weatherization.

Hurricane Irma in 2017 is a case study in adaptation of infrastructure in response to natural disasters which once affected homes with a loss of power. Utilities faced significant challenges as the hurricane caused widespread damage to power lines, substations and other critical infrastructure. Florida Power & Light (FPL), the largest utility in Florida, had invested significantly in storm hardening efforts prior to Irma, including strengthening poles, undergrounding power lines, and enhancing smart grid technologies. These investments paid off, as FPL was able to restore power to most customers within days, demonstrating the value of proactive resilience measures.

This view of resilience remains relevant, and while transformation of the energy system is creating many new opportunities, there are also new risks. The commitment to extensive electrification is central to the approach for delivering a Net Zero future but brings with it a new risk profile. More electrification—industrial processes, transport, and space heating, for example—creates greater social and economic dependence on one energy type. The new, more distributed architecture of the electricity system makes some aspects of operation more complex. The move from fossil fuel-based sources of energy to intermittent renewables sources means there is greater dependence on weather. There is increased reliance on flexibility services to align supply and demand which depend on customer participation that may not always be reliably forthcoming. These risks are not insurmountable, but they must be acknowledged, understood, and addressed with measures that enable the benefits of change to be realized, while ensuring that security of service is sustained.

Of particular note is the increasing reliance on digitalization in the emerging energy system. This creates an intimate reciprocal interdependence between digital and energy, electricity in particular; when one fails, they will both fail. This implies that resilience of the energy system is not limited to what is typically considered to fall within its boundaries but now extends to digital infrastructure including data centers and communications systems and networks. This effect is magnified by increased dependence across the economy and society on digitalization.

These changes are reflected in new and emerging threats to energy system resilience:

- As energy systems become increasingly interconnected and digitalized, **cyber-physical attacks** pose a growing threat to energy infrastructure. These attacks exploit vulnerabilities in operational technology and industrial control systems to disrupt energy production, transmission, and distribution processes, potentially causing widespread outages and cascading failures.
- **Ransomware and extortion** attacks targeting energy companies can encrypt critical systems and data, disrupting operations and demanding ransom payments for decryption keys. These attacks not only cause financial losses but also pose significant operational and reputational risks.
- **New types of physical threats** are potentially more likely as global tensions rise and the risk of conflict or war situation increases. The changing assets and architecture of the energy system may create new vulnerabilities that justify specific consideration. Offshore assets, including platforms and interconnectors, may be more suspectable to submarine attack, which is both more difficult to detect and defend against.
- **Climate change impacts** pose new challenges to energy system resilience, including more frequent and severe extreme weather events, such as hurricanes, floods, wildfires, and heatwaves. These events can damage energy infrastructure, disrupt operations, and strain emergency response resources, highlighting the need for climate resilience planning, adaptation measures, and infrastructure hardening. Climate threats could extend beyond extreme weather events to include, for example, permanent changes in the jet stream or Gulf Stream that could fundamentally change the climate in terms of what becomes "normal." This could have significant impact given the increasing reliance on weather-dependent sources of energy. EPRI is undertaking substantial work in this area.[8]

8 Climate READi (epri.com)

EPRI's Climate READi program aims to enhance climate resilience in the power sector through collaborative research and development. It focuses on risk assessment, adaptation strategies, and innovative solutions to mitigate the impacts of climate change on energy infrastructure. The program promotes knowledge sharing and the integration of climate resilience into utility planning and operations. Workstream 3 of EPRI's Climate READi Initiative focuses on developing tools and methodologies to integrate climate resilience into utility planning processes. This workstream emphasizes creating practical applications and frameworks that utilities can use to assess risks and enhance the resilience of their operations. It includes collaborating with stakeholders to ensure these tools are effective and widely adopted, therefore supporting the overall resilience of the power sector against extreme weather events and long-term climate changes.

An EPRI report from Workstream 3[9] highlights the increasing disruption of the electric grid by extreme weather due to climate change. Energy companies are seeking methods to incorporate these events into their planning models to enhance reliability and resilience. The report supports the need for accurate representation of both spatial and temporal characteristics of extreme events in power system models. It discusses the integration of climate-informed data in long-term planning, resource adequacy, transmission, and distribution planning to mitigate risks and ensure system resilience. The temporal and spatial aspects of events like wildfires, heatwaves, and hurricanes are important to understand the impacts on generation, transmission, and distribution. By using chronological datasets and improved modeling tools, extreme events can be monitored and guided with adaptation to facilitate robust and resilient power systems.

- Distributed energy resources (DERs) and grid-edge technologies, such as smart meters, sensors, and IoT devices, introduce **new vulnerabilities and attack surfaces** to energy systems. Cyberattacks targeting grid-edge devices can compromise data integrity, disrupt communications, and undermine grid stability.
- A consequence of rapid transformation of the energy system can be the development and introduction into service of **systems and assets (or materials) that are immature** or not time-proven, and which might have unexpected or unfamiliar failure modes or patterns. They may not conform to classic failure characteristics, implying a need for a more focused inspection and diagnostics regime such that early indications of pre-failure conditions can be detected.
- There is a **need for diversity of systems and assets** to reduce exposure in the event that business-critical systems or high population assets need to be quickly taken out of service. This is potentially more likely to occur with the accelerated investment in energy infrastructure that characterizes system transformation rather than incremental development.
- **Electromagnetic pulse (EMP)** events, whether natural (solar storms for example) or intentional (nuclear detonations for example), can induce powerful electromagnetic waves that disrupt electronic systems and infrastructure, including energy grids. EMP events pose a low-probability but high-impact threat to energy system resilience, necessitating investments in EMP-hardened infrastructure and protective measures.
- **Social unrest, political conflicts, and geopolitical** tensions can disrupt global energy supply chains, impede infrastructure development, and undermine regulatory stability, affecting energy system resilience. These risks highlight the importance of geopolitical risk assessment, contingency planning, and diversification strategies.
- **The growing scarcity of people with the right skills** to undertake key roles in the energy system means that there is potential exposure to failures in design, build, operation, and recovery processes.
- Local or global events such as a **pandemic or serious pollution** incident (due to natural or man-made or malicious causes) could require prolonged isolation or lockdown and/or result in high levels of mortality or incapacity. This is a consideration for business continuity planning to address if there are specific critical skills invested in a small number of staff.

9 *Program RAPP: Workstream 3 – Resilience and Adaptation Planning and Prioritization*. EPRI, Palo Alto, CA: 2023, 3002028574.

Addressing these increasingly significant threats to energy system resilience requires a multi-dimensional approach that integrates cybersecurity measures, climate resilience strategies, supply chain resilience planning, and adaptive governance mechanisms. It is also important to note that transformation of the energy system opens opportunities to think differently about resilience. Flexibility for example, may mean great complexity in the balancing of supply and demand, but it can also create the potential for more distributed management of networks and the use of autonomous techniques. Another opportunity can arise from the multi-vector nature of the whole energy system, and the ability to take advantage of interactions between vectors to deliver energy services. This might include the use of hybrid heating solutions in domestic environments for example, where both electrification and clean gases could be used, and security of service assured through optimization across the two vectors.

VALUING RESILIENCE … FROM A UTILITY PERSPECTIVE

Valuing resilience in an energy system involves assessing and, where possible, quantifying the benefits and costs associated with enhancing the system's ability to withstand and recover from disruptions. Valuation of resilience is challenging due to its complex and multifaceted nature, the mix of tangible and intangible factors, and the uncertainty of potential risks.

Valuing resilience should start with an understanding of the risks that the utility faces, including those that are known and likely, those that are known but unlikely, as well as those that are unforeseen. This assessment should account for new risks that could reasonably be expected to arise during energy system transformation and in the merging energy system itself. Historical data and information from comparator companies can be used to help reveal insights about previous events and the response to them. This understanding will allow the utility to set its strategic and operational resilience objectives and set out its approach for measuring performance and maturity.

The utility can then undertake an **economic valuation** to try to quantify the costs of disruption including direct and indirect costs and accounting for factors such as the duration, frequency, and severity of disruptions. This should include the potential financial and non-financial costs of lost revenue, lost productivity, regulatory penalties, damages to infrastructure and assets, damage to reputation, and impacts on customer satisfaction. This analysis will involve estimating the probability and potential impact of risks on the energy utility's operations, assets, and stakeholders.

VALUING RESILIENCE

Cost of Outages
- Customer compensation
- Repair and replacement costs
- Revenue losses

Infrastructure Investments
- Hardening infrastructure
- Backup systems
- Smart Grid technology

Operational Efficiency
- Reduced downtime
- Maintenance savings

Regulatory Compliance
- Avoided fines
- Incentives and subsidies

The utility is then in a position, using information regarding its current resilience capabilities, to **determine and prioritize the resilience investment** required to achieve its strategic and operational objectives. This will include determining the costs of implementing resilience measures and initiatives to mitigate identified risks and enhance the resilience of the energy infrastructure to deal with those that are unforeseen. This will encompass upfront capital investments, ongoing operational expenses, and lifecycle costs associated with resilience-enhancing technologies, infrastructure upgrades, and risk management programs.

RESILIENCE COSTS

Capital Investments

- Infrastructure hardening
- Backup systems
- Advanced technologies
- Cyber measures

Operational Costs

- Maintenance and upkeep
- Training and workforce development
- Monitoring and analytics

Regulatory Compliance

- Compliance costs
- Reporting and documentation

Planning and Management

- Risk assessment
- Strategic planning

Insurance Premiums

- Higher premiums

A **cost-benefit analysis** can then be prepared to compare the costs of resilience investments with the expected benefits in terms of cost savings, revenue enhancement, risk reduction, avoided damages, and improved system reliability associated with reduced risk exposure and enhanced operational performance. One option available to the utility is to decide to accept the risk and not invest further; if this approach is fo

RESILIENCE BENEFITS

Improved Reliability and Reduced Outages

- Fewer and shorter outages
- Avoided costs

Economic Benefits

- Value of Lost Load (VoLL) measures
- Revenue stability

Operational Efficiency

- Reduced maintenance costs
- Efficiency gains

Regulatory and Compliance

- Avoided penalties
- Incentives and grants

Customer Satisfaction and Retention

- Increased trust
- Reduced churn

Environmental Benefits

- Sustainability goals
- Reduced emissions

Insurance and Risk Management

- Lower insurance claims
- Risk reduction

Strategic and Long-Term Benefits

- Future-proofing
- Investment attractiveness

Social and Community Benefits

- Equity and Inclusion
- Community resilience

Risk transfer can be evaluated to understand the potential for mechanisms such as insurance, reinsurance, and risk-sharing arrangements to manage and mitigate the financial impacts of energy disruptions. Insurance premiums and risk transfer costs provide a proxy for the value that stakeholders place on resilience and their willingness to pay to reduce risk exposure.

Real options analysis permits assessment of the flexibility and strategic value of resilience investments in adapting to changing conditions and uncertainties. This approach considers the value of maintaining optionality in decision making to respond effectively to emerging threats and opportunities.

It is also important that the utility account for **stakeholder preferences** in order to accommodate non-monetary factors, such as safety, security, reliability, and social welfare, that contribute to the overall value of resilience. Surveys, focus groups, and stated preference methods can help elicit stakeholders' willingness to pay for resilience-enhancing measures and their perceived value of resilience outcomes.

The utility can align resilience investments with **regulatory mandates, policy priorities, and stakeholder expectations** to ensure compliance and enhance regulatory support for resilience initiatives. In doing this, it is important to consider relevant incentives and penalties.

By valuing resilience in these ways, energy utilities can make informed decisions about allocating resources, prioritizing investments, and managing risks to enhance the resilience of their operations and infrastructure. This holistic approach to resilience valuation helps utilities balance short-term costs with long-term benefits and create value for customers, shareholders, and society as a whole. This will provide key input to the design and implementation of business models that are aligned with resilient service delivery.

The utility should develop resilience metrics and indicators to track the performance of the energy system over time and assess the effectiveness of resilience measures. These metrics may include outage duration, system reliability, customer satisfaction, and economic losses avoided, providing quantitative measures of resilience that can inform decision-making and future investment prioritization. These metrics will be important in measuring the returns that business models achieve and the outcomes they deliver.[10]

VALUING RESILIENCE … FROM A CONSUMER PERSPECTIVE

Understanding the value of resilience requires an appreciation of the value that consumers place on it. This appreciation can then be reflected in the service propositions made to consumers and in the business models that reflect the interests of both the utility and the consumer.

Energy consumers value resilience in several ways, reflecting their preferences for reliable, uninterrupted, and secure energy services. They prioritize the **reliability of energy supply**, expecting uninterrupted access to electricity and other energy services for their homes, businesses, and critical operations. They value resilience measures that minimize the frequency, duration, and impact of power outages, avoiding disruptions to daily activities, productivity, and quality of life. Value of Lost Load (VOLL) is a typical measure used in electricity supply but gives only a partial view if it does not account for the fact that different consumers will perceive value differently at different times and experience different impacts.

Commercial and industrial (C&I) energy consumers place a premium on **business continuity and operational reliability** as disruptions to energy supply can lead to downtime, production losses, revenue impacts, and reputational damage. Different C&I consumers will value resilience according the specific nature of their business. Some, such as data centers for example, cannot maintain operations without near 100% demand, where others may be able to maintain some operations with significantly less than 100% of regular demand.

Energy consumers assess the financial **costs associated with downtime and service interruptions**, including lost sales, productivity losses, spoilage of perishable goods, and potential penalties for non-compliance with contractual obligations. They value resilience measures that minimize

10 Some utilities have already developed internal metrics. IEEE's Distribution Resiliency Working Group ("DRES") is in the process of developing industry standard grid resilience metrics, to be finalized in 2025.

the economic impact of disruptions and provide financial protection against revenue losses and business risks.

Safety and security considerations may be prioritized, particularly in critical infrastructure sectors such as healthcare,[11] telecommunications, transportation, and emergency services. They also value **high-quality service standards** and resilience initiatives that maintain consistent power quality and minimize variations in voltage and frequency, reducing the risk of equipment damage, operational inefficiencies, and safety hazards.

Energy consumers increasingly recognize the importance of **environmental sustainability and climate resilience**, supporting investments in renewable energy, distributed generation, energy efficiency, and grid modernization. They value resilience solutions that promote environmental stewardship, reduce greenhouse gas emissions, mitigate climate risks, and enhance the long-term sustainability of the energy systems.

Energy consumers value resilience as a critical attribute of energy services, influencing their preferences, behaviors, and purchasing decisions. The challenge is for utilities to reflect these values in business models that will generate sustainable returns and, at the same time, serve the needs of their customers. It is acknowledged that there is little survey-driven consumer willingness-to-pay data available when it comes to resilience. This is an industry gap that utilities and governments are seeking to address and for which research is being conducted.[12]

WHO SHOULD BE ACCOUNTABLE FOR ENERGY SYSTEM RESILIENCE?

Accountability for energy system resilience should be shared among various stakeholders, including government entities, energy companies, regulatory bodies, industry partners, local communities, and consumers.

Governments at the national, regional, and local levels play a critical role in setting policies, regulations, and standards that promote energy system resilience. They are responsible for developing and enforcing building codes, infrastructure standards, and emergency response plans to enhance the resilience of energy infrastructure. Governments also allocate funding for resilience projects, provide incentives for investments in resilient technologies, and coordinate with other stakeholders to address cross-cutting resilience challenges.

Regulatory bodies ensure that energy companies comply with applicable regulations and standards related to resilience. They establish performance metrics, reliability standards, and reporting requirements to assess and monitor the resilience of energy infrastructure. Regulatory bodies may also provide guidance, incentives, and enforcement mechanisms to encourage investments in resilience and hold energy companies accountable for meeting resilience goals.

Energy companies, including utilities, grid operators, and energy service providers, are responsible for operating and maintaining critical energy infrastructure to ensure reliability and resilience. They should invest in resilient infrastructure, technologies, and practices to minimize disruptions and maintain service continuity during emergencies. Energy companies also have a responsibility to engage with stakeholders, conduct risk assessments, and develop resilience plans to address potential threats and vulnerabilities.

Industry partners, suppliers, and vendors play a crucial role in enhancing energy system resilience by providing equipment, technologies, and services that improve the reliability and performance of energy infrastructure. Collaboration with industry partners is essential for implementing resilience solutions, integrating new technologies, and sharing best practices to enhance the resilience of the energy supply chain.

Community organizations are important stakeholders in energy system resilience, as they are directly impacted by disruptions and play a vital role in emergency response, recovery, and community resilience-building efforts. Local communities are directly affected by energy disruptions and have a vested interest in the resilience of energy infrastructure. They can play a role in supporting resilience efforts by participating in emergency preparedness initiatives, advocating for investments in resilient infrastructure, and

11 Hospital Generator Benefit-Cost Analysis, Federal Emergency Management Agency, 2021.

12 Consumer willingness-to-pay for a resilient electrical grid, Energy Economics, Vol 131: March 2024, https://www.sciencedirect.com/science/article/pii/S0140988324000537.

engaging with energy companies and government agencies to address community-specific resilience challenges. Communities can also contribute to resilience through energy conservation, distributed energy resources, and community-based resilience initiatives.

Energy consumers, including businesses, households, and institutions, rely on energy services for their daily activities and economic prosperity. Consumers can support energy system resilience by adopting energy-efficient technologies, investing in backup power systems, participating in demand response programs, and practicing energy conservation measures. They can also advocate for policies and investments that enhance the resilience of energy infrastructure and promote sustainable energy practices.

Accountability for energy system resilience requires a collaborative and multi-stakeholder approach, with each stakeholder playing a distinct but interconnected role in enhancing the resilience, reliability, and sustainability of the energy infrastructure and services in the face of evolving threats and challenges.

WHO SHOULD PAY TO MAKE AN ENERGY SYSTEM RESILIENT?

Determining who should pay to make an energy system resilient involves considering various factors, including regulatory frameworks, stakeholder responsibilities, cost-sharing mechanisms, and societal benefits.

Energy companies, including utilities, grid operators, and energy service providers, often bear primary responsibility for ensuring the resilience of energy infrastructure. They own, operate, and maintain critical energy assets and have a duty to provide reliable and secure energy services to customers. Energy companies may finance resilience investments through capital expenditures, operational budgets, and rate recovery mechanisms approved by regulatory authorities. Shareholder support is key to assuring the right investments are made. One option available to energy companies is to accept the risk and address issues if/as they arise, effectively self-insuring.

Energy consumers, including businesses, households, and institutions, benefit directly from a resilient energy system by avoiding disruptions, maintaining productivity, and safeguarding their well-being. Consumers may contribute to resilience investments through electricity rates, surcharges, or fees allocated for infrastructure improvements and system upgrades. Alternatively, consumers may invest in backup power systems, energy efficiency measures, and other resilience measures to enhance their self-reliance and resilience capabilities.

Governments at the national, regional, and local levels play a role in financing resilience investments through public funding, grants, subsidies, and incentives. Government agencies may allocate funding for resilience projects, provide low-interest loans or loan guarantees, and offer tax incentives or rebates to support investments in resilient infrastructure and technologies. Government funding helps address market failures, overcome financial barriers, and promote the public interest in enhancing energy system resilience.

Regulatory authorities can provide incentives and rewards to encourage energy companies to invest in resilience and prioritize resilience planning and implementation. Regulatory mechanisms, such as performance-based regulation, revenue decoupling, and performance incentives, align financial incentives with resilience objectives and ensure that energy companies are accountable for meeting resilience targets and performance standards. Regulatory authorities may also establish cost-recovery mechanisms to allow energy companies to recover prudently incurred costs associated with resilience investments.

Insurance and risk transfer mechanisms, such as insurance policies, reinsurance, and catastrophe bonds, can help manage and mitigate the financial impacts of energy disruptions. Energy companies may purchase insurance coverage or transfer risk to third-party insurers to protect against potential losses and liabilities associated with resilience risks. Insurance premiums and risk transfer costs reflect the value of resilience and the willingness to pay to reduce risk exposure, providing an indirect mechanism for allocating costs among stakeholders.

Allocating the costs of making an energy system resilient requires a coordinated approach involving energy companies, consumers, governments, regulatory authorities, and other stakeholders. By considering the distribution of benefits, responsibilities, and risks, stakeholders can develop equitable and efficient mechanisms for financing resilience investments and ensuring the reliability and security of energy services.

EMERGING INNOVATIONS THAT CAN IMPROVE ENERGY SYSTEM RESILIENCE

Several innovations have the potential to improve energy system resilience by enhancing reliability, adaptability, and response capabilities.

- **Microgrids and distributed energy resources (DERs)** enable localized generation, distribution, and consumption of electricity, allowing communities, campuses, and critical facilities to operate independently from the main grid during disruptions. Integration of DERs such as solar PV, wind turbines, energy storage systems, and combined heat and power (CHP) units into microgrids enhances resilience by diversifying energy sources, increasing grid flexibility, and providing backup power capabilities.
- **Smart grid technologies** leverage advanced sensors, meters, communication networks, and control systems to improve real-time monitoring, management, and optimization of energy infrastructure. Smart grids enable predictive maintenance, fault detection, and outage management, enhancing grid reliability, efficiency, and resilience to disruptions.
- **Multi-vector energy solutions**, such as hybrid heating solutions, can be used to provide continuity of services to consumers in circumstances where systems in one vector fail. Use of these solutions can be optimized through digitalization and tailored to reflect customer preferences.
- **Grid-interactive buildings** leverage automation, energy management systems, and demand response capabilities to adjust energy usage in response to grid conditions, price signals, or supply-demand imbalances. Demand response programs enable customers to reduce energy consumption during peak periods, alleviate grid stress, and enhance grid resilience by optimizing load management and grid balancing.
- **Advanced energy storage systems**, such as lithium-ion batteries, flow batteries, and thermal storage systems, provide grid-scale energy storage capabilities for storing excess renewable energy, smoothing out fluctuations, and providing backup power during outages. Energy storage enhances grid stability, reliability, and resilience by providing fast-response capabilities, frequency regulation, and grid support services.
- **Resilient communication networks** provide redundant and decentralized communication connectivity for energy infrastructure monitoring, control, and coordination. Robust communication networks enable reliable data exchange, situational awareness, and coordinated response efforts during emergencies or disruptions.
- **Predictive analytics and artificial intelligence (AI)-based solutions** analyze vast amounts of data from energy infrastructure, weather forecasts, and other sources to predict potential disruptions, identify vulnerabilities, and optimize system operations. AI-based solutions enable proactive risk management, condition-based maintenance, and predictive maintenance strategies, enhancing resilience and reliability of energy systems.

By leveraging these innovations, energy systems can become more resilient, adaptive, and responsive to evolving challenges and disruptions, helping ensure the reliable and sustainable delivery of energy services to customers and communities. However, technology innovation is not sufficient on its own; business model innovation is also needed.

RESILIENCE AND UTILITY BUSINESS MODELS

The journey to Net Zero is expected to provide a broad spectrum of challenges and opportunities for utilities and see significant change in their business models. The relationship between these business models and resilience will be important as it should draw on an understanding of the value that both utilities and consumers place on resilient energy supply.

Traditional business models in the electricity sector, for example, are centered around fossil fuel-based power generation and a one-way flow of electricity to consumers; they do not align with the emerging decentralized, distributed, digitalized system of the future and therefore may not account for the realities and expectations for resilient energy in this new environment. To navigate this transition successfully, utility companies may pursue new business models that prioritize low-carbon energy sources, energy efficiency, multi-vector solutions, flexibility, and customer engagement but should do so with resilience as a key consideration.

In earlier work undertaken by EPRI,[13] attention was given to scenarios that describe possible futures for utilities and how these might be reflected in new or refreshed business models. These scenarios are shown in Figure 1.

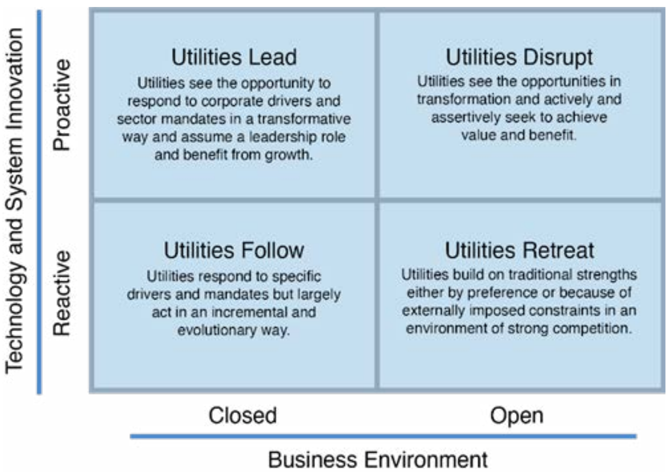


Figure 1. *Energy system transformation scenarios for utilities*

These scenarios provide a way of organizing and describing the context in which utilities are likely to be required to operate and reveal options for how they might choose to participate. They do this by showing possible relationships between the approach adopted for innovation and the extent to which the policy, regulatory, financial, and commercial environment offers encouragement and support for change. They reveal questions that require well-informed, timely decision making across key strategic areas:

- Possible responses to changes that are happening or could happen in the energy landscape, either in the commercial environment or the innovation environment
- Conditions that must be true in order for a utility to respond in a particular way
- Perspectives of other stakeholders and how they might align or conflict with those of the utility
- The transformation destination being sought
- Possible strategic options for reaching the destination successfully
- The potential to maintain optionality in decision making to respond effectively to emerging threats and opportunities

In considering resilience, these scenarios could be helpful in two ways. First, they could guide discussion that is led by business model preferences which are then used to illuminate the implications for resilience and how these might be addressed. Second, approaches to resilience could lead the thinking with business model options being identified that are revealed or constrained by the demands of resilient service delivery.

There is likely to be a degree of correlation between the perspectives. A "Utilities Disrupt" approach may employ new business models that will create new risks (or opportunities) from a resilience point of view. An energy-as-a-service offering for example, could enable the utility to assure home comfort but to do so using non-network assets, thereby lowering risk from some types of threats. A business model that is based on assuring a resilient service might imply a more conservative "Utilities Lead" positioning, relying on strengthened infrastructure. Alternatively, a resilient business model could be more commercially disruptive based on offering "bronze, silver, or gold" levels of service, for example.

The scenarios can help shape the discussions that explore the possibilities and their implications and support the broader decision-making process. This discussion would consider both "Technology and System Innovation," and the "Commercial Environment," both axes in the scenario quadrants, and may encompass aspects such as:

- **Risk assessment and planning** to identify potential threats and vulnerabilities to the energy system, including physical, operational, cyber, supply chain, and social risks. With knowledge of the risks, business models can be designed that mitigate these risks (potentially a

13 *Towards Net Zero: The Evolving Utility Business Model and Possible Future Scenarios*, EPRI, Palo Alto, CA: 2022. 3002025745.

"Utilities Follow" approach) or exploit them (a "Utilities Disrupt" approach). Horizon scanning[14] and scenario modelling will help identify what credible new threats might emerge, their potential impacts, and how can they be mitigated.

- **Investing in infrastructur**e needed to build or upgrade equipment and systems to enable the level of resiliency to be provided. This may include advanced technologies such as sensors, and real-time monitoring tools to improve situational awareness, early detection of disruptions, and rapid response capabilities.
- **Diversifying energy sources** to reduce dependence on any single fuel or technology. This extends to supply chains to reduce reliance on single points of failure and mitigate the impact of disruptions, including partnerships and collaborations with multiple suppliers and vendors to ensure resilience in the supply chain and access to critical resources during emergencies.
- **Modernizing the infrastructure** to improve reliability, flexibility, and responsiveness. This includes deploying automation, advanced metering infrastructure, and distributed energy resources such as microgrids, energy storage, and demand response programs.
- **Strengthening cybersecurity** measures to protect energy infrastructure and data systems from cyber threats. This may involve implementing robust cybersecurity protocols, conducting regular security audits and assessments, and providing cybersecurity training for personnel.
- **Strengthening supply chain resilience** by diversifying supply sources, building redundancy into supply chains, and developing contingency plans to mitigate risks associated with supply chain disruptions. This includes securing critical components, materials, and fuels from multiple suppliers and regions.
- Developing robust **business continuity** plans that outline procedures for maintaining essential services, communications, and operations during disruptions or emergencies.
- Pursuing **collaboration and coordination** with government agencies, regulators, industry partners, customers, and communities to address resilience challenges collectively.
- **Engaging with communities** and stakeholders to raise awareness about energy resilience, build social networks and support systems, and empower local residents to take proactive measures to protect their energy supply during emergencies. This may include providing information about backup power options, energy efficiency measures, and emergency preparedness.
- Developing **supportive policies and regulatory frameworks** to incentivize investments in energy resilience, promote innovation and technology adoption, and facilitate collaboration among government agencies, industry stakeholders, and other actors involved in energy resilience planning and implementation.

By exploring strategies and understanding their interactions with potential business models in mind, new opportunities may be identified and developed to the benefit of both the utility and the energy consumer.

BUSINESS MODELS THAT COULD HELP ENSURE RESILIENCE

Business models that integrate resilience considerations into their operations and value propositions could help ensure resilience for energy utilities and their customers. These complement other interventions that utilities may make in infrastructure and operation to deliver good outcomes and may include:

- **Subscription-based resilience services:** Offer subscription-based resilience services to customers, providing access to backup power systems, energy storage solutions, and other resilience-enhancing technologies. Generate recurring revenue streams by providing ongoing maintenance, monitoring, and support for these services, helping customers prepare for and recover from disruptions.[15]

14 *Perspectives on Transforming Utility Business Models, Paper 1: Horizon Scanning and Forecasting*. EPRI, Palo Alto, CA: 2024, 3002028820.

15 Green Mountain Power Bring Your Own Device program

- **Resilience as a Ssrvice (RaaS):** Provide resilience as a service to industrial and commercial businesses and critical infrastructure facilities, offering customized resilience solutions tailored to their specific needs and risk profiles. Offer bundled packages that include risk assessments, contingency planning, infrastructure upgrades, and ongoing support to help improve their resilience position.[16]
- **Microgrids as a service (MaaS):** Develop and operate microgrids in partnership with communities, campuses, industrial estates, and commercial facilities, offering resilient and decentralized energy solutions. Generate revenue through electricity sales, capacity contracts, and service agreements with microgrid customers, while also providing grid services and resilience benefits to the broader energy system.[17,18]
- **Energy as a service (EaaS):** Offer integrated energy solutions that combine generation, storage, demand management, and grid services to optimize energy performance and resilience. Customers pay a subscription fee for access to reliable, resilient energy services while service providers assume responsibility for system design, operation, maintenance, and performance guarantees.[19]
- **Energy storage and demand response aggregation:** Aggregate DERs such as energy storage systems, electric vehicles, smart appliances, solar PV, and demand response assets to provide grid services and enhance system resilience. Generate revenue by participating in energy markets, providing ancillary services, and responding to grid emergencies, while also offering reliability and resilience benefits to utilities and grid operators.[20,21]

16 Duquesne Light Company worked with a Carnegie-Mellon University MBA class on a resilience as a service research project in Pittsburgh. The class presented to EPRI's Value of Resilience Working Group during the November 2023 webcast. The final report is available by contacting EPRI. Capstone Presentation.

17 ReNCAT: The Resilient Node Cluster Analysis Tool, Sandia National Laboratory, 2022.

18 Sandia's Resilient Node Cluster Analysis Tool (ReNCAT) Tool

19 ENEL X Energy as a Service

20 Order No. 2222 Explainer: Facilitating Participation in Electricity Markets by Distributed Energy Resources, Federal Energy Regulatory Commission.

21 Texas moves ahead with expanded 80 MW distributed energy resource pilot designed to boost grid reliability (article on ERCOT ADER Pilot), Utility Dive), 2022.

- **Resilience-enhanced tariff structures:** Develop tariff structures that incentivize resilience investments and behaviors among customers, such as offering discounted rates or rebates for installing backup power systems, energy-efficient appliances, or grid-connected DERs. Create value-added services and benefits for customers who participate in resilience programs, such as priority restoration during outages or access to community resilience resources.
- **Risk sharing and insurance solutions:** Build partnerships with insurance companies and risk management firms to offer resilience-focused insurance products and risk-sharing arrangements to customers and stakeholders. Pool resources and spread risks across multiple entities to provide financial protection against disruptions, while also incentivizing investments in resilience and risk-mitigation measures.
- **Community-based resilience initiatives:** Engage with local communities and stakeholders to develop community-based resilience initiatives, such as community microgrids, neighborhood resilience hubs, and emergency preparedness programs. Facilitate partnerships and collaborations with local governments, nonprofits, and community organizations to co-create resilience solutions that address the unique needs and challenges of each community.[22]

By adopting business models such as these, energy utilities can not only enhance their own resilience but also contribute to building resilience across the broader energy ecosystem and society as a whole.

ENSURING BUSINESS MODELS PRIORITIZE RESILIENCE AS THEY EVOLVE

As the energy system transforms, the impact of known risks is likely to increase, and new threats are likely to emerge. Together these could compromise resilience in significant ways. This implies the need for measures that seek to secure or enhance resilience; these measures should be part of the process that is included as scenarios are studied, options are identified, and decisions are made relating to business models. Such measures might include:

22 Urban Sustainability Directors Network Resilience Hubs

- **Integrated risk assessment:** Incorporate comprehensive risk assessments into business planning processes to identify vulnerabilities and prioritize resilience investments. This involves assessing physical risks from extreme weather events, cyber risks, supply chain disruptions, and other potential threats to the energy system. The role that business models can play in mitigating these risks or the impact on the potential for sustainable returns from business models should be an important avenue of assessment.
- **Resilience metrics and targets:** Develop resilience metrics and targets that align with broader business objectives. This could include metrics related to outage duration, recovery time, system reliability, and customer satisfaction during disruptions. These metrics should reflect the behavior of business models as well as be reflected in their ongoing development and application. There is a substantial body of work being undertaken on such metrics including, for example, at the National Renewable Energy Laborator (NREL) in the United States or work sponsored by the European Commission in Europe.
- **Planning exercises:** Conduct planning exercises to anticipate and prepare for a range of potential disruptions, including extreme weather events, cyber attacks, and supply chain disruptions. This helps businesses understand the potential impacts of different scenarios and develop appropriate response strategies. By considering a range of scenarios, companies can develop flexible strategies that enhance resilience across different potential futures. This planning should explicitly include the role of business models.
- **Investment in redundancy and diversity:** Invest in redundancy and diversity within the energy system to enhance resilience. This could involve diversifying energy sources, pursuing multi-vector solutions, building redundant infrastructure, deploying storage, and investing in microgrids. These investments must be accommodated in the utility's business models and in addition should be a source of inspiration for new value propositions to consumers.
- **Technology integration:** Leverage emerging technologies such as AI, Internet of Things (IoT), and blockchain to improve the monitoring, management, and response capabilities of energy systems, thereby enhancing resilience to various threats. Technology and system innovation should be seen as a source of opportunity for business model development.
- **Partnerships and collaboration:** Collaborate with other stakeholders, including government agencies, regulatory bodies, and technology providers, to enhance resilience across the entire energy ecosystem. This may involve sharing data, resources, and best practices to collectively address resilience challenges. Collaboration can lead to opportunities for new customer offerings that are differentiated in the market.
- Incentive mechanisms: Use regulatory incentives or insurance discounts that encourage investments in resilience to de-risk or enhance existing or new business models.
- **Customer engagement and education:** Engage with customers to understand how they would prefer to see resilience reflected in the value propositions offered to them and include willingness-to-pay surveys to help ensure better alignment of value and price. This could generate increased interest and commitment to resilience as an important decision-making criterion.
- **Continuous improvement and adaptation:** Foster a culture of continuous improvement and adaptation within the organization to respond effectively to evolving resilience challenges. This involves regularly reviewing and updating resilience strategies and business models as new information emerges and conditions change.

By incorporating these principles into the development, deployment, and potentially retirement of their business models, energy utilities can better prepare for and respond to the growing threats to system resilience, ultimately enhancing their ability to deliver reliable and secure energy services in an increasingly complex and uncertain operating environment.

CONCLUSION

Resilience in an energy system requires a holistic approach that considers technical, operational, economic, social, and institutional dimensions of providing energy services to consumers. This must encompass provisions to anticipate, mitigate, and respond to a wide range of potential threats and challenges. This means being proactive in anticipating and preparing for disruptions, as well as building the ability to respond and recover when they occur.

Not having a resilient energy system can have significant impacts on various aspects of society, the economy, and the environment. These risks are multifaceted and interconnected, with implications for public health, safety, economy, environment, and national security. Enhancing the resilience of the energy system is essential for mitigating these risks, ensuring reliable and secure energy services, and building a more sustainable and resilient society.

The level of resilience required for an energy system depends on various factors, including the criticality of energy services, the likelihood and consequences of potential disruptions, and the priorities and preferences of stakeholders. While achieving absolute resilience may be impractical or cost-prohibitive, energy systems should aim to achieve a sufficient level of resilience to ensure the reliable and secure delivery of essential energy services under a wide range of conditions.

Technical and operational innovation has an important role to play as energy system transformation introduces new resilience risks, but business model innovation is also needed. Business models have the potential to reveal and deliver the value of resilience to both the utility and the energy consumer.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

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