Innovating Future Power Systems

From Vision to Action

The Electricity Technology, Regulation, and Market Design Working Group

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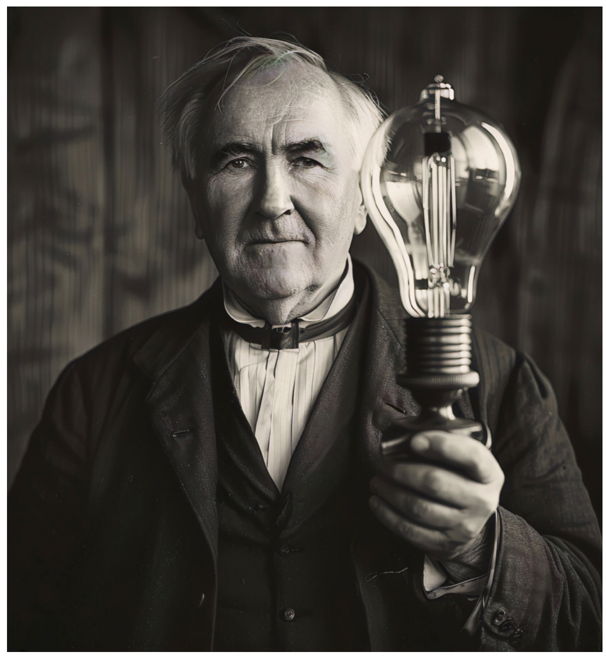
Contents

Executive Summary

The global energy landscape is transforming, and nowhere is this more evident than the electricity sector. Technological advancements, shifting economic conditions, and evolving environmental policies are converging to reshape the way power systems operate.

This report explores the implications of these changes for the future of power systems, focusing on the intersection of technology, regulation, and market design. It offers a vision for a dynamic, clean, prosperous energy future that balances dependability, decarbonization, democratization, and justice, with innovation playing a central role.



Thomas Edison
Image generated with AI by AdnanArif. Adobe Stock Images.

The Challenge of Energy System Transformation

The transformation of power systems is driven by several key factors: electrification trends, technological advances, and decarbonization. These changes are about not just reducing carbon emissions but also integrating new technologies, improving resilience, and rethinking how systems are managed and regulated. These forces are exerting pressure on traditional business models, regulatory institutions, and market designs.

Traditional utilities, operating under a cost-of-service regulatory model, are facing new opportunities and challenges from distributed energy resources such as solar, wind, and battery storage. Technological advancements, particularly in digitalization, are enabling new forms of energy management, allowing consumers to play a more active role in electricity markets. As a result, the boundaries between centralized and decentralized power systems are becoming increasingly blurred, challenging the regulatory frameworks that have governed the industry for decades.

Historically, the electricity sector has focused on three primary policy objectives: safety, affordability, and reliability. Evolving priorities in the electricity sector have introduced three additional dimensions: resilience, decarbonization, and justice. Balancing these six objectives will be critical to ensuring the success of future power systems, but doing so will require significant innovation, both technological and institutional.

A Framework for a Clean and Prosperous Future

To navigate changing power systems, this report presents a framework centered around six key concepts: digitalization, decentralization, democratization, dependability, decarbonization, and justice. These interrelated concepts provide a holistic approach to understanding the challenges and opportunities that lie ahead.

- **Digitalization.** The integration of advanced technologies such as smart meters, sensors, and automation into the grid is transforming how electricity systems operate. Digitalization enables real-time monitoring, optimizes grid operations, and facilitates the integration of distributed energy resources, improving flexibility and resilience.

- **Decentralization.** As energy generation becomes more distributed, power systems are shifting away from centralized control to include smaller, decentralized resources such as rooftop solar, battery storage, and microgrids. This shift enhances resilience, reduces transmission losses, and empowers consumers to play a more active role in managing their energy needs.

- **Democratization.** Technological advances and regulatory reforms are enabling broader participation in energy markets. Consumers can now generate and manage their electricity, participate in community solar projects, and engage in peer-to-peer energy trading. Democratization also emphasizes equity, ensuring that all communities have access to the benefits of the energy transition.

- **Dependability.** As power systems become more decentralized, ensuring reliability and resilience becomes more complex. Dependability must be redefined from a consumer-centric perspective, focusing on providing consistent, reliable power while allowing consumers to choose how they use and produce electricity.

- **Decarbonization.** The shift to low-carbon energy sources, such as wind, solar, and battery storage, is reshaping power systems and creating new regulatory and market challenges and opportunities. Achieving decarbonization will require significant investment in grid modernization, energy storage, and renewable energy integration, in addition to developing technologies like advanced geothermal and advanced nuclear.

- **Justice.** Future power systems must also address issues of distributive, procedural, and commutative justice. Ensuring equitable and affordable access to energy, fair distribution of costs and benefits, inclusive decision-making processes, and equality before the law is essential for creating a just energy future.

Innovation and Institutional Change

For this vision of the future to become a reality, significant institutional changes are required. Current regulatory frameworks are often outdated and ill-suited to the dynamic nature of technological change in the electricity sector. In many cases, regulation stifles innovation, preventing the adoption of new technologies and business models that could enhance grid flexibility, reduce costs, and improve resilience.

Innovation, in the Schumpeterian sense, is the process of turning human creativity into new inputs, products, services, production techniques, and organizational methods. This process is essential for balancing competing policy objectives and driving economic growth. Schumpeterian dynamism often means that legacy technologies and incumbent firms become less profitable unless they innovate.

To foster innovation, regulatory reform must focus on removing barriers to entry, encouraging competition, and incentivizing the adoption of new technologies. This focus includes revisiting the traditional utility business model, which is based on cost-of-service regulation and often discourages utilities from investing in innovative solutions that could benefit consumers. Policymakers must also consider the role of digitalization and decentralization in creating a more dynamic and adaptable regulatory framework.

Case Study: Winter Storm Uri and the Importance of Resilience

The devastating impacts of Winter Storm Uri in 2021 highlighted the vulnerabilities of centralized power systems. The storm caused widespread power outages, leaving millions of Texans without electricity for days. While decentralization alone would not have prevented the storm's impacts, it could have mitigated the consequences, as could have more consumer digital management technologies and retail services like virtual power plants. Decentralized solutions such as microgrids and backup generators could have provided localized resilience, allowing communities to maintain power even as the larger grid failed.

This case study underscores the importance of integrating resilience into future power systems. As extreme weather events become more frequent and severe due to climate change, power systems must be designed to withstand and recover from disruptions. Decentralized solutions, combined with advanced digital technologies, offer a path forward for creating more resilient and dependable power systems.

Recommendations and the Path Forward

The report concludes with a set of actionable recommendations for decision-makers in four key policy actor groups: executive-branch policymakers, legislators, federal and state regulators, and agencies. The analysis and recommendations are also relevant to utility executives, other industry members, electricity consumers, and other stakeholder organizations. These recommendations include the following:

- Reform regulatory frameworks to encourage innovation, competition, and the integration of new technologies.

- Support the development and deployment of decentralized energy solutions such as microgrids, virtual power plants, and transactive energy systems.

- Invest in grid modernization and digitalization to enhance flexibility, resilience, and consumer participation.

- Promote justice by ensuring that all people, including those in historically marginalized communities, experience commensurate distribution of benefits and costs and have access to and are treated equally in regulatory and legal procedure.

- Encourage collaboration among regulators, policymakers, industry stakeholders, and consumers to foster a dynamic and adaptable energy system.

The future of power systems depends on our ability to embrace innovation, reform regulatory frameworks, and invest in new technologies. By focusing on digitalization, decentralization, democratization, dependability, decarbonization, and justice, we can create power systems that are not only more dependable but also cleaner and more just. Changing power systems present significant challenges, but with the right strategies in place, they also offer tremendous opportunities for creating a dynamic, prosperous, and sustainable energy future.

I. A Clean and Prosperous Energy Future Relies on Innovation and Dynamism

It's almost cliché to observe that electricity was the most transformational invention of the 20th century. In 2000, the National Academy of Engineering named electrification as the greatest engineering achievement of the past century.[1] Electricity has increased our productivity and quality of life by orders of magnitude compared with the candles, whale oil and kerosene lanterns, town gas lighting, water wheels, and steam engines of the 19th century and before. Over the 20th century, we built the infrastructure, operating procedures, utilities, and regulatory commissions that made this progress possible; we created industrial and consumer machines and devices predicated on the electric service platform.

In the late 19th and early 20th centuries, the commercialization of large-scale electricity technologies, such as power plants and transmission networks, was driven by vertically integrated investor-owned utilities. These utilities were regulated under a cost-based rate-of-return framework, ensuring they could recover their costs and earn a reasonable profit. This business model resulted in fixed, regulated retail prices based on the average cost of service, and it established a uniform definition of electric service that applied to all customers in each of the three customer categories—residential, commercial, and industrial—regardless of their specific needs or usage patterns.

In the United States, the legacy model of vertically integrated monopolies has given way in many regions to various forms of unbundling and competition in generation and, in some regions, retail supply. However, in nearly all regions, state-regulated electric distribution utilities are still granted exclusive franchises, giving them the right to operate distribution wires in a defined geographic area. This right creates a monopoly, where the utility controls the physical infrastructure delivering electricity to homes and businesses. While competition for the sale of electricity over the distribution grid has been introduced in some states, in most areas this is not the case, and where competition exists it is often constrained in practice. The monopoly distribution structure is justified by the high capital costs and efficiency of having a single operator manage the local grid rather than multiple companies duplicating infrastructure.

However, this structure has a trade-off: It limits competition even as technology and services in and around the delivery of electricity evolve, potentially stifling innovation and customer choice in services like distributed energy resources (DERs), unless regulatory frameworks allow for more open access or competition at the service level. This structure reinforces the centralized nature of power distribution but creates friction as options like self-supply, microgrids, and transactive energy challenge the traditional utility model.

Today power systems are experiencing significant transformations, driven by technological advancements, economic shifts, and changing environmental and geopolitical policy goals. The push for decarbonization and electrification is putting pressure on current business models, regulatory frameworks, and market structures. These shifts present both opportunities and challenges, affecting consumer value propositions, reshaping industry structures and firm boundaries, and influencing regulatory approaches.

Technological advancements, particularly the development of the combined-cycle gas turbine in the 1980s, began to erode the economic basis for the monolithic vertically integrated, regulated business model, so in some regions utilities are no longer fully vertically integrated. More recent innovations in digitalization enable more DERs, such as solar, storage, and demand response, to participate in the grid and form other business models, like nonutility microgrids. As these technologies proliferate, they challenge the traditional utility's monopoly, shrinking the *economic* boundaries of the regulated utility footprint, although an increasingly outdated regulatory footprint precludes new and different business models. Technological change has been happening more quickly than institutional change.

As American consumers and producers of electricity sitting today with this inherited history and legacy systems, we face a substantive challenge: trying to decarbonize power systems quickly while maintaining safety, affordability, and reliability and ensuring that power systems are more just, including equitable distribution of benefits and costs, than they have been historically. Balancing these objectives presents a complex challenge.

Decarbonization to mitigate climate change's effects introduces its own set of investment, policy, and cultural challenges. The shift toward low-carbon technologies requires significant capital investment in renewable energy, grid modernization, and energy storage, creating financial risks and uncertainties for investors, utilities, innovators, and customers. Wood Mackenzie forecasts that "262 gigawatts (GW) of new DER and demand flexibility capacity will be installed from 2023 to 2027, close to matching the 272GW of utility-scale resource installations also expected during that period."[2] At the regulatory level, outdated frameworks often hinder the integration of these technologies, requiring reforms to incentivize innovation, ensure market fairness, and balance reliability with environmental goals. Culturally, the goal of decarbonization challenges traditional energy systems, pushing for decentralized models and changing consumer behaviors, while navigating political resistance and societal adaptation to new energy paradigms.

To the extent that climate change manifests as variability in climate-based phenomena, we are likely to see greater variability in storm intensity, increases in the scope and duration of droughts, and other costly and disruptive phenomena. For example, Hurricane Beryl made landfall on July 8, 2024, and maintained hurricane strength until it reached Houston, delivering 10–15 inches of rain in some areas and resulting in 2.7 million power outages in the region.[3] Four days later, over one million customers were still without power.[4] The confluence of events diminished the region's resilience and recovery: flooding and outages from a strong derecho in May, then Beryl, and then a July heat wave, almost like a summer version of the combination in 2021's Winter Storm Uri. This pattern is called a compound disaster, in which multiple events cascade and affect a system's resilience, its ability to rebound from damage and return to full functionality.[5]

Balancing Policy Objectives and Economic Growth: The Role of Innovation

Where historically we have balanced three policy objectives of safety, affordability, and reliability, we now strive to balance six policy objectives, including resilience, decarbonization, and justice. Balancing three policy objectives in power systems has been challenging enough; balancing six will be even more difficult and costly unless something changes to reduce those trade-offs.

That something is *technology*. Following the economist Joseph Schumpeter, we characterize new technology as emerging from innovation, an ongoing process of turning human creativity into new inputs, products and services, production techniques and methods, organization methods, and business models.[6] This process is essential, but not sufficient, for balancing these policy objectives with a view toward future prosperity and flourishing.

In *The Lever of Riches*, Joel Mokyr distinguishes between *invention*, the initial creation or discovery of novel ideas, technologies, or methods, and *innovation*, the practical application of those inventions involving the actual implementation and widespread adoption of new technologies in a way that transforms economic processes and industries.[7] While inventions are often the product of individual or small-group creativity, innovations depend on broader societal, economic, and institutional factors that facilitate the diffusion of these new ideas, allowing them to generate tangible economic impact. Innovation, not just invention, is crucial for long-term economic growth.

Similarly, Brian Arthur argues that technological progress of the kind described by both Schumpeter and Mokyr is, like biological systems, a combinatorial process in which new technologies are created by combining existing technologies in novel ways.[8] Rather than being entirely original, most innovations result from recombining and integrating preexisting components, ideas, or processes. This combinatorial process means that the pace of innovation can accelerate as the "library" of available technologies grows—each new addition increases the potential combinations, creating more opportunities for further innovation.

Innovation and the novel recombination of existing technologies are often incompatible with the current utility industry structure, dominated by regulated monopolies. The utility industry is designed for stability and control, not the nimble adaptability required for rapid innovation. This rigidity can stifle the experimentation and diffusion necessary for innovation, creating a disconnect between technological advances and the industry's capacity to adopt them efficiently.

We also see it as imperative to pursue dependability, decarbonization, and justice on a foundation of innovation and economic growth. Technological change is necessary for achieving these often-conflicting objectives and lessening the associated trade-offs. Such innovation is often a consequence of economic growth and increased living standards and is essential for further advances.

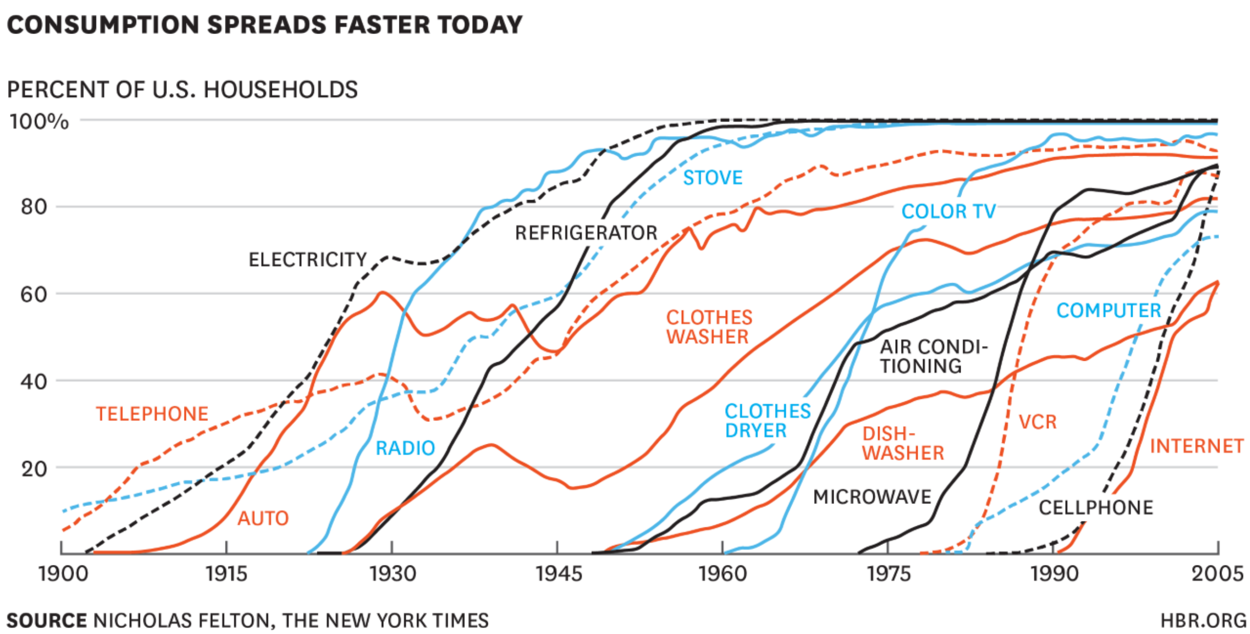
Over the past two decades, digital innovation has transformed the global economy, enabling unprecedented connectivity, data analytics, and automation across industries. The rise of the internet, cloud computing, and artificial intelligence has facilitated new business models, enhanced productivity, and revolutionized consumer experiences.

In parallel, the energy sector has witnessed significant technological advancements, particularly in renewable energy and storage solutions. Innovations in wind and solar power have reduced costs, making them increasingly competitive with traditional fossil fuels. Battery technology has evolved, enhancing grid reliability and enabling the broader integration of intermittent renewable resources. Other energy technologies, such as geothermal and various forms of energy storage, have advanced, contributing to a more resilient, sustainable, and decentralized energy system. These innovations underscore the critical role of markets and regulatory reform in fostering a dynamic environment where technological progress can deliver the energy systems compatible with future flourishing.

The pace of innovation has increased since the late 19th century, as Figure 1 indicates. As they mature and reach mass adoption, earlier technologies become (complementary) inputs into recent new technologies like AI.

Technologies do not exist—and innovation does not occur—in a vacuum. The institutional context matters greatly in determining whether, how, and how much any innovation incentives exist. Institutions are the formal and informal rules that shape our incentives and govern how we act and interact, ranging from formal laws and regulations to informal customs and social norms.[9] All kinds of institutions can affect incentives to innovate, although

Figure 1. The Speed of Technological Adoption over Time



Source: Rita McGrath, "The Pace of Technology Adoption Is Speeding Up," *Harvard Business Review*, November 25, 2013, https://hbr.org/2013/11/the-pace-of-technology-adoption-is-speeding-up.

in the electricity setting the primary focus is public utility regulation.[10]

In much the same way that older technologies become obsolete over time through innovation, institutions can become obsolete due to dynamic changes in the economy and our expectations—or, at the very least, they can become misaligned with new economic and technological settings that have changed our expectations. Cost-based rate-of-return regulation of monopoly utilities creates incentives that hinder the invention, innovation, recombination, and adoption processes, both inside the utility and by insulating the utility from competition, that enable a beneficial—and, indeed, sustainable—balance of those six policy objectives with continued high living standards and a vision of flourishing and prosperity for all.

For these reasons, the animating question of this report is one of *institutional change*: how to improve the association among regulation, industry business models, and innovation to increase our chances of creating a vibrant, dynamic, abundant future with power systems that are dependable, decarbonized, democratized, and just. Technological change, particularly in digitalization and decentralization, unlocks those opportunities if the institutional environment does not erect barriers to it.

Our Vision

Reorienting the dominant industry perspective to the end-use consumer is paramount. The pace of innovation in consumer engagement, as reflected in the treatment of demand-side options in resource plans and forecasts across the industry, is far behind what it needs to be to decarbonize the electric supply and reliably and affordably meet the demands for energy services. Innovation is occurring, but meeting these challenges requires amplified innovation, in new and creative ways, including both technological and institutional innovation.

A Case Study in Reimagining Power Systems: Winter Storm Uri

Winter Storm Uri, which struck the south-central United States in February 2021, led to catastrophic power outages. In Texas in particular, power plants shut down, natural gas infrastructure froze, and utilities failed to rotate outages effectively and, later, reenergize customers even after adequate supply once again had become available. Some customers retained power throughout the multiday event, while others were left without electricity for extended periods. The grid's failure at scale and its lack of decentralization worsened the situation. While decentralization wouldn't have prevented the event, it could have mitigated the consequences.

First, the grid was not granular enough to distribute the outages caused by Winter Storm Uri equitably. This failure magnified the harm of the power outages, as customers who lost power ended up without it for days, rather than experiencing the "rolling" outages that a grid with a more granular architecture would provide. As federal regulators identified in their post-storm report, Texas's advanced metering infrastructure was not capable of "rotating" outages in the Texas electricity network.[11] Advanced metering infrastructure is used in routine business operations, such as disconnecting customers for nonpayment. The regulated utility business model, under which utilities profit from capital expenditures but not directly from operational performance, contributed to underutilization of these technologies.

The larger grid infrastructure also failed during the storm. Distribution circuits were too large, and their design made it difficult to rotate outages without destabilizing the grid's frequency. Circuits serving critical infrastructure, like hospitals or police stations, remained powered, while other circuits experienced complete blackouts.

While much of Austin, Texas, lost power, for example, downtown remained powered to support essential services. This decision left many residential neighborhoods without electricity for days. But as Austin Energy's manager explained, "'There is no more energy we can shut off at this time so we can bring those customers back on' as all available circuits were serving critical load such as hospitals and water treatment centers."[12]

Decentralized solutions like microgrids that could have allowed neighborhoods to maintain power—capable of islanding and self-supplying a local area when power supply is interrupted at a larger scale—are rare in residential neighborhoods in Texas. These systems could have reduced dependence on the central grid.

Similarly, while the adoption of backup generators is growing, it remains limited. According to one supplier, only 6.25 percent of US single-family homes have backup power, despite increasing demand in areas prone to outages.[13] Texas has appropriated funding for backup power installations in critical institutions, but the program has yet to be implemented.[14] Residential customers also do not yet have widespread access to digital systems to automate their participation in markets or enable automated or remote adjustments to their energy demand in emergency situations.

Winter Storm Uri has many lessons to offer policymakers, covering such issues as how energy infrastructure should be weatherized, the dependability of certain power resources and the implications on electricity market design, and the codependency of natural gas and electric networks. The storm's devastation illustrates the crucial interplay of technology and institutions for dependable, decarbonized power systems.

As supply becomes more variable and as more demand becomes inherently flexible, we can no longer assume the system must be prepared to serve every kilowatt-hour of demand at a flat rate at whatever time it may appear, no matter how much it costs to do so. We can meet consumers' demand for energy services dependably at much lower cost, but doing so will require an acceleration of innovation in products and services targeted to flexible consumers.

This report is guided by the following vision statement:

> We should strive toward an energy system that seeks to remove barriers to innovation and enable vibrant ecosystems to accelerate opportunities for consumers to have access to affordable and dependable power systems, decide how and when they consume (and produce) the electricity they want and need, and invest in the solutions that bring them the greatest value.

We recognize, as do many industry professionals, policy experts, and academics, that aspects of the technologies, regulatory institutions, and industry business models in electricity have become obsolete and in some ways have become obstacles to achieving the vision we have articulated. In this report, we propose a holistic framework for reflecting on and analyzing the changes we are experiencing in our technologies, our economies, and our expectations and for articulating the dimensions of this vision. We also suggest some actionable principles to inform steps that stakeholders can take to address institutional obsolescence and make this vision of a dynamic, clean, prosperous future a reality.

In the following analysis, we adopt a specific scope and make some assumptions. This report does not address transmission innovation, investment, planning, or cost-allocation issues in depth; it also does not examine deeply the implications of our analysis for wholesale power market design and regional transmission organization governance, although we discuss these macro-grid topics when relevant to our primary focus. We also do not examine in detail changes in areas like geothermal or nuclear energy.

We assume that safety and affordability continue to be paramount objectives of future power systems. We also assume that the transmission and distribution wires networks still have economies of scale and scope but that wires networks are increasingly contestable due to digital innovation and advances in storage and other distributed energy technologies.[15] Investor-owned utilities and the distribution grid remain important elements of future power systems and our framework. We do not see DERs and utilities as a (false) dichotomy, but rather claim that utilities can help or hinder DER innovation and that regulatory reform can improve their complementarity.

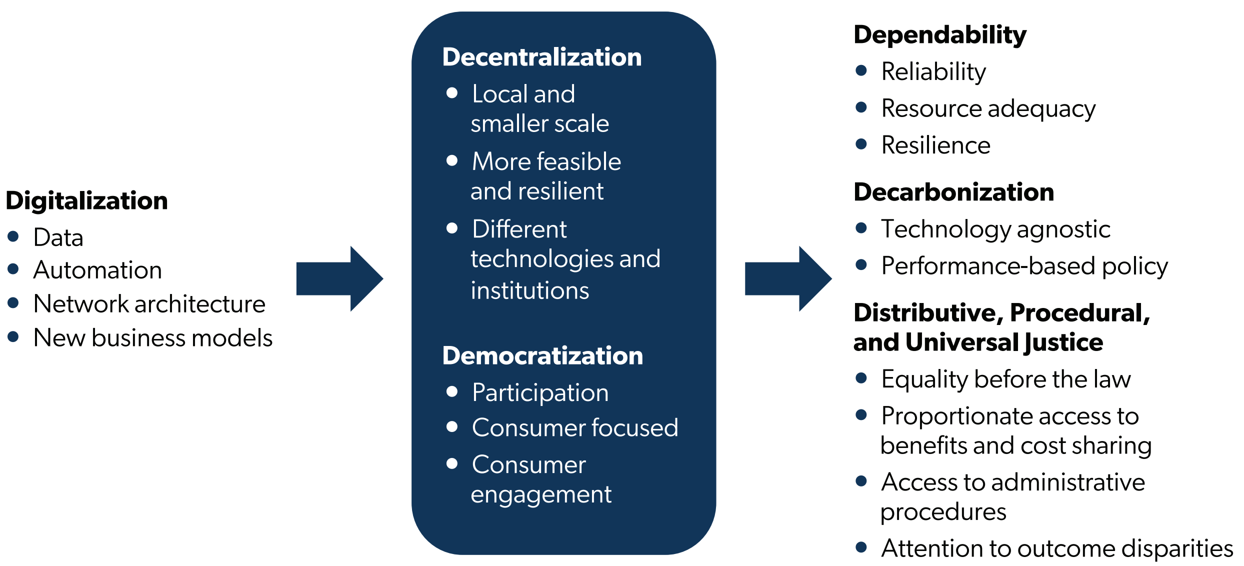
A Framework for a Clean and Prosperous Future

The energy transition requires a profound transformation in how we generate, distribute, and consume electricity. This transformation is not just about replacing fossil fuels with renewable sources; it also necessitates a reimagining of regulatory frameworks and industry business models. Central to this reimagining are six interrelated concepts: digitalization, decentralization, democratization, dependability, decarbonization, and justice. As seen in Figure 2, each plays a critical role in shaping a future energy system that is innovative and aligned with consumer perspectives.

Digitalization in the electricity industry involves integrating advanced technologies like smart meters, sensors, automation, data analytics, and grid-edge consumer electronics. These tools enable real-time monitoring and management, optimizing grid operations and enhancing flexibility. Flexibility is essential as it allows the grid to respond dynamically to fluctuations in supply and demand, especially with the integration of renewable energy.

Digitalization supports more efficient load balancing, facilitates the integration of DERs, and gives consumers greater control over energy use. It also lowers DER interconnection costs and enables decentralized, decarbonized systems that were previously unattainable with analog controls. AI and digital

Figure 2. The Framework



Source: Authors.

infrastructure are vital for managing complex, decentralized systems with millions of participants, a core feature of the modern grid.

Decentralization expands the focus from centralized power plants to include smaller, distributed resources like rooftop solar, battery storage, and microgrids. It is a set of technologies, grid architecture, and organization that enables consumers to choose to generate and manage their electricity, reducing reliance on traditional utilities and challenging existing regulatory frameworks. As the grid decentralizes, regulations must evolve to support new forms of energy exchange and ensure broad access to these innovations.

Decentralized systems enhance resilience by reducing the risk of widespread outages. They offer flexibility, improving reliability with low-carbon, intermittent resources and supporting local energy markets and demand-response programs. By dynamically adjusting supply and demand, decentralized systems reduce grid strain during peak periods and optimize energy use when renewable supply is abundant, making evolving systems more dependable.

Democratization of the electricity industry is an institutional approach that emphasizes increasing accessibility and consumer participation in the energy market. Historically, a few large entities have controlled energy generation and distribution, but technological advances and regulatory reforms are opening the door for broader participation. Community solar projects and the rise of "prosumers"—individuals who both produce and consume electricity—are key examples of democratization (and decentralization). For public utility regulation, democratization necessitates a shift toward policies that promote equity, ensuring that all consumers, regardless of socioeconomic status, have access to the benefits of power systems. This concept also ties into broader discussions about energy justice and systemic inequities in energy access.

Dependability encompasses the traditional pillars of reliability, resilience, and resource adequacy but from a consumer-centric perspective. Consumers expect that their electricity supply will be consistent, resilient to disruptions, and adequate to meet their needs at all times. However, in a more flexible and dynamic energy system, dependability also includes consumers' ability to adjust their demand if doing so is advantageous. For example, consumers might choose when and how to cool their homes or charge their electric vehicles according to market prices and their own preferences.

As the energy landscape evolves with increasing reliance on intermittent renewable resources, ensuring dependability becomes more complex. Technological advancements, such as grid modernization, energy storage, and advanced forecasting methods, are essential for maintaining dependability in a decentralized and digitalized grid. Regulators must also consider new metrics and standards that reflect the changing nature of the grid and consumers' increased role in ensuring dependability.

Decarbonization aims at reducing greenhouse gas emissions. This change involves a substantial shift from fossil fuels to a mix of low-carbon energy sources, including renewables like wind, solar, and hydropower, as well as nuclear and geothermal energy. The incremental process of decarbonization also involves substituting natural gas for coal-fired generation and diesel backup generation.

Decarbonization is not only a technological challenge but also an institutional one, as existing regulatory frameworks were not designed for decarbonization. Utilities are central to this process, as they must balance the integration of these diverse low-carbon resources with maintaining grid stability and affordability for consumers. Decarbonization efforts are also closely linked to other aspects of this framework, as achieving a low-carbon future requires advances in digitalization, decentralization, and dependability.

Justice in the context of changing power systems is a multifaceted concept that includes distributive justice, procedural justice, and foundational principles of universal and commutative justice. *Distributive justice* focuses on the equitable distribution of the benefits and burdens of changing power systems. *Procedural justice* emphasizes the importance of inclusive and transparent decision-making processes, where all stakeholders, including consumers, have a voice in the regulatory and policy decisions that affect them. Procedural justice builds trust and ensures that all parties involved perceive the transition to future power systems as fair.

Beyond these, energy justice must also be guided by *universal justice* principles, rooted in the Aristotelian notion of justice as equality before the law. Universal justice includes respecting individuals' rights. The related concept of *commutative justice* refers to requirements not to harm others, often understood as negatively defined rights to freedom from harm to one's life, liberty, and property. By incorporating these broader concepts of justice, changing power systems can be more than just a technical shift; it can become a transformation that respects and enhances all individuals' rights and well-being.

Together, these six concepts provide a holistic framework for understanding the challenges and opportunities of the energy transition. They highlight the interconnected nature of technological innovation, evolving business models, and regulatory reform, emphasizing that a successful transition must consider not only the technical and economic aspects but also the institutional and social implications. By focusing on digitalization, decentralization, democratization, dependability, decarbonization, and justice, we can build power systems that enable a clean and prosperous future.

What This Report Provides

This report presents a holistic vision of future power systems with desired attributes and, after developing a framework for articulating that vision, proposes some recommended actions for four key policy actor groups: executive-branch policymakers, legislators, federal and state regulators, and agencies.

Chapter II provides a detailed description and analysis of the report's framework and its six dimensions and a synthesis of the complementarities across the six dimensions. Chapter III draws some implications for future power systems from this framework. Chapter IV provides some actionable implementation principles and paths forward for decision-makers.

II. Framework

The changing electricity landscape is shaped by the integration of digitalization, decentralization, democratization, dependability, decarbonization, and justice. This framework highlights the important role each factor plays in transforming power systems.

Digitalization

Digitalization, the process of using digital technologies, data, and real-time communications networks to digitize once-analog information, is transforming economies and societies and creating new value. This transformation makes intelligent systems possible, improving productivity, consumer experiences, and personal opportunities. These changes are both visible in daily life and taking place behind the scenes.

Banking and retail are clear examples of digitalization's broader impact. From ATMs in the 1970s to mobile banking and online shopping today, digitalization has reshaped industries. While challenges like privacy and cybersecurity have emerged, the overall effect has been widespread greater well-being. Digitalization also spurs further innovation, creating new products, services, and markets across the economy.

The digital age has been driven by technologies like big data, cloud computing, the Internet of Things, blockchain, and AI. These tools alone are not necessarily disruptive, but when combined, they change how organizations and societies create value, shape norms, and communicate. Continuous connectivity is driving rapid social and economic shifts and creating systemic social-economic changes at a scale and pace unprecedented in human history.[16] Digitalization has also created platforms for further innovation and creation of new products, services, business models, and markets more generally throughout the economy, reducing transaction costs and making market exchange in previously unreachable areas easier.

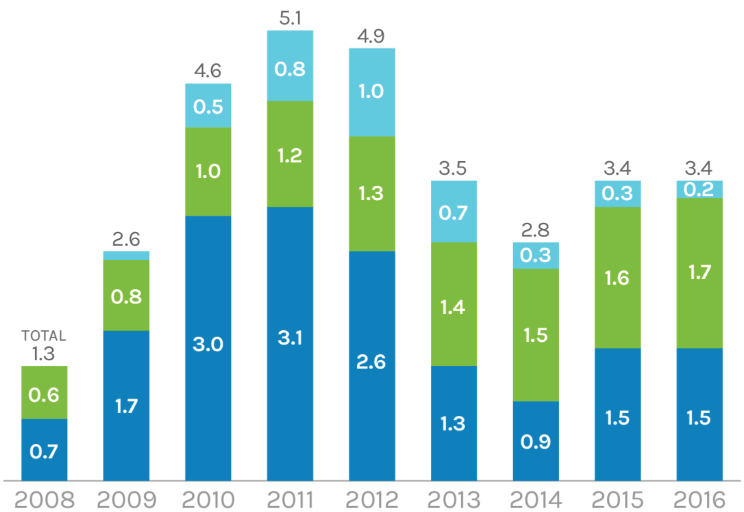
Digitalization and Digitization in Electricity

Whether referred to as "the smart grid," "grid modernization," or "digitalization," the intersection of information and communications technologies with power systems is growing. This intersection includes data collection, analytics, and real-time communications for sensing, monitoring, power electronics, distributed energy resource (DER) interfaces, and grid management.

Electricity systems generate three types of data: consumer consumption, resource performance, and grid state. Consumer data have been digital for over 20 years; advanced meter reading and advanced metering infrastructure have automated data collection for the past 15 years. Resource performance data are gathered through Supervisory Control and Data Acquisition systems and telemetry, managed by grid operators and resource owners. Grid state data have been digital in high-voltage systems for decades, and distribution systems have been digitizing for the past 20 years, although full digitization may take another decade.

While many distribution systems still lack real-time communications at smaller substations, feeders,

Figure 3. Annual Smart Grid Investment



DISTRIBUTION-LEVEL INVESTMENTS INCLUDE:

SMART METERING

$1.5 BILLION

Smart meters and related communications and IT infrastructure

DISTRIBUTION AUTOMATION

$1.7 BILLION

Feeder and substation automation; distribution management; volt/VAR optimization (VVO); conservation voltage reduction (CVR); fault detection, isolation, and restoration; and outage management

ADVANCED SMART GRID

$0.3 BILLION

Grid applications that go beyond basic DA, including active network management, distributed generation integration, load control, home energy management, and EV charging.

Source: US Department of Energy, *2020 Smart Grid System Report*, January 2022, https://www.energy.gov/sites/default/files/2022-05/2020%20Smart%20Grid%20System%20Report_0.pdf.

and meters, digitalization has accelerated since the mid-2010s. These efforts enhance reliability, support technologies like dynamic line rating, enable flexible demand, and improve energy management. Digitalization also facilitates electric vehicle (EV) integration, including bidirectional charging and better energy storage connections.[17] Figure 3 presents actual and forecast data on smart grid investments in the US by subcategory of investment.

Digitalization is a foundational key to a decentralized, dependable, decarbonized energy future. By integrating DERs, such as low-carbon generation and storage, it supports a more resilient and reliable grid. Technologies like digital inverters simplify DER-grid coordination, and grid-forming inverters stabilize frequency swings and allow higher DER penetration without sacrificing reliability.[18]

An operations-focused digital tool gaining importance is the use of digital twins—virtual models that replicate physical systems in real time. These models integrate data from sensors and devices, allowing operators to monitor, analyze, and optimize system performance. Digital twins simulate asset behavior and conditions, model scenarios, predict outcomes, and optimize operations without disrupting the actual system, making them essential for decision-making in complex infrastructures. In electricity grids, digital twins provide real-time simulations of power systems, from generation to distribution, allowing utilities to predict and address issues like load changes, renewable integration, and outages before they occur. In smart grids, digital twins can optimize DERs such as solar panels and batteries by simulating interactions with the grid during peak demand to optimize energy dispatch and manage voltage.

As digital technologies and DERs expand, consumers will have a more active role in meeting energy needs, reducing costs, and enhancing sustainability. Automation will ease participation in energy markets, enabling consumers to optimize their usage and support grid stability. This shift will create a more resilient energy ecosystem and foster new retail business models based on decentralized consumer aggregation.

The Role of AI

In the age of generative AI, digitalization's role in the grid has expanded significantly. AI can optimize grid operations by providing real-time insights to transmission and distribution operators, helping them make informed decisions and forecast potential grid disruptions. AI processes vast datasets to assist in planning equipment placement, reinforcing infrastructure against extreme weather, improving system efficiency, and calculating real-time assessments of the maximum amount of power that transmission lines can carry (i.e., dynamic line rating). It also enhances grid maintenance by enabling remote inspections, predicting equipment failures, and arranging for preventive maintenance. On the distribution grid, AI aids fault detection and repair for smoother operations. The US Department of Energy is funding AI-driven projects to improve grid resilience, such as undergrounding power lines.[19] Table 1 summarizes a framework for how AI enables climate change adaptation and mitigation.

As digitized DERs like smart thermostats, EVs, and batteries generate data, AI will enhance grid dependability by managing demand and integrating clean energy. A decentralized grid requires greater coordination and flexibility, which AI can provide by reducing demand during shortages and increasing it during surplus. AI optimizes EV charging, rooftop solar, energy storage, and distributed resources by integrating grid services and demand response and enabling transactive energy platforms.[20]

AI, along with smart-grid technologies, can help large electricity consumers like data centers and buildings become more flexible with energy. By unlocking flexible demand, AI reduces the need for curtailments, especially in regions with supply or transmission constraints. AI-driven systems enable homes, industries, and data centers to shift and lower energy consumption using building management systems and sensor data to optimize HVAC and other operations. Micro-grids powered by AI also help consumers manage when to buy, sell, or store energy.[21]

While AI use for grid operations will be beneficial, AI-enabling data centers and their growth present challenges due to their high and continuous energy demand for AI inference. (Energy demand for AI model training is more inter-temporally flexible.) Their strain on infrastructure often requires costly capacity investments that have long construction times. As data centers grow with cloud computing and AI, their energy use risks outpacing low-carbon generation. Advanced energy management and efficiency improvements are essential to balancing this demand with clean, affordable power and supporting grid decarbonization.[22]

Digitalization in Practice: Some Examples

In the short term, digitalization-driven decentralized approaches will mainly originate from top-down initiatives by grid operators at both the bulk and distribution levels, aiming to manage DERs and ensure system stability. However, these trends will foster bottom-up change, with consumers increasingly taking charge of their energy needs and focusing on cost, sustainability, and efficiency.

Schneider Electric's EcoStruxure Microgrid Advisor is a software platform that connects, monitors, and controls a facility's DERs to optimize performance. Using machine learning, it analyzes data from energy sources, EV charging stations, batteries, HVAC systems, and lighting systems to forecast and optimize energy consumption, production, and storage.[23]

The IEEE Standard 1547 has simplified the integration of DERs like solar panels and batteries by setting uniform requirements for performance and safety. The 2018 and 2020 revisions have reduced costs and effort for utilities and developers, making it easier to incorporate renewable energy while maintaining grid stability and reliability.[24]

AI helps optimize the siting and sizing of solar and wind projects, maximize output, and improve supply and demand predictions. For example, while weather models predict wind power, deviations in wind flow can cause unexpected output. To address this, Google and DeepMind developed a neural network that uses historical data to predict renewable energy output up to 36 hours in advance with greater accuracy.[25] In 2023, Google also implemented demand

Table 1. Using AI to Combat Climate Change

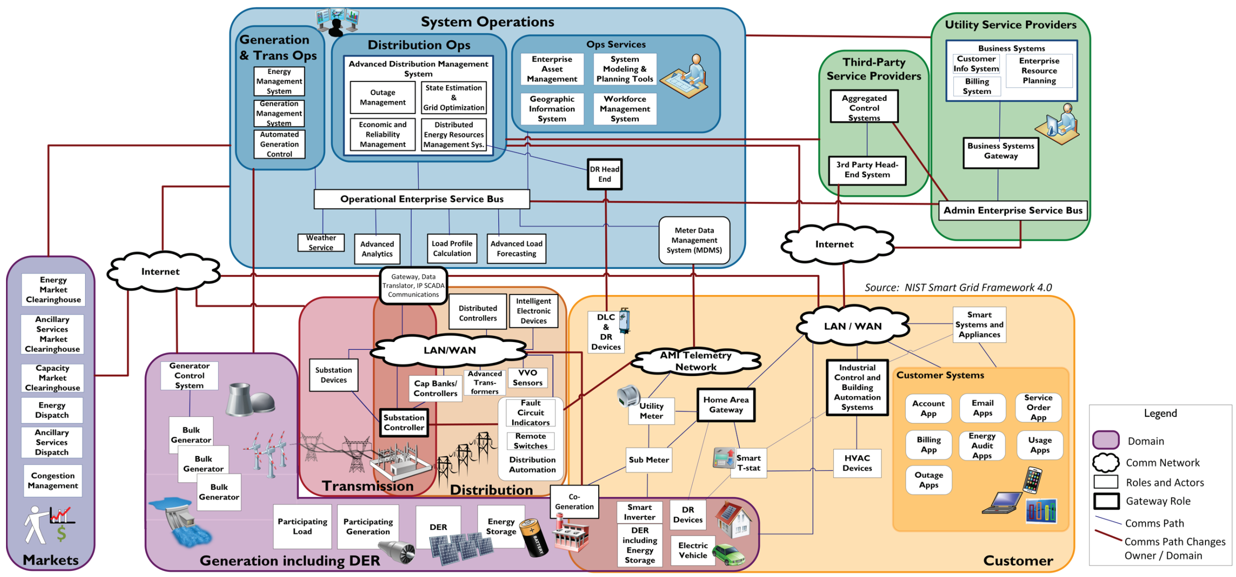
Topics	Mitigation			Adaptation and Resilience		Fundamentals
	Measurement	Reduction	Removal	Hazard Forecasting	Vulnerability and Exposure Management	
Subtopics and Examples	• Macro-level measurement (e.g., estimating remote carbon stock) • Micro-level measurement (e.g., calculating the carbon footprint of individual products)	• Reduction of the intensity of greenhouse gas emissions (e.g., supply forecasting for solar energy) • Improvement of energy efficiency (e.g., encouraging behavioral change) • Reduction of greenhouse gas effects (e.g., accelerating aerosol and chemistry research)	• Environmental removal (e.g., monitoring encroachment on forests and other natural reserves) • Technological removal (e.g., assessing carbon-capture storage sites)	• Projections of localized long-term trends (e.g., regionalized modeling of sea-level rise or extreme events such as wildfires and floods) • Early-warning systems (e.g., predicting extreme events such as cyclones)	• Crisis management (e.g., monitoring epidemics) • Stronger infrastructure (e.g., implementing intelligent irrigation) • Population protection (e.g., predicting large-scale migration patterns) • Preservation of biodiversity (e.g., identifying and counting species)	• Climate research models (e.g., modeling economic and social transition) • Climate finance (e.g., forecasting carbon prices) • Education, nudging, and behavioral change (e.g., providing recommendations for climate-friendly consumption)
Uses for AI	Gather, complete, and process data • Satellite and Internet of Things data • Gaps in temporally and spatially sparse data	Strengthen planning and decision-making • Policy and climate-risk analytics • Modeling of higher-order effects • Bionic management		Optimize processes • Supply-chain optimization • Simulation environments	Support collaborative ecosystems • Vertical data sharing • Enhanced communication tools	Encourage climate-positive behaviors • Climate-weighted suggestions • Climate-friendly optimization functions

Source: Digital Climate Alliance, *Promise and Peril: Sustainability & the Rise of Artificial Intelligence*, June 2024, https://www.digitalclimate.io/2024-ai-white-paper.

response in its data centers, shifting nonurgent tasks to times of lower grid congestion.[26]

Formerly OhmConnect, Renew Home enables residential customers to actively participate in energy conservation and grid management as a virtual power plant. It connects to smart home devices, such as thermostats and smart plugs, and notifies users during peak demand, encouraging reduced energy use. Using real-time data and predictive analytics, Renew Home forecasts peak grid demand and coordinates energy

Figure 4. High-DER Communication Pathways



Source: Avi Gopstein et al., *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0*, US Department of Commerce, National Institute of Standards and Technology, February 18, 2021, https://doi.org/10.6028/NIST.SP.1108r4.

reduction across its network, rewarding participants with financial incentives or bill credits. This helps balance the grid, prevents outages, and increases consumer engagement in energy conservation, making it a key tool in grid digitalization.

Grid Architecture and Why It Matters

Fully leveraging new technologies requires rethinking grid design, connection, and operation, which is where *grid architecture* plays a key role. Grid architecture combines system architecture, network theory, and control theory to manage complex grid interactions and drive modernization.[27] A well-designed architecture ensures stability, reliability, and the seamless integration of new technologies by addressing costs and challenges in the planning phase.[28]

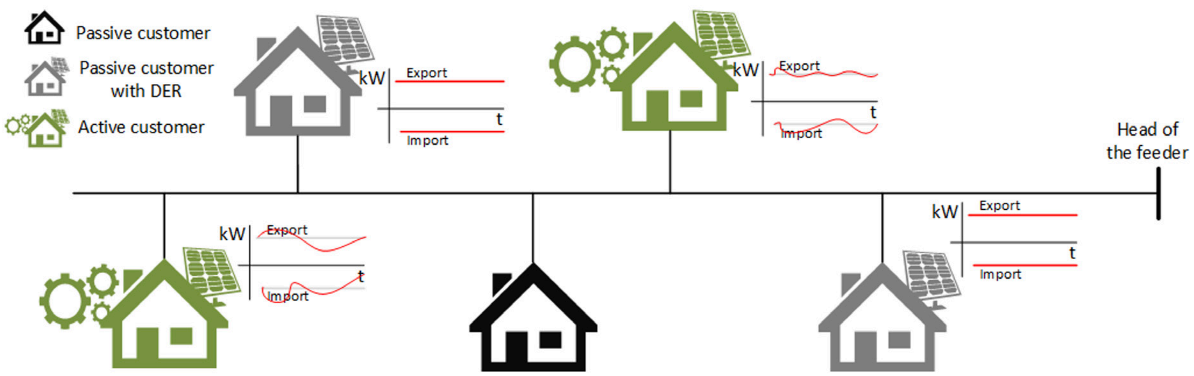
Key systems theory concepts—layered systems, loose coupling, and interoperability—are essential for grid architecture. *Layered systems* organize the grid by function for easier management, *loose coupling* allows components to operate independently, and *interoperability* ensures different technologies work together, even if from different manufacturers. These principles make the grid more adaptable, resilient, and efficient.

The National Institute of Standards and Technology's smart-grid framework is a key reference for digital grid architecture, offering a high-level analysis of digitalization and grid modernization through a layered system-of-systems approach to grid communications.[29] This report presents a set of graphical scenarios representing the layered system-of-systems approach to the communications networks in a digitalized grid. Figure 4 shows the graphic scenario for a system with a large share of DER.

Modern grids are complex, with decentralized data and evolving demands. Proper grid architecture streamlines investment, future proofs technology, and reduces DER integration costs. By minimizing costly integration issues and stranded investments, it enhances economic efficiency in grid modernization.

Grid architecture also boosts resilience by creating agile, modular systems that limit failure spread and enable rapid reconfiguration during events like wildfires. For example, in Humboldt County, California, Pacific Gas and Electric Company and local

Figure 5. Dynamic Operating Envelope Concept



Source: University of Melbourne, *Project EDGE: Fairness in Dynamic Operating Envelope Objective Functions*, April 2023, https://aemo.com.au/-/media/files/initiatives/der/2023/the-fairness-in-dynamic-operating-envelope-objectives-report.pdf.

governments developed nested microgrids, allowing segments to "island" during disruptions. This modularity at the transmission, distribution, and customer levels enables key facilities to maintain power independently, showcasing the benefits of decentralization and digitalization.

Digitalization supports DER coordination through approaches ranging from direct utility control to decentralized autonomy. For example, Australia's dynamic operating envelopes on distribution networks set flexible, real-time limits on DER exports and imports according to grid conditions. They optimize infrastructure use and maintain stability by mitigating issues like voltage fluctuations and overloads, allowing the grid to accommodate more renewable energy without major upgrades. This approach to DER coordination relies more on centralized control and curtailment than the Humboldt County nested microgrids. Figure 5 illustrates the concept.

In the US, the Department of Energy and some utilities are developing flexible practices for DER and EV interconnections. California has implemented a Limited Generation Profile architecture, enabling autonomous, decentralized customer operation through dynamic operating envelopes. Southern California Edison is piloting this approach in an EV project.

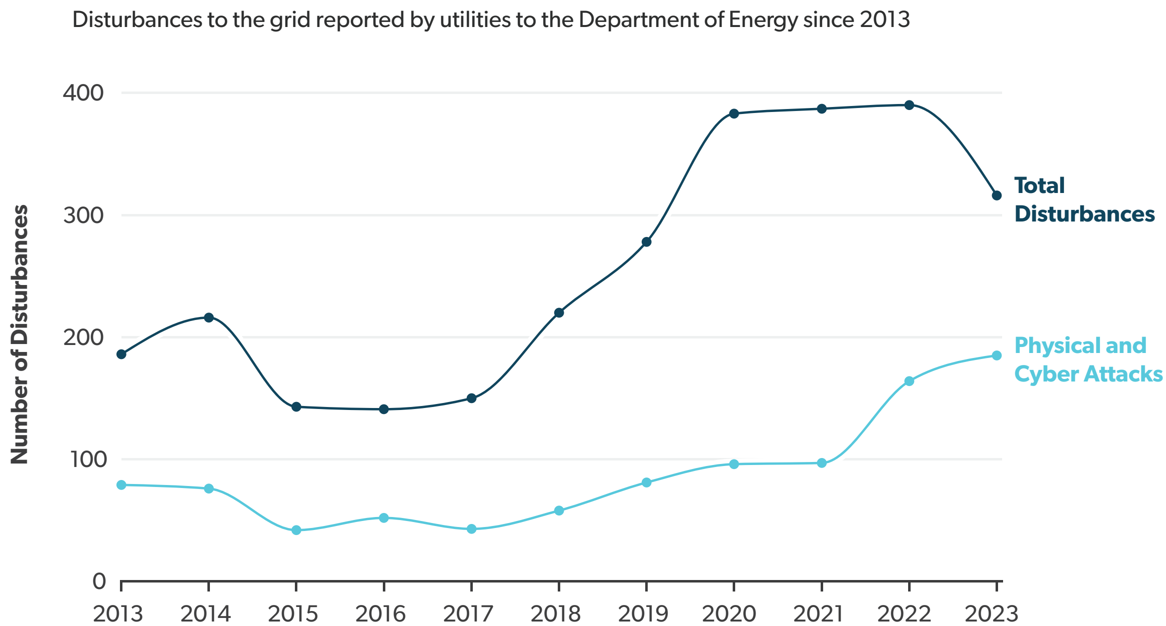
By defining and organizing the grid's structure, grid architecture ensures dependability, affordability, and decarbonization. Applying system architecture principles provides the tools to navigate modernization challenges and build future-proof power systems.

Data Access

Data access is a critical issue in power system digitalization. As digital technologies become more integrated into the grid, large amounts of data are generated from smart meters, DERs, and other intelligent devices. These data could improve grid management, enable innovative energy services, and empower consumers with more control over their energy usage and more flexibility in their consumption and production. However, access to these data is often tightly controlled by incumbent regulated utilities, which can limit the ability of customers and third-party service providers to employ these data effectively.

Incumbent utilities, motivated by regulatory, competitive, and operational concerns, may restrict access to data to maintain their market position or comply with outdated regulatory frameworks that do not fully account for the benefits of open data. These restrictions can stifle innovation, limit consumer choice, and slow down the transition to a more decentralized and customer-centric energy system. Addressing these data-access issues is essential for unlocking the full potential of digitalization in the electricity sector, ensuring that customers and third parties can

Figure 6. Electric Grid Disturbances



Source: US Department of Energy.
Note: Physical attacks include reports of vandalism, suspicious activity, cyber events, theft, and actual physical attacks.

leverage data to enhance efficiency, sustainability, and grid resilience.

Challenges and Risks

The digital revolution also contains significant risks, with cybersecurity being the most critical. The electricity grid is especially vulnerable for two reasons.

First, the grid has evolved with minimal coordination among stakeholders, increasing its susceptibility to cyberattacks. Historically, utilities used legacy systems relying on isolation and security perimeters to protect assets.[30] But this strategy has become less effective as the grid has grown more complex. Today's grid mixes residual legacy architecture with modern internet-based tools like sensors and smart meters, operated by various stakeholders with little coordination. The North American Electric Reliability Corporation (NERC) estimates that the number of attack points grows by 60 daily, rising from 22,000 in 2022 to 24,000 in early 2024.[31]

Second, the grid's crucial role makes it a prime target for hackers. The 2021 ransomware attack on Colonial Pipeline's billing infrastructure highlighted the risks, causing significant disruptions and fuel shortages. Two years earlier, a successful attack on an electric utility briefly knocked out firewalls without disrupting power.[32] The ripple effects of a successful attack make the grid a valuable target for state-sponsored cyberattacks, political hacktivists, organized crime, and cybercriminals seeking ransom.[33] Figure 6 indicates the increase in physical and cyberattacks despite an overall decrease in disturbances.

In recent years, the government has taken steps to improve cybersecurity in the electricity industry. NERC has developed Critical Infrastructure Protection standards focusing on significant threats to the bulk power system. Some states have additional requirements. NERC also oversees the Electricity Information Sharing and Analysis Center's biannual GridEx simulations for cyberattack response practice.[34] The Department of Energy is implementing a national cybersecurity strategy, though Government Accountability Office reports highlight deficiencies, especially in distribution systems.[35]

As digitalization increases grid complexity, the cybersecurity threat will grow. Stakeholders must make cybersecurity an important component of their overall business strategy, incorporating security by design, regularly testing systems, and innovating with cybersecurity in mind. Investment in preventive measures and response planning is essential. Stakeholders should create ways to share key practices and insights in the cyberattack space. As in other industries, players in the electricity industry must train their workforces to be vigilant to the cybersecurity threat and up-to-date on common attack vectors.[36]

The Future Grid Is Digital

The future grid will be digital, enabling more efficient, resilient, and adaptable energy systems. As we integrate DERs, advanced technologies, and AI, the tools of grid architecture will help manage complexity while ensuring stability. Digital tools will also enhance consumer participation, allowing individuals to optimize energy use, provide grid services, and engage in energy markets without inconvenience or discomfort. This shift fosters greater market flexibility and consumer empowerment. By embracing these innovations, we can build a grid that supports cleaner energy, economic efficiency, and active consumer involvement while achieving decarbonization and resilience goals.

Decentralization

Decentralization involves shifting decision-making and resources from a central authority to smaller, autonomous units. In power systems, this shift means moving on a continuum from centrally planned and operated electricity systems to a more dispersed model in which informed consumers play a larger role and investment and control are shared among many stakeholders. It harnesses technological innovation through changes to grid architecture, regulatory institutions, and the set of possible industry business models.

A useful analogy is the evolution since the 1960s from mainframe computers to mini computers to personal computers. Mainframes centralized computational power, while personal computers democratized access, allowing individuals to perform complex tasks independently; mini computers were a transition between the two. Digitalization and standardization, like the USB interface, further supported decentralization by enabling seamless connectivity without centralized control.

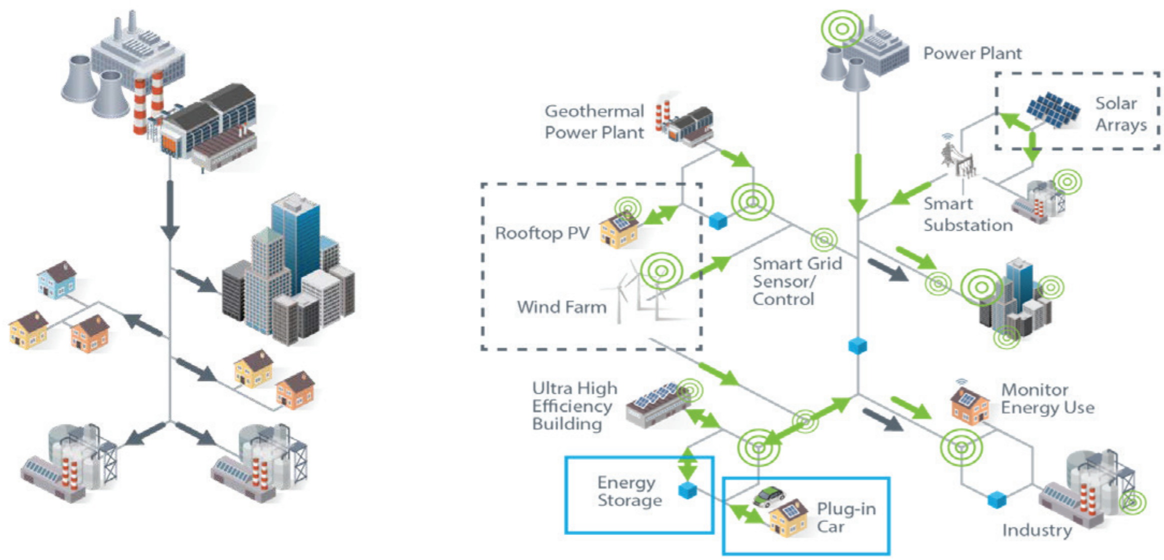
In a decentralized power system, the grid and the utility remain important, but the influence of large, centralized production decreases as smaller, distributed units, such as municipalities, commercial consumers, communities, and individuals, have and use DERs. Just as computing evolved from centralized systems to personal control, power systems are moving toward greater grid-edge autonomy. Figure 7 represents the shift from a one-way grid to a "grid of things."

The electricity industry began with Thomas Edison's small-scale, vertically integrated systems, but innovation quickly led to large-scale generation located away from population centers, connected by networks of wires. As systems interconnected, investor-owned electric companies merged, forming vertically integrated utilities that managed generation, transmission, and distribution. Centralized generation became the norm, supported by economies of scale and scope under government-regulated monopolies, especially after the Federal Power Act of 1935.

While early technologies favored centralization, recent advancements in rooftop solar, energy storage, and EVs have shifted the balance. Households and businesses can now generate and store their own electricity, reducing dependence on centralized plants. These technologies enhance energy security, reduce transmission losses, and increase grid resilience. Factors driving this shift include research, venture-backed commercialization, government subsidies, and geopolitical influences. Although centralized systems still benefit from economies of scale, decentralized systems offer flexibility, localized production, and greater consumer empowerment.

DERs also benefit from economies of scale via modularity. Traditional power plants take years to build and require large financial investments. DERs,

Figure 7. The Existing One-Way Grid Architecture and the Digital, Decentralized Grid Architecture



Source: National Renewable Energy Laboratory, *Autonomous Energy Systems: Building Reliable, Resilient, and Secure Electrified Communities*, June 2024, https://www.nrel.gov/docs/fy24osti/87629.pdf.

on the other hand, are modular and scalable by, for example, installing a single rooftop solar system today and expanding it tomorrow by adding a battery storage unit or connecting an EV charger. This modularity makes it much easier to scale up clean-energy generation incrementally, rather than depending on large, risky projects.

As consumers adopt electric appliances that blur the line between demand and supply, the one-way flow of energy and information is becoming obsolete. A decentralized ecosystem, leveraging internet-enabled devices and flexible services like behind-the-meter generation, energy storage, and smart EV charging, is becoming essential. With millions of distributed resources and billions of smart devices, decentralization is not just advantageous—it's a practical necessity.

Why Is Decentralization Valuable?

Power system decentralization offers numerous benefits, including lower costs, increased resilience, efficient integration of low-cost variable generation, local empowerment, economic development, technological innovation, and reduced carbon emissions.[37] Unlike centralized systems reliant on a few large power plants, decentralized systems engage grid-edge resources through smaller, flexible technologies that can be deployed autonomously. This approach enhances productivity, reliability, resilience, and adaptability, eventually lowering costs for all consumers, whether or not they participate in DERs or flexible pricing. As these technologies mature, their costs will decrease, and their capabilities will improve.

Decentralized systems are also more dependable, distributing power generation and storage to the grid edges and reducing vulnerability to single-point failures. They offer a cost-effective alternative to hardening centralized infrastructure against threats like storms, wildfires, and large-scale failures.[38] By distributing power generation and storage, decentralized systems strengthen resilience against disruptions and transmission grid vulnerabilities, both as independent systems (microgrids) and when integrated into utility distribution systems.

A Decentralization Continuum

Enhanced digital metering technology and advanced grid-forming inverters, combined with a culture of innovation, enable new business models like virtual power plants (VPPs), microgrids, and transactive energy. Advances in technology and business models are enabling a more balanced partnership between grid operators and consumers at the grid's edge, offering greater diversity and choice in value creation. This partnership can (1) increase the productivity of low-cost, variable resources by better matching demand with supply; (2) reduce the need for long-term investments in centralized networks and backup generation that may be needed only occasionally; and (3) support the development of local microgrids, reducing vulnerability to single-point failures during extreme events.[39] Aggregating DERs can improve the grid's operating efficiency by contributing to increasing capacity utilization. Instead of building large new assets like peak power plants that sit idle for much of the year, leveraging customer assets (such as smart thermostats and batteries) can reduce peak demand and improve the efficiency of large grid assets.

Even in a decentralized system, energy movement across regions remains essential for flexibility and adaptability. Regional transmission and distribution operators play a crucial role in balancing the variable energy resources available at different times and locations. But as resources become more valuable, a decentralized grid shifts the focus from varying supply to meet demand to varying demand to match supply, incentivizing consumers to adjust usage.

VPPs

A VPP is a network of decentralized DERs, including solar panels, batteries, and flexible end uses such as EV charging, aggregated and managed through advanced software to function collectively as a single dispatchable power plant, optimizing energy production, storage, and consumption.[40] VPPs still rely on centralized control. They require that the evolving variety of grid-edge opportunities be screened and bundled into packages that can be treated as peak-shaving resources in the traditional generation-focused utility operations paradigm.

VPPs are an important step toward decentralization, and activity is ramping up rapidly in the US and abroad. Figure 8 shows a general VPP model.

VPPs can provide services at the wholesale and distribution levels. For distribution utilities, VPPs can be designed to provide system peak shaving or can be deployed for locational dispatch at the feeder level to provide relief exactly when and where the grid needs it. For wholesale markets, VPPs can provide capacity or ancillary services.

Success depends on establishing the right regulatory frameworks. Many state utility commissions are creating the market development frameworks to successfully deploy VPPs to provide distribution-level benefits while enabling VPPs to integrate into wholesale markets. Similarly, the Federal Energy Regulatory Commission's (FERC) Order 2222 requires grid operators to allow DER aggregations to participate in wholesale energy markets, similar to VPPs. Order 2222 allows an aggregation that is sufficiently sized to have access to regional energy markets.[41]

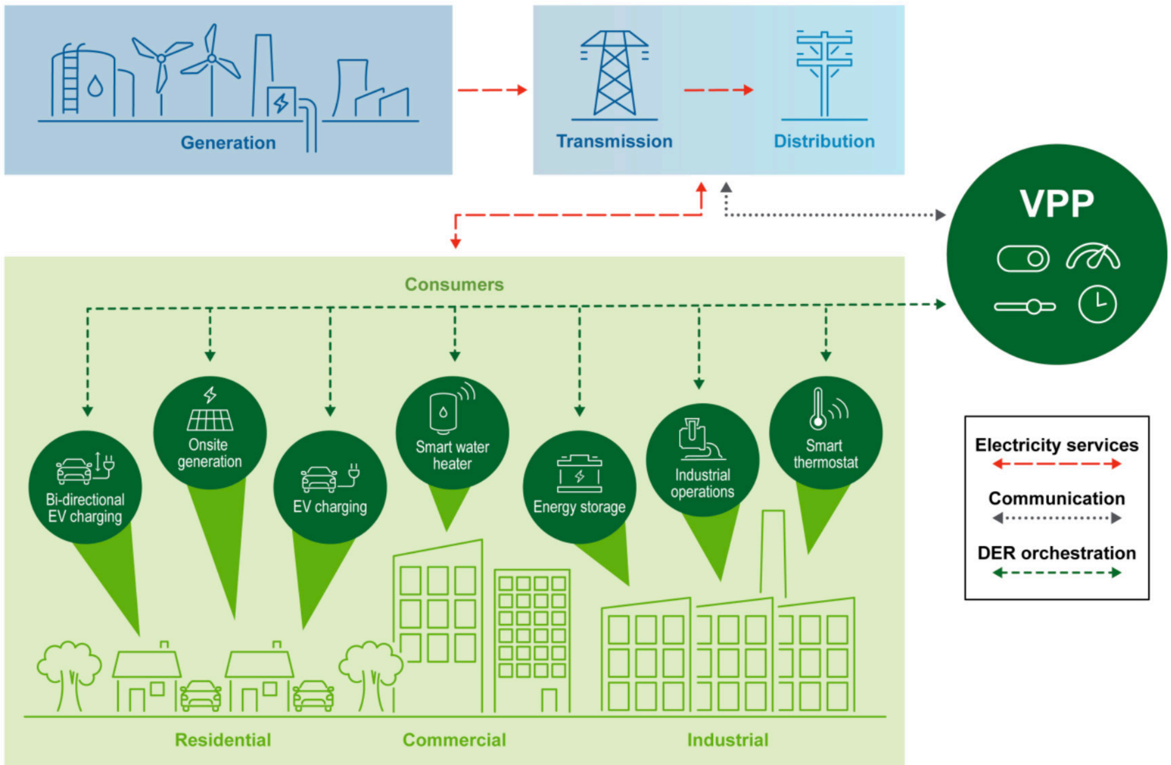
Microgrids

Microgrids are a group of interconnected loads and DERs that act as a single controllable entity with respect to the grid and that can disconnect from the grid if necessary to provide continuity of local service.[42] They are another example of decentralization. Enabling microgrids allows for decentralized control of individual resources, optimized energy consumption, energy sharing and peer-to-peer exchange, and coordinating grid and ancillary services with the grid operator to strengthen the bulk power system. Microgrids need not be restricted to specific buildings or locations but can be developed at larger sizes according to economic feasibility and needs. In terms of business models, microgrids can operate independently from a utility, or a utility can integrate microgrids into its distribution grid architecture.

Transactive Energy

A more decentralized approach to power systems at the distribution level is transactive energy. Transactive energy refers to a decentralized electric grid architecture that uses digital technologies to

Figure 8. Virtual Power Plants

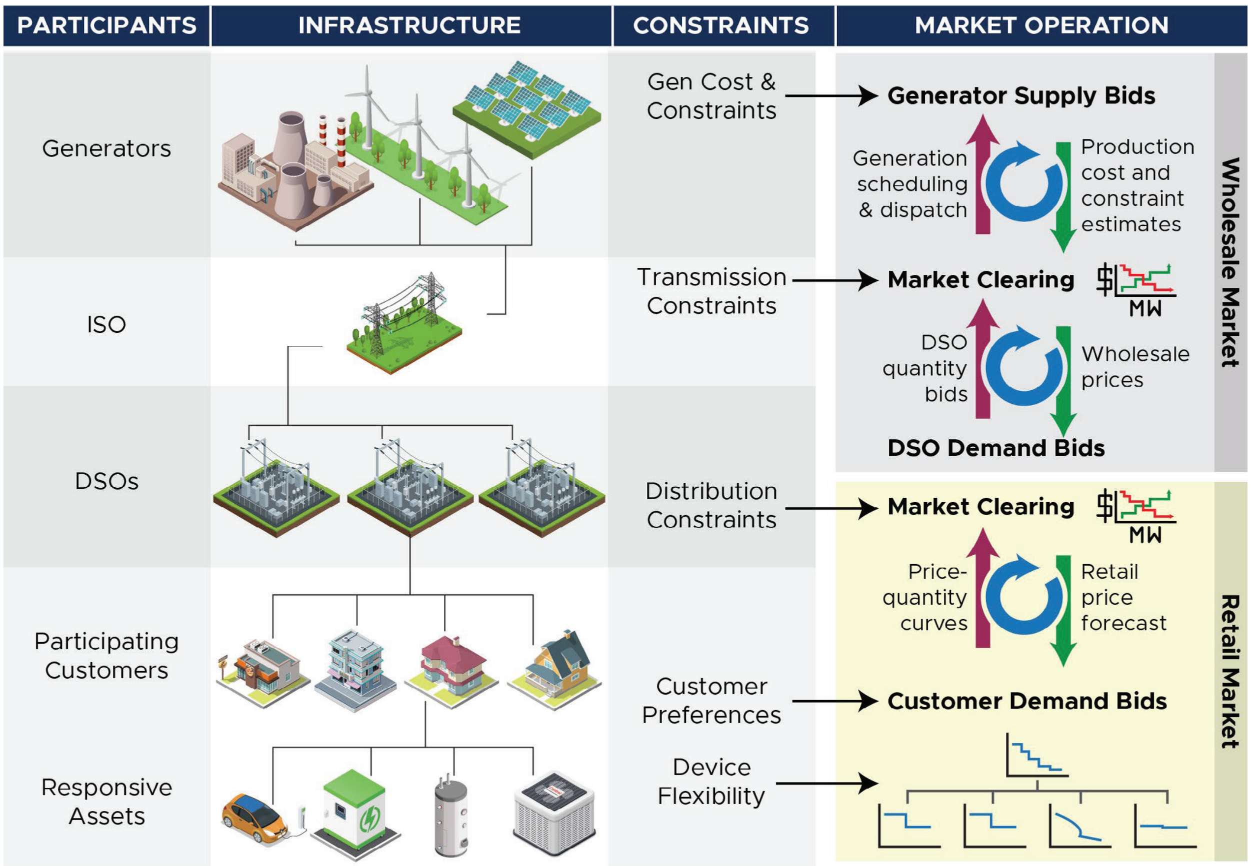


Source: US Department of Energy, "Virtual Power Plants Projects," https://www.energy.gov/lpo/virtual-power-plants-projects.

manage and optimize electricity generation, distribution, and consumption through dynamic pricing and automated transactions. Through the process of price discovery and using prices as device control signals, transactive energy harnesses individual preferences to create a more flexible and adaptable system. This approach is designed to enhance the grid's efficiency, reliability, and flexibility by enabling direct, real-time interactions among various energy resources and consumers.[43]

An important analysis of the potential value of transactive energy is the Pacific Northwest National Laboratory's Distribution System Operator with Transactive (DSO+T) study.[44] This study explores how a transactive energy system can coordinate DERs like HVAC systems, EVs, water heaters, and batteries to provide demand flexibility and improve grid reliability. The study simulated the use of transactive energy in a hypothetical grid system modeled on the Electric Reliability Council of Texas region, finding that such a system could reduce peak load by 9–15 percent and daily load variation by 20–44 percent. This coordination not only lowers electricity prices by optimizing energy use during low-price periods but also defers expensive infrastructure investments, resulting in annual customer benefits of $3.3–$5.0 billion for Texas and a potential national benefit of $33–$50 billion. The study highlights the scalability and economic feasibility of integrating flexible customer assets into grid operations, providing stability in a high-renewables future while reducing the need for additional generation capacity. Figure 9 summarizes the transactive energy framework used in the DSO+T study.

Figure 9. Summary of Market Participants, Constraints, and Market Operation



Source: Hayden M. Reeve et al., *Distribution System Operator with Transactive (DSO+T) Study: Main Report*, Pacific Northwest National Laboratory, January 2022, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32170-1.pdf.

Examples of Decentralization in Action

While VPPs are growing and serve an estimated 30–60 gigawatts of peak demand, examples of advanced decentralization have not yet realized their full economic potential.[45]

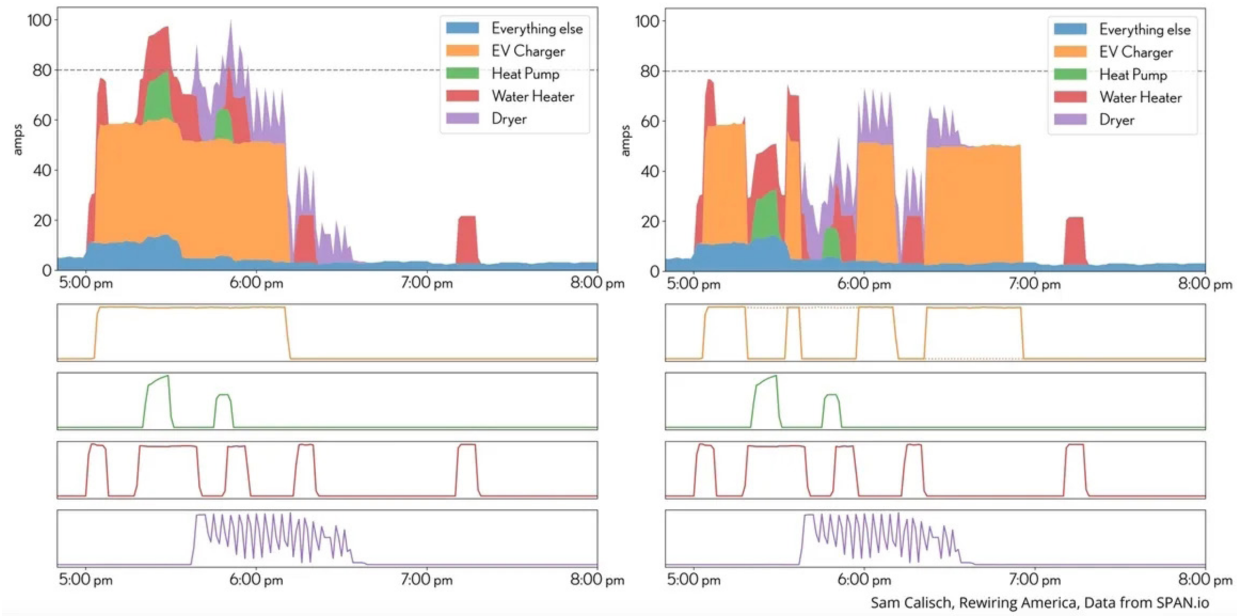
Technologies, System Integration, and Regulatory Innovation

The National Renewable Energy Laboratory's autonomous energy systems project has developed a framework for a decentralized, "self-driving" electricity system, with promising results from various pilot projects.[46] Notable efforts include those by Holy Cross Energy in Colorado, Southern Company, and DTE Energy. The National Renewable Energy Laboratory's work builds on the Pacific Northwest National Laboratory's DSO+T analysis, which quantified some of the benefits of decentralized grid operations driven by a transactive tariff architecture.[47]

Technology companies, service providers, and standards organizations are driving the transition to a decentralized electric system. Companies like SPAN are advancing smart electrical panels that optimize electricity delivery for building energy services based on dynamic pricing. Fermata Energy has introduced bidirectional EV charging systems, turning EVs into customer-centric energy exchanges with the grid that can provide grid services (Figure 10).[48]

The value of these emerging approaches to demand flexibility, compared with more traditional "interruptible service" peak-shaving approaches, is the minimal consumer effort, local control, and convenient

Figure 10. EVs as Grid Resources



Source: Sam Calisch and Cora Wyent, *Circuit Breakers: Electrification Won't Break the Grid, It Will Make It Smarter.*, July 4, 2022, https://www.rewiringamerica.org/research/circuit-breakers/electrification-myths-circuit-breakers/electric-grid-smart-panel-technologies.

delivery of energy services. States are catching up to the opportunities offered by innovators and making it possible for consumers to save money commensurate with the value of the flexibility and responsiveness they can offer, directly or via a service provider. After years of successful pilot projects that saw little follow-through,[49] regulators in a growing number of states are now ramping up efforts to implement dynamic pricing options, including in some cases as the default opt-out tariff.[50] These options range from basic peak shaving like peak-time rebates to more interactive multi-period time-of-use and even real-time pricing tariffs, including price differentials that more clearly reflect temporal differences in the cost of electricity at the point of delivery.

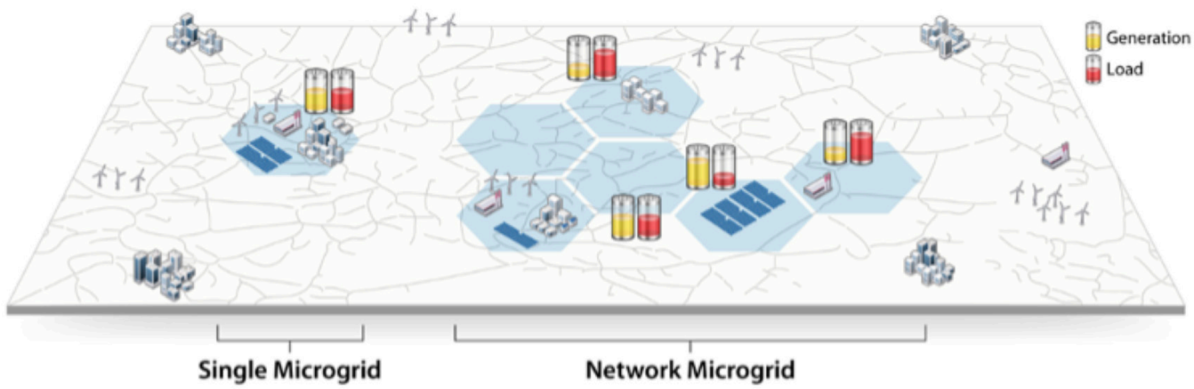
Energy retailer Octopus Energy has shown that customers will engage enthusiastically in managed electricity procurement for services like transport and heating if it is convenient, easy, and financially rewarding.[51] The California Public Utilities Commission staff has proposed California Flexible Unified Signal for Energy (CalFUSE), a comprehensive policy roadmap for a decentralized electric system.[52] CalFUSE incorporates transactive pricing architecture and a transitional tariff approach, allowing consumers to save money by making electricity purchases responsive to local grid conditions while maintaining reliable service.

Technical organizations are also developing necessary interoperability standards, such as the recently adopted SAE J3068/2_202401 standard for Control of Bidirectional Power for AC Conductive Charging.[53] These efforts collectively facilitate the shift toward a decentralized electric system.

VPPs

One example of a VPP is the ConnectedSolutions program in the northeast United States. The program provides cost savings for participants through financial incentives for using their stored battery energy during peak times and helps reduce peak demand, which also benefits nonparticipants. The

Figure 11. Microgrids in Action



Source: US Department of Energy, "Grid Systems," https://www.energy.gov/oe/grid-systems.

result is improved system capacity utilization and reduced need for expensive peak generation. ConnectedSolutions lowers greenhouse gas emissions, boosts resilience for participants by giving them an incentive to install a battery that can be used to provide backup power during outages, and fosters economic growth in the storage market. The program also has provisions for low-income and underserved communities.

ConnectedSolutions has reduced peak electricity demand and has proved to be cost-effective. It delivers $4.18 in benefits for every dollar spent on commercial and industrial participants and $2.14 for every dollar spent on residential participants. High levels of customer satisfaction have been reported due to financial and resilience benefits.[54]

Microgrids

Microgrids can optimize energy resources, provide grid services, and inject energy during peak demand periods. During outages, like those occurring after hurricanes, communities can disconnect from the grid, remain safe, and provide services for neighboring areas.

Microgrids created electric sanctuaries in Florida, Georgia, Virginia, and the Carolinas after Hurricane Ian made landfall in southwest Florida on September 28, 2022, packing winds as high as 155 miles per hour. The storm knocked out power to more than two million people, leveled homes, and sparked floods and water shortages. At least three residential communities equipped with solar microgrids met their residents' electrical needs during and after Hurricane Ian in 2022:

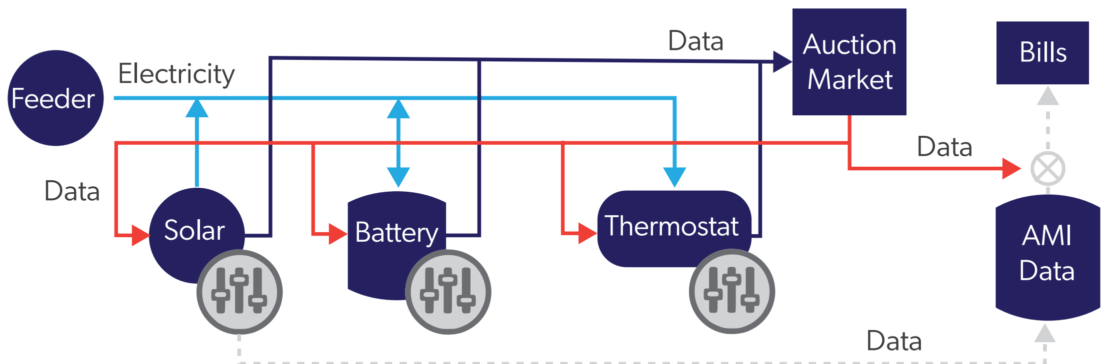
1. Medley at Southshore Bay in Wimauma, Florida, which uses an Emera Technologies BlockEnergy microgrid platform owned and operated by Tampa Electric

2. Hunters Point in Cortez, Florida, an LEED Platinum and net-zero community

3. Babcock Ranch in Punta Gorda, Florida, an 870-acre solar farm operated by Florida Power & Light Company that includes two 74.5 megawatt solar facilities

Recent events such as Winter Storm Uri and Hurricane Beryl in Texas, recovery efforts in Puerto Rico following Hurricane Maria, and wildfire-driven power shutoffs across the West have brought increased attention to distributed microgrids as a more effective, lower-cost, and more readily implementable alternative to investments in redundancy and hardening of large, centralized networks (Figure 11).

Figure 12. The Transactive Energy Services System



Source: SLAC National Accelerator Laboratory, Grid Integration Systems and Mobility, "TESS (Transactive Energy Services System)," https://gismo.slac.stanford.edu/research/tess-transactive-energy-services-system.

International Projects

Strategic developments and pilot projects are emerging globally. Elia, a Belgian grid operator, has embraced its vision for a decentralized electric system, described in its study *The Power of Flex: Enabling Consumers to Benefit from the Energy Transition*.[55] National Energy System Operator, an independent system operator in Great Britain, has adopted a similar vision of an increasingly decentralized system called Crowdflex and has demonstrated significant cost savings and sustained consumer participation.[56] In Germany, smaller pilot projects like SoLAR Allensbach are providing decentralized, self-organized energy management with lower costs and improved reliability.

The International Energy Agency's Global Observatory on Peer-to-Peer, Community Self-Consumption, and Transactive Energy Models is an interdisciplinary initiative that bridges research and industry. It collects data, analyzes case studies, and shares best practices to support the integration of DERs. The goal is to foster flexible, resilient, and consumer-driven energy systems worldwide by promoting new market structures and technological innovation.[57]

The Transactive Energy Services System

The Transactive Energy Services System (TESS) is an innovative platform developed by a team led by the Post Road Foundation.[58] TESS is designed to enhance grid efficiency and resilience by leveraging transactive energy principles, integrating advanced digital technologies to facilitate dynamic pricing and automated transactions across DERs and consumers. This platform coordinates energy use and distribution through real-time data exchange and decentralized value-based decision-making, promoting a more adaptive and efficient energy system. Figure 12 shows the data and energy flows in TESS.

The TESS platform is being deployed in a project with Efficiency Maine, funded by the US Department of Energy's Connected Communities program. This initiative aims to demonstrate how connected technologies and smart-grid solutions can enhance energy efficiency and reliability at the community level. By integrating TESS with local energy resources, the project seeks to create a scalable, replicable model for energy management. This collaboration highlights the potential of transactive energy systems to transform energy consumption patterns and support DER integration.

Challenges to Decentralization

Decentralization in the power system will evolve gradually, as many challenges are institutional rather than technological. Technological change presents a juxtaposition between large-scale centralized resources and smaller, more modular, distributed resources. While rate-regulated utilities have been the owners of large-scale resources, they need not be barriers to technological change and decentralization more generally. Utilities and regulators can accelerate the pace of change through, for example, rate reform, incorporation of DERs into planning, and better data-access standards.

A regulation-related challenge to realizing the benefits of decentralization is embedded in the century-long interpretation of monopoly utility franchises, which grant exclusive rights to operate distribution wires and in many cases to sell goods and services to customers, within specific areas.

Sharing power across property lines is complicated by legacy regulations and opposition from utilities invested in the status quo. In the 1980s, Tom Casten's company Trigen Energy faced legal challenges from Commonwealth Edison (ComEd) when building a combined heat and power system for McCormick Place in Chicago. ComEd challenged the project, asserting franchise rights that only the utility could operate wires across public rights of way.[59] This case exemplified the obstacles to decentralization in the late 20th century and shows how franchise rights can challenge what might otherwise be the best alternatives.

More recently, California's "over-the-fence rule" (Public Utility Code § 218) requires entities selling energy across more than two parcels to become regulated electrical corporations. In 2022, Sunnova sought unsuccessfully to create neighborhood microgrids in California, allowing homeowners to share energy, but the fight over regulatory approval continues.[60]

To promote decentralization and microgrids, the over-the-fence rule must be reevaluated to enable community-based systems. Microgrid service providers should be allowed to build, own, and operate microgrids independently of utilities, ensuring costs aren't shifted to ratepayers. Microgrid service providers would coordinate with grid operators for safe islanding and reconnection, offering valuable solutions for industries like data centers that face rising energy demands.

Decentralization for Value Creation and Dependability

Enabling power systems to grow from the ground up (rather than the top down), including small building blocks that can be both aggregated and isolated, allows for a more dynamic, dependable, and cost-effective grid. Engaging consumers as participants and matching demand to supply, rather than the other way around, helps integrate large-scale renewables, shave peak demand, increase the productivity of invested capital, meet increasing energy demand, and keep costs lower for consumers.[61]

Consumers are already investing in digitally enabled energy technologies like solar, storage, EVs, smart thermostats, smart water heaters, and efficient HVAC systems. Failing to use these resources to meet demand and lower costs makes them stranded assets and results in ineffective system utilization. VPPs, microgrids, transactive energy, and other concepts can help meet future demand effectively, but these and other innovative technologies are stymied by our current centralized paradigm and the way that existing regulations are implemented. Taking advantage of the significant benefits of digitally enabled decentralization requires reimagining our power systems and their regulatory and business models.

Democratization

Democratization refers to the distribution of power, resources, and opportunities to a broader segment of society. In power systems, it involves promoting participation, equality, transparency, and accountability; expanding individual freedoms; and increasing collective decision-making in matters that affect communities, states, and regions. It takes advantage of the technological and architectural aspects of decentralization.

Democratization dates back to ancient Athens, gained prominence after the Enlightenment, and is now a fundamental political principle. In power systems, democratization has two key aspects: enabling individual freedom and technology choices and facilitating inclusive collective decision-making.

For much of the past century, democratization in power systems was considered impractical due to the economies of scale and the grid's operational structure. Regulation "stood in for" competition, with regulators representing consumers, especially small residential customers. As a result, individuals had no direct role in making decisions or choosing representatives, leading to less autonomy compared with consumers in other markets, where decision-making was more direct.[62]

As we move deeper into the 21st century, the constraints (physical, economic, and technological) that made a highly centralized regulatory model preferable have largely dissolved. Innovations ranging from the combined-cycle gas turbine to pervasive digitalization have made competitive wholesale and retail markets possible, shrinking the economic footprint of the natural monopoly (even in states where the regulatory footprint remains vertically integrated). Digitalization and decentralization, discussed in the previous two sections, make democratization accessible and potentially valuable in ways that were not feasible in the 20th century.

Americans should have the power and autonomy to make choices in the energy that powers their homes and businesses. Such choices have many dimensions:

- From whom to buy energy
- The type of energy used
- The option to supply oneself and the right to sell one's excess production
- The ability to associate with others to take or provide energy services with the wider energy sector

These considerations entail a large number of important policy considerations in the retail and wholesale energy markets, regulated by state and federal agencies.

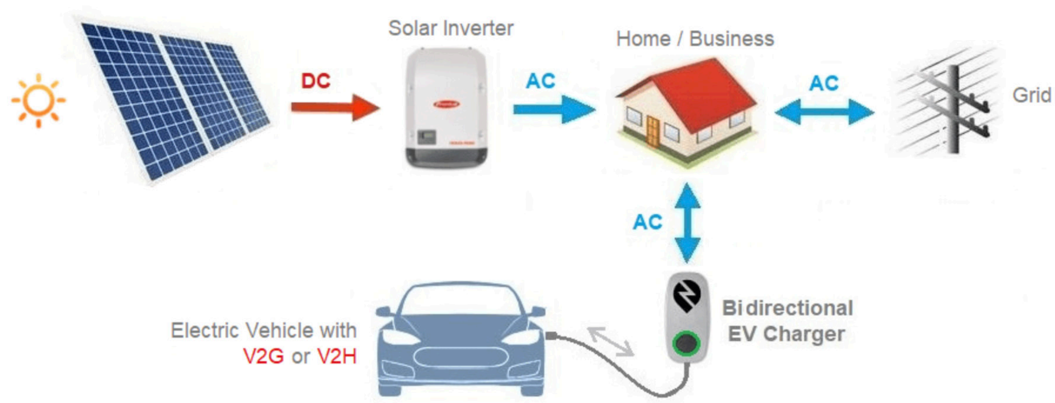
Investor-owned utilities in some states in the US are permitted to maintain vertical monopolies, subject to rate regulation, even as segments like generation have been recognized as competitive in other regions and other industries like telecommunications and transportation have been liberalized. While energy monopolies persist, technological advances should enable competition, and government-set rates should reflect actual costs of service. These rates should allow customers to avoid high costs by shifting usage and benefit from lower rates at different times. Without such price signals, customers remain captive to government decisions, with no control over their energy choices.

A Use Case of Democratizing Energy: EVs

Integrating EVs into the power grid presents a transformative opportunity to democratize energy for customers. As the adoption of EVs grows, their potential as a grid asset becomes increasingly significant. Leveraging EVs in this way can help save customers money, stabilize the grid, optimize energy use, and facilitate the transition to renewable energy sources. While EVs provide only one example of democratizing energy, here we explore how customers can use EVs as a grid-balancing asset, the technological and regulatory challenges involved, and the potential benefits for all end-use customers, not only EV owners.

One key benefit of integrating EVs into the grid is their ability to provide grid services and enhance stability. The grid needs constant balance between supply and demand to avoid blackouts or infrastructure damage, and EVs can help achieve this balance through managed charging and bidirectional vehicle-to-grid (V2G) or vehicle-to-everything (V2X) capabilities.[63] Managed charging is the strategic coordination of EV charging to align with grid conditions, energy prices, and system reliability needs. This approach leverages digital technologies and communication platforms to adjust the timing, rate, and duration of EV charging dynamically based on factors such as electricity demand, renewable energy availability, and grid capacity. By optimizing charging schedules, managed charging can reduce strain on the grid during peak demand periods, enhance the integration of intermittent renewable energy, and lower costs for both utilities and EV owners.

Figure 13. Bidirectional EV Charging



Source: Jason Svarc, "Bidirectional EV Charging Explained—V2G, V2H & V2L," Clean Energy Reviews, October 10, 2024, https://www.cleanenergyreviews.info/blog/bidirectional-ev-charging-v2g-v2h-v2l.

One example of managed charging policy is the New York State Energy Research and Development Authority SmartCharge program. Through partnerships with utilities, SmartCharge integrates advanced data analytics and communication technologies to monitor and manage charging behavior.[64] Participants in the program benefit from lower electricity rates during off-peak hours, encouraging them to charge their vehicles when grid demand is low or when renewable energy generation is abundant. One notable success of the SmartCharge program has been its ability to significantly reduce peak load impacts, demonstrating the potential for widespread adoption of managed charging to mitigate stress on the grid as EV penetration grows.

V2X means that EVs can not only draw electricity from the grid to charge their batteries but also discharge stored energy back into the grid when needed. This bidirectional capability transforms EV owners from mere consumers of electricity to active participants and asset owners in the energy system.[65] Figure 13 illustrates the process of bidirectional EV charging and discharging.

Managed charging allows EVs to adjust charging according to grid conditions, reducing stress during peak times and optimizing schedules for low-demand periods or high renewable energy generation. Transactive charging goes further, letting EV owners sell demand flexibility and respond to real-time price signals, which turns EVs into valuable grid resources that support resilience and renewable integration and reduce the need for costly grid upgrades. Digitally enabled automation makes active participation convenient for EV owners.

Facilitating Renewable Energy Integration

Another advantage of using EVs as grid assets is their potential to facilitate renewable energy integration. Renewable sources like solar and wind are variable, creating challenges for grid operators who must maintain consistent electricity supply. EVs can help by acting as distributed energy storage. When renewable generation is high, EVs can store excess energy and discharge it back to the grid when generation drops.

Managed and transactive charging systems allow EVs to shift demand to times of abundant renewable energy, reducing the need for backup fossil fuel generation. As a result, the system is less reliant on expensive energy generation for peak periods, lowering system costs and emissions, increasing the productivity of scarce invested capital, and transforming EV owners from mere consumers to active participants in the energy system.

Economic and Environmental Benefits of EVs

Using EVs as grid assets has significant economic and environmental benefits.[66] Economically, EVs can provide additional revenue for owners through demand-response programs, VPPs, and transactive energy, helping offset ownership costs and accelerating EV adoption. Environmentally, EVs support greater use of renewable energy, reducing greenhouse gas emissions and the need for capital investments in traditional power infrastructure. By offering flexible, distributed storage, EVs contribute to decarbonizing both the grid and the transportation sector.

Technological and Regulatory Challenges

Despite the benefits, several technological and regulatory challenges must be addressed to fully realize EVs as grid assets.[67]

Technological Challenges to EVs for Grid Services

One key challenge is potential battery degradation from frequent charging and discharging, which can reduce EV battery lifespan and performance. Improvements in battery chemistry, thermal management, and software controls can help ensure EVs maintain longevity while supporting grid operations.

The successful deployment of V2X technology also depends on expanding smart charging infrastructure capable of bidirectional energy flow. This infrastructure requires significant investments and grid modernization, as the current system was not designed for bidirectional flow. Collaboration among utilities, regulators, and private industry is essential for this transition.

Interoperability is another challenge, as EV models, charging stations, and grid systems must work together seamlessly. Standardized protocols and communication systems are needed to ensure uniform integration, reduce costs, and encourage widespread adoption of V2X technology. Such standardization will ensure that all stakeholders, from EV manufacturers to utilities, can invest confidently in V2X technology.[68]

Regulatory Challenges

EVs as grid assets also face regulatory hurdles. Governments and regulatory bodies must create policies that reduce barriers to EV and V2X adoption. Clear grid interconnection standards are necessary to ensure seamless integration, and utility companies should be encouraged to launch V2X pilot programs for real-world testing.

State regulators and legislatures should allow EV owners to participate directly or through aggregators, as intended by FERC Order 2222. Fair access and compensation for services like energy storage and demand response will make EVs valuable participants in the energy transition.

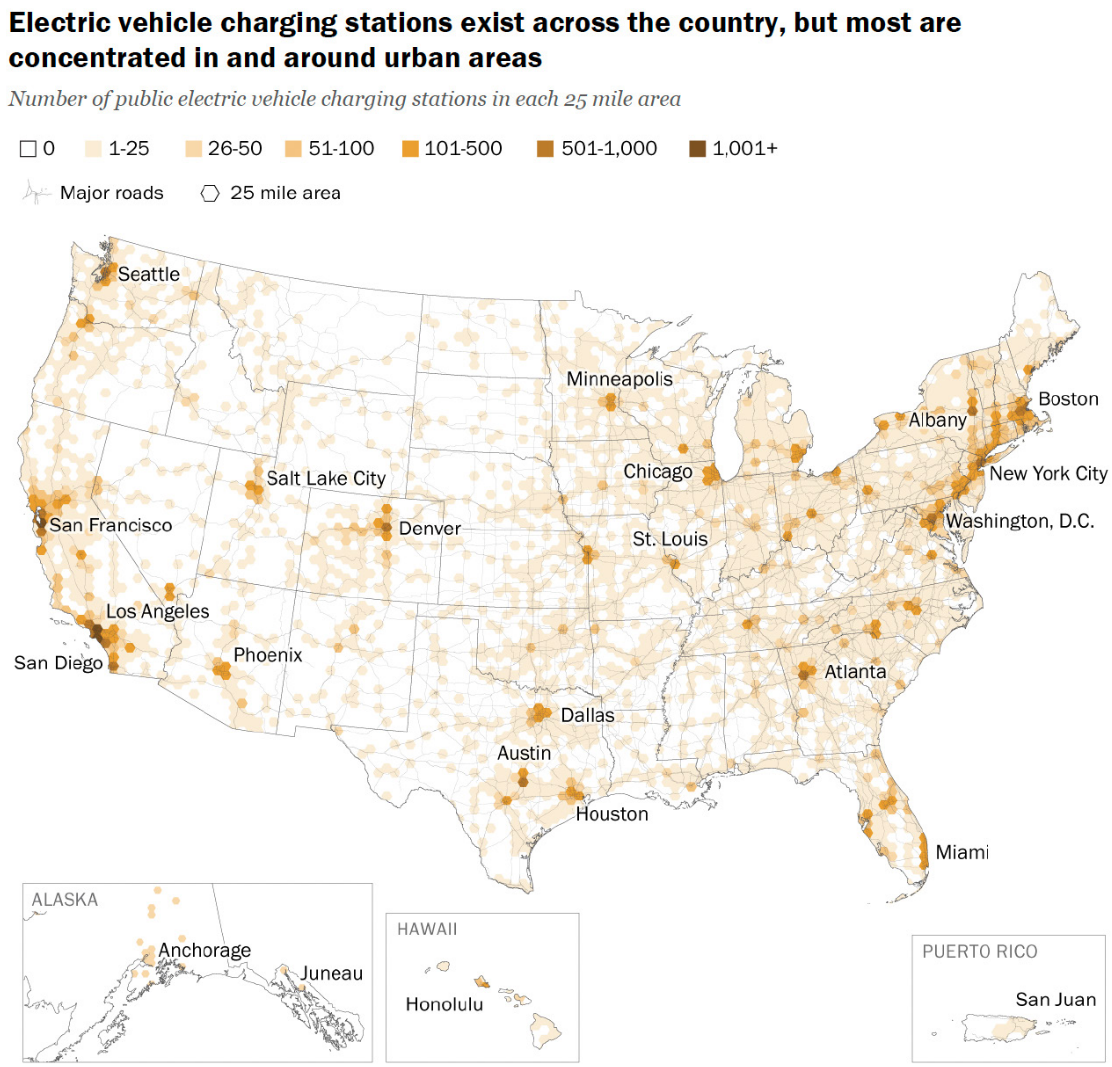
The bidirectional flow of energy and data with V2X raises concerns about data privacy and cybersecurity. Developing robust standards to protect user data and ensure grid security will be crucial. Collaboration among manufacturers, utilities, and regulators is needed to create secure frameworks that can scale with EV integration.

While not directly a regulatory challenge, the development of EV charging infrastructure faces a classic chicken-and-egg problem, as the growth of EV adoption and the expansion of charging networks are interdependent. Consumers are hesitant to purchase EVs due to concerns about the availability of charging stations, especially in less densely populated areas. At the same time, companies are reluctant to invest in building widespread charging infrastructure until there is a larger base of EV users to justify the investment. This situation creates a cycle that hinders EV adoption, as most existing chargers are concentrated in urban areas (Figure 14).

Future Outlook

As technological advancements and supportive policies emerge, EVs will play a key role in democratizing energy. Innovations like solid-state batteries will improve EV suitability for grid services, while smart grids and advanced energy management systems will enable seamless integration. On the policy front, state regulators are recognizing the potential of V2X technology and beginning to evaluate supportive measures.[69] Local distribution utilities in certain states,

Figure 14. EV Charging Stations in the US



Source: Pew Research Center, "Electric Vehicle Charging Stations Exist Across the Country, but Most Are Concentrated in and Around Urban Areas," May 21, 2024, https://www.pewresearch.org/data-labs/2024/05/23/electric-vehicle-charging-infrastructure-in-the-u-s/pl_2024-05-24_ev-chargers_0_02/.

including California, are also exploring pilot programs and regulatory frameworks to support the use of EVs as grid assets.

V2X can also enhance resilience as part of local microgrids, allowing consumers to maintain service during extreme weather and grid failures. Using EVs as grid assets presents a compelling opportunity to democratize energy by empowering consumers to enhance grid stability, optimize energy use, and support the transition to renewables. While technological and regulatory challenges remain, the potential economic and environmental benefits make it worthwhile. As EV adoption grows, V2X will play an increasingly important role, providing customers with more choices and tools to shape their energy usage while fostering innovation.

Moving Democratization Forward

The growth of digitalization and decentralization offers individuals greater self-determination in energy systems. These forces democratize energy by empowering customers to take control of a critical aspect of their daily lives.

Historically, regulated, centralized systems made sense due to the scale advantages of 20th-century technologies. However, today's advancements in digital and distributed energy technologies have reduced the efficient scope of monopolies, making democratization more feasible. The "natural monopoly" boundaries have receded and have expanded the scope for the autonomy that customers deserve.

Dependability

Dependability refers to the customer's experience with their electric service. Traditionally, grid planners and operators have focused on "reliability," framed in terms of operational security and resource adequacy. Operational security ensures that generation, transmission, and distribution systems function within safe limits in real time. Resource adequacy addresses being able to call on enough energy production to meet projected demand in every hour to an economically efficient standard over the long term.

However, the increasing frequency and severity of grid disruptions have shifted attention to "resilience," the grid's ability to withstand, avoid, and recover from disruptions like natural disasters and cyberattacks. Traditional reliability approaches have focused on supply-side infrastructure and centralized resource hardening, but advances in technology now call for consumer-driven solutions. While reliability considers normal operations, resilience and dependability also account for extreme events and "black swan" scenarios, affecting both transmission and distribution grids.

We have chosen the term "dependability" to reframe the issue from the consumer's perspective: ensuring continuous access to power when and where it's needed, focusing on service rather than infrastructure. Centralized power is no longer always the most reliable or affordable option. Increasingly, off-grid and grid-edge solutions—like distributed generation and batteries—offer consumers affordable and dependable power without continuous grid connectivity.

Building a resilient grid means not only maintaining reliability but also enabling the system to anticipate, withstand, and recover from disruptions. Enhancing interregional transmission allows surplus energy to flow to areas with shortages, minimizing service interruptions.[70] Distributed generation and battery storage add flexibility and resilience, ensuring access to power even during grid outages. In this environment, dependability comes from diverse power sources, greater interconnectivity, and adaptability to future challenges.

Dependability in Action

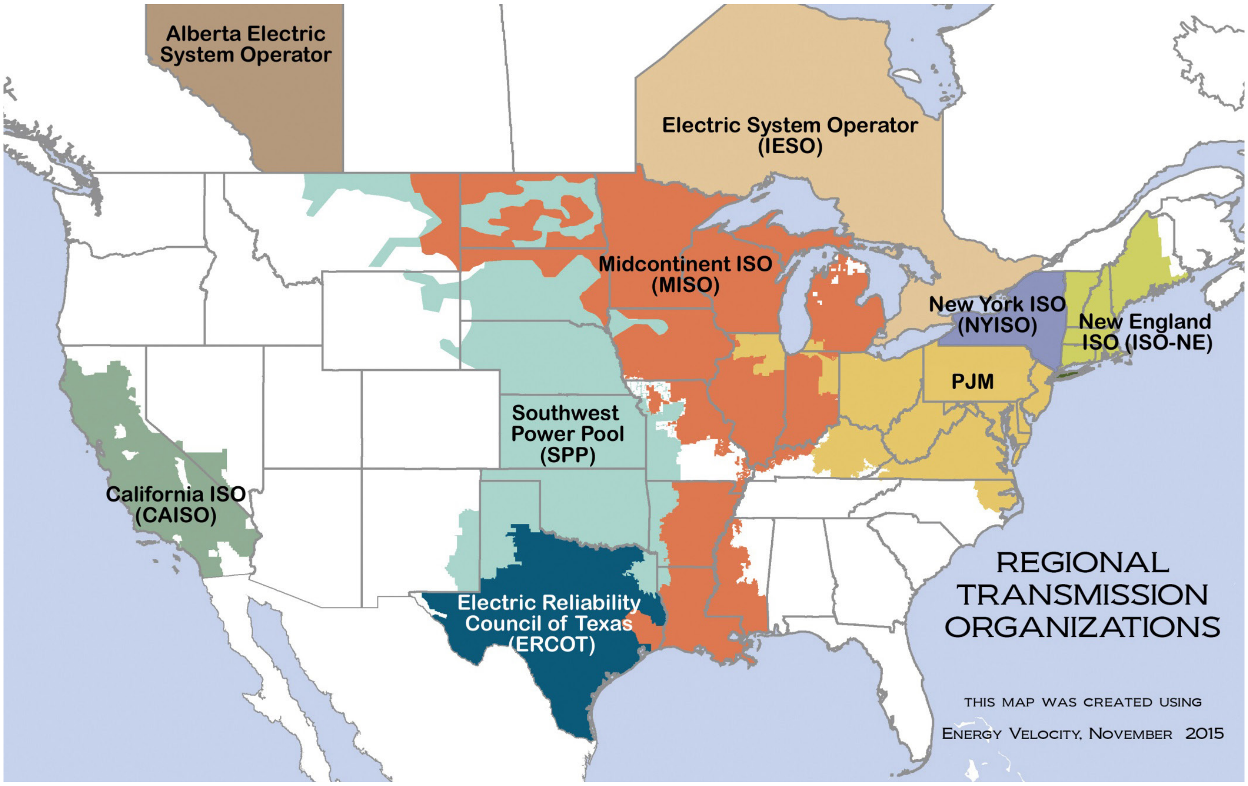
Improvements to electric grid operations range from the bulk power system to the grid edge, from incremental process enhancements to major changes in system architecture. To capture the diversity of actions targeted at improving dependability, consider these four examples.

Bulk Power System Planning and Operations

Traditional centralized approaches to resource adequacy have become outdated. PJM, the largest regional transmission organization (RTO) in the US, serving 65 million people, is shifting its resource adequacy analysis to an hourly basis, improving how electricity supply and demand are assessed. PJM is also updating resource accreditation to better evaluate performance during high-stress periods and refining its risk-assessment process to more accurately identify correlated risks. These changes, mirrored by other RTOs, aim to enhance the performance and reliability of bulk power resources. Figure 15 shows the locations of the nine North American RTOs.

This report is intended to address the benefits from migrating more resources, control, and decision-making to stakeholders at the edge of the power system. This is envisioned as a robust complement to the bulk power grid as part of a decarbonizing power system that is reliable, resilient, and just. The bulk power grid will continue to be a critical feature

Figure 15. Regional Transmission Organizations in North America



Source: Federal Energy Regulatory Commission, "Regional Transmission Organizations," November 2015, https://www.ferc.gov/sites/default/files/2020-05/elec-ovr-rto-map.pdf.

of such a system, facilitating the efficient and reliable movement of energy across and between regions, but it is not the subject of this report. The bulk power grid will remain a net source of tremendous benefits to electricity consumers, while the greater distribution and decentralization of resources and control described in this report will mitigate exposure to its inherent single-point failure risks.

Investment in innovation at the grid edge will need to be complemented by investment in a more capable, more integrated pan-regional and interregional high-voltage grid capable of optimizing the utilization of an increasingly capital-intensive resource mix. The modernized, innovation-friendly power system envisioned here can be thought of in terms of a barbell—with the focus of investment shifting from the last century's patchwork of highly centralized grids to one that invests communities and customers with greater agency while expanding and integrating the bulk power grid's capacity to function as an interregional backbone.

V2X Capabilities

EVs with bidirectional charging, such as Ford's F-150 Lightning and GM's upcoming models, offer a new form of household energy dependability.[72] By powering homes during outages, EVs act as mobile generators, providing an additional layer of reliability. While some view this as a novelty, it gives consumers greater control over their power needs. As V2X capabilities expand, EVs and other decentralized resources will support grid services, helping stabilize distribution systems and reduce stress on the transmission grid.

Microgrids and Decentralized Architecture

Microgrids are becoming essential for enhancing dependability. The US Department of Energy has declared a vision in which microgrids are "essential

PJM's Shift in Resource Adequacy Analysis

RTOs like PJM operate the transmission network and organized wholesale power markets and have the statutory responsibility for reliable service and planning for adequate resources to ensure future reliability.[71] PJM's recent changes in resource adequacy analysis provide a more accurate assessment of risks to grid reliability, shifting the focus from summer peak loads to winter risks driven by correlated outages. This shift aligns with recent industry observations of increased winter vulnerabilities. While PJM's new analyses will still use the standard "one day in 10 years" metric to set the reliability target, other fundamental changes have been made to provide a more complete picture of the changing risks to resource adequacy.

The first change is PJM's shift to an hourly analysis of supply and demand. Traditional resource adequacy focused on peak demand, but PJM now evaluates each hour of the year, helping identify new risks for load shedding, which can occur at any time because of correlated thermal plant failures or when net load (rather than gross load) exceeds available dispatchable capacity. This change demonstrates how RTOs are recognizing the value of distributed resource flexibility.

Second, PJM has improved resource accreditation using Marginal Effective Load Carrying Capability (ELCC) and a metric called expected unserved energy to evaluate resources. Traditional methods averaged performance over time, often missing critical periods. PJM's new system credits resources according to their ability to reduce the risk of power shortages during high-stress periods, providing better incentives for resources that perform well during emergencies.

Finally, PJM now models supply outages as correlated rather than independent. Events like the 2019 polar vortex and Winter Storm Elliott in 2022 have shown that extreme weather often causes simultaneous outages, particularly in winter. PJM's Marginal ELCC methodology accounts for this by correlating outages with temperature and other factors. This approach also captures interdependencies with the natural gas supply and delivery system and the performance of renewable resources, which can experience correlated reductions when concentrated in the same geographic area.

building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability."[73] The US Army is exploring microgrid implementation at every base to ensure continuous power for critical operations, independent of the main grid.[74]

In the commercial sector, the grocery chain H-E-B partnered with Enchanted Rock to install natural gas microgrids at over 100 stores in Texas.[75] This investment proved crucial during Hurricane Harvey and more recently Hurricane Beryl, allowing H-E-B to keep stores open and serve communities when much of the region lost power.[76]

Distribution System Planning

The dependability of electric service heavily relies on the distribution grid, the source of most outages. Nearly half of US states now require some form of distribution system planning, akin to bulk power system planning, to manage unpredictable load growth driven by population increases, new industries, and distributed energy integration. Distribution system planning provides essential data, like circuit-level hosting capacity analysis, to better plan and maintain grid dependability.

Dependability for the Future

New digital technologies, like grid-forming inverters and grid-enhancing technologies such as dynamic line rating, are improving grid dependability and flexibility in both transmission and distribution grids. Grid-forming inverters enable renewable sources like solar and wind to establish stable voltage and frequency even when isolated from the central grid. Dynamic line rating uses real-time data to adjust power line capacity according to conditions like temperature and wind. These innovations help the grid handle more power, respond to fluctuations, and reduce the risk of outages, enhancing dependability in a more digitalized, decentralized, and decarbonized system. They also enable new customer solutions to improve electric service dependability.

Dependability in power systems includes not only supply-side engineering but also customer strategies. It reflects varying consumer willingness to pay for reliable power when and where it's needed. These technologies support an open-access model, allowing customers to choose solutions that meet their needs while contributing to overall grid stability.

Current reliability standards are based on a single-point estimate of the value of lost load—the cost of an outage to consumers—but this single estimate does not capture differences in how various consumers value on-demand power for various loads at various times. For instance, a restaurant may value uninterrupted power more than a household, and the value each customer attributes can change depending on the nature of the different energy services they need, the time of day, or the season. A more decentralized, democratized power system will empower consumers to act on these highly varied preferences, and system planners should take advantage of the opportunity to reduce the investment needed to ensure dependability, to better reflect consumer diversity and changing needs.

Dependability does not always mean "always on." It aligns with the concept of differentiated reliability, in which consumers choose their level of service based on needs, the ability to store electricity thermally or in a battery for later use, and cost. This change in operations, service offerings, and mindsets could allow critical infrastructure to have uninterrupted power while offering more flexible options for other users that are mutually beneficial. Balancing such choices with energy justice will be crucial in evolving regulation. Dependability integrates supply-side reliability and resilience with consumer-driven solutions, giving consumers more options to benefit from choosing service providers, technologies, and participation in energy markets.

Decarbonization

Fossil fuels have played a key role in industrialization and improved living standards, but they contribute to pollution and greenhouse gas emissions. Fossil fuel combustion for heating, transportation, and electricity generation are among the largest sources of human-made greenhouse gases, contributing to climate change and threatening ecosystems and societies. Fossil fuel combustion also releases pollutants like particulate matter, nitrogen oxides, and sulfur dioxide, leading to respiratory and cardiovascular diseases.[77] The combustion of fossil fuels for electricity generation is a significant source of these pollutants.

Decarbonization refers to reducing carbon dioxide (CO_2) emissions from electricity generation and industrial activities. Decarbonizing electricity by shifting to cleaner energy sources can also reduce air pollution, leading to improved public health outcomes and lower health care costs.[78]

Decarbonizing the electricity system involves transitioning from fossil fuels like coal and natural gas to low- or zero-carbon sources such as wind, solar, hydro, geothermal, and nuclear power. Recent advancements in renewable technologies and digitalization have already spurred innovation-driven decarbonization. Evolving technologies like advanced geothermal and advanced nuclear and future technologies like carbon sequestration and direct air capture could reduce emissions further.

While decarbonization involves significant upfront estimated costs—such as infrastructure development, energy storage, and grid upgrades—the estimated benefits, including reduced health care costs and climate impacts, outweigh these expenses. For example, Yang Qiu et al.'s recent cost estimates for various scenarios found that an 80 percent reduction in CO_2 emissions from the US electricity sector by 2050 would cost $220–$490 billion (in 2020 USD). This estimate corresponds to an increase of 0.15 to 0.34 cents per kilowatt-hour of electricity. These costs are relatively low compared with the value of the potential benefits.[79]

Projections indicate that continued decarbonization efforts will yield significant climate and economic benefits. According to the Intergovernmental Panel on Climate Change's Representative Concentration Pathway 4.5 model, global temperatures are expected to rise by about 2.5–3°C by 2100 under business as usual. Reducing greenhouse gas emissions (mitigation) and hardening infrastructure (adaptation) could prevent the most severe impacts of climate change and preserve ecosystems and biodiversity. The New Climate Economy suggests that bold climate action could generate $26 trillion in global economic benefits by 2030, through cost savings from cleaner air, better public health, and enhanced energy efficiency.[80]

Countries and states are setting ambitious decarbonization goals. California aims for carbon neutrality by 2045, and New York and the UK target net zero by 2050.[81] Sweden has set an even more ambitious target of 2045 for net-zero emissions.[82] Achieving these goals involves trade-offs, including high upfront costs and potential economic disruptions, especially in fossil-fuel-dependent regions.

In this report, we focus on aligning decarbonization with innovation as a key driver for economic growth. Aligning decarbonization with economic growth requires leveraging markets, innovation, and entrepreneurship and reducing regulatory barriers to innovation. Entrepreneurs are key to developing new technologies and business models that reduce emissions while adding economic value. Venture capital, private equity, and green finance can accelerate the commercialization of these innovations. Market-driven initiatives like the Clean Energy Buyers Association demonstrate how collective purchasing power can drive renewable energy deployment, fostering innovation and economic growth.

Achieving emission targets while retaining the ability to be productive and promoting abundance and flourishing in other aspects of life will be a transition in which innovation creates winners and losers. A good example is the shale gas revolution, which accelerated the shift away from coal and dislocated many vulnerable communities. Addressing these disruptions, with innovation and policy, will be critical to the transition's success.[83]

Examples of Decarbonization Innovation

Technological and commercial innovation are driving decarbonization efforts across sectors. From the transformative impact of the shale gas revolution in reducing carbon emissions to the ambitious clean-energy goals set by industry players like Holy Cross Energy, each example underscores the dynamic interplay among innovation, decarbonization, and economic well-being. These case studies highlight the diverse approaches and tangible progress being made toward a low-carbon future.

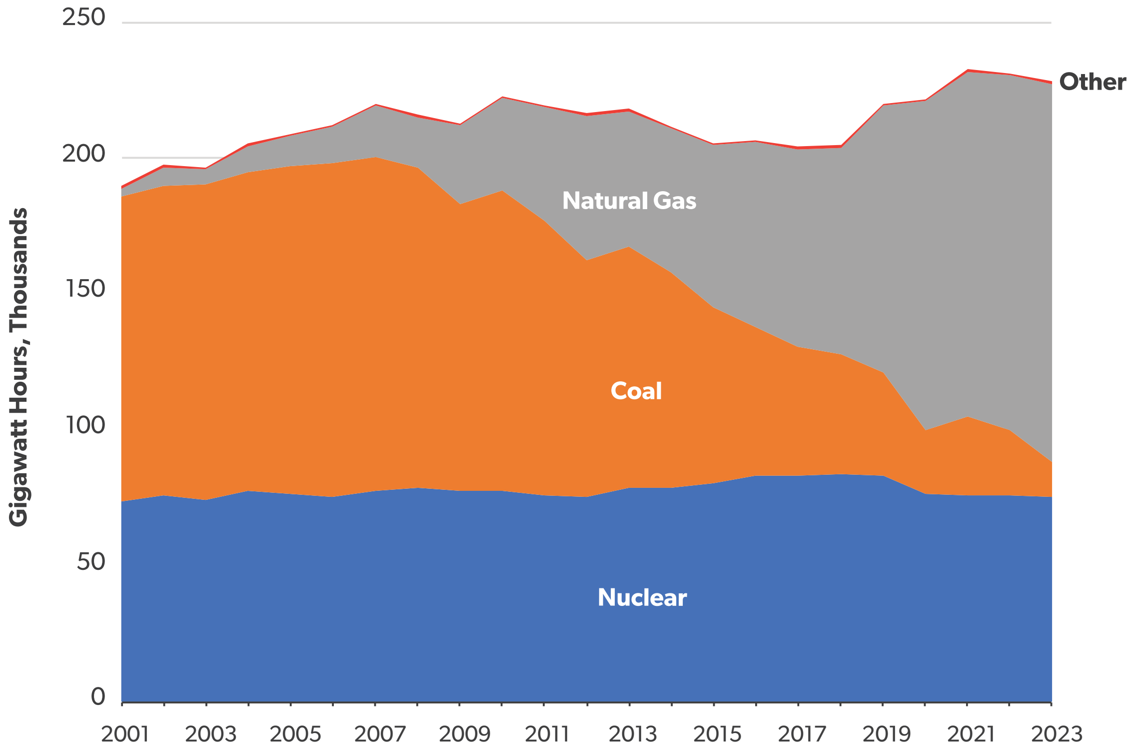
The Shale Revolution

The US shale gas revolution, driven by advances in hydraulic fracturing and horizontal drilling, has reduced CO_2 emissions significantly by shifting power generation from coal to natural gas, which emits about 50 percent less CO_2 from combustion. The closure of coal plants like the Navajo Generating Station and the rise of natural gas plants in states like Pennsylvania and Texas—driven largely by shale gas innovation—have reduced the US energy grid's carbon footprint significantly. Figure 16 shows the growth in natural gas generation and the reduction in coal-fired generation in Pennsylvania over the past two decades, with an evident growth in gas use post-2008.

Holy Cross Energy's 2030 Goals

Holy Cross Energy, a rural electric cooperative in Colorado, aims for 100 percent clean energy by 2030 and net-zero emissions by 2035.[84] It is focusing on wind, solar, battery storage, energy efficiency, and demand response.

Figure 16. Annual Utility-Scale Electricity Generation by Source in Pennsylvania (2001–21)



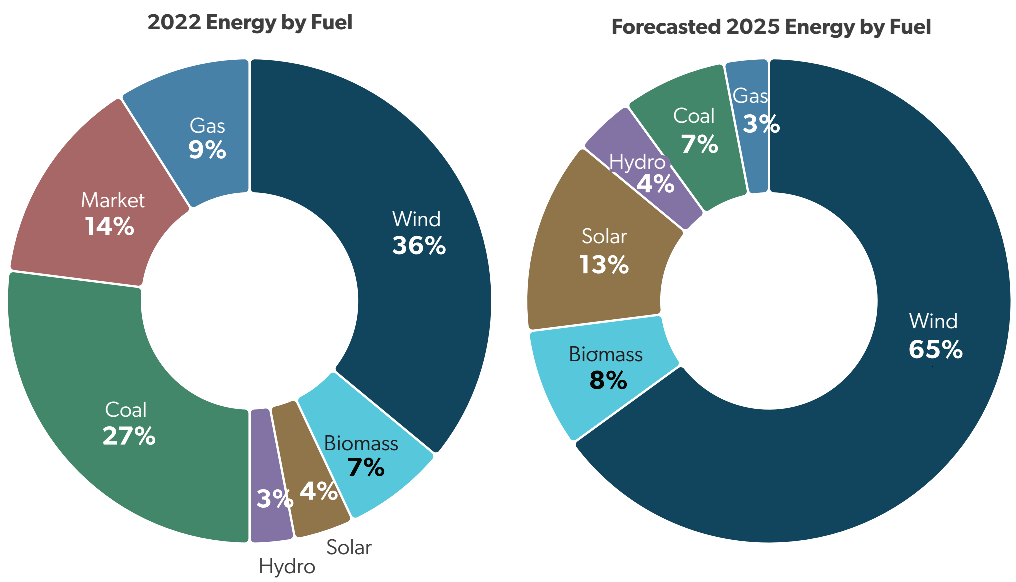
Source: US Energy Information Administration, Electricity Data Browser, https://www.eia.gov/electricity/data/browser/#/topic/0?agg=21&fuel=vvg&geo=0001&sec=g&linechart=ELEC.GEN.COW-PA-99.A~ELEC.GEN.NG-PA-99.A~ELEC.GEN.NUC-PA-99.A~ELEC.GEN.OTH-PA-99.A&columnchart=ELEC.GEN.ALL-PA-99.A&map=ELEC.GEN.ALL-PA-99.A&freq=A&start=2001&end=2023&ctype=linechart&ltype=pin&rtype=s&pin=&rse=0&maptype=0.

Currently, 44 percent of its power comes from clean sources, and it has contracted 100 megawatts (MW) of wind and 30 MW of solar projects. An additional 3 percent comes from member-purchased renewable energy through the PuRE program, which allows members to directly purchase renewable energy from Holy Cross Energy. Building on its Seventy70Thirty plan, Holy Cross Energy has moved to contract 100 MW of new wind and 30 MW of new solar projects, sell its share of the Comanche Unit 3 coal plant, and develop local renewable energy resources paired with significant battery storage. Holy Cross Energy's progress shows the power of local action in the broader decarbonization effort (Figure 17).

Geothermal Energy Development

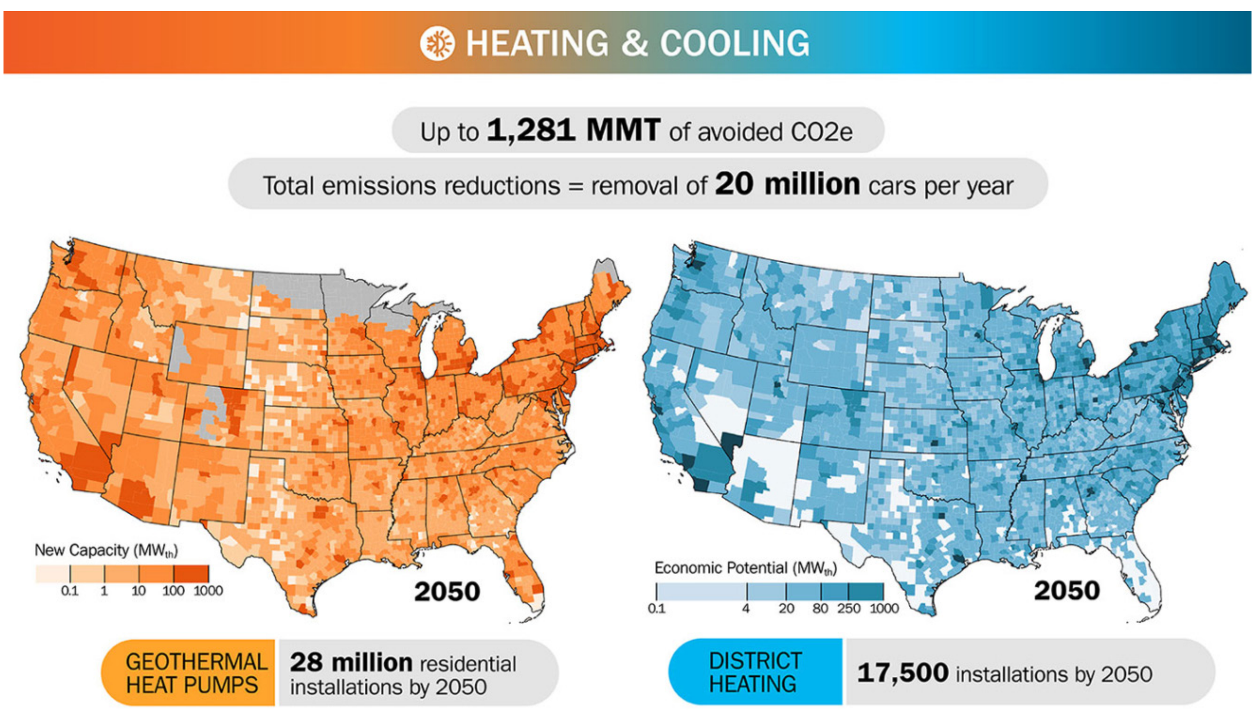
Geothermal energy, a reliable and low-impact power source, is gaining traction due to technological advancements in drilling and reservoir management. Companies like Fervo Energy and AltaRock Energy are pioneering enhanced geothermal systems, using hydraulic fracturing techniques to create and manage geothermal reservoirs.[85] Fervo's Nevada project, capable of generating 60 MW of clean energy, and AltaRock's Newberry Volcano project in Oregon demonstrate geothermal's potential as a sustainable energy source.[86] Figure 18 presents estimates of emissions reductions in 2050 from advanced geothermal generation.

Figure 17. Holy Cross Energy's 2030 Goals



Source: Holy Cross Energy, *2023 Power Supply Roadmap*, https://www.holycross.com/wp-content/uploads/2024/05/HCE_PowerSupplyRoadmap2023_upload.pdf.

Figure 18. The Potential of Geothermal Energy



Source: US Department of Energy, Office of Energy Efficiency & Renewable Energy, "GeoVision," https://www.energy.gov/eere/geothermal/geovision.

New Nuclear Strategies

Nuclear fission remains a low-carbon energy source with potential to aid decarbonization. Innovations like small modular reactors (SMRs) and micro-reactors aim to reduce costs and construction times. While NuScale Power's early efforts at SMR technology have faced challenges, TerraPower's 345 MW Natrium plant in Wyoming and NANO Nuclear Energy's micro-reactor concept show promise as strategies to overcome historical cost barriers and achieve timely deployment. Nevertheless, commercial viability remains to be proven.

Decarbonization Challenges

The transition to decarbonized power systems is complex and requires new regulatory approaches and policy principles that foster technological innovation and empower consumers, producers, and intermediaries to make informed, cost-effective decisions. Allowing decision-makers to make choices, take risks, innovate, and collaborate while reducing transaction costs will enable transactive, collaborative, and scalable paths to clean energy.

Opportunities for grid decarbonization lie in technological innovation, effective resource management, engaged consumers, and dedicated financial systems for investment and risk management. However, these efforts must be supported by institutional and regulatory frameworks that lower barriers to swift action, transactions, and collaboration. Competitive market processes that provide clear price signals can guide resources to the most effective approaches in a decentralized manner. Regulators should focus on not only increased capacity but also decentralized strategies that enhance productivity and foster grid-edge innovation, reducing the need for large-scale investments with long deployment times.

While decentralized, market-based approaches are important, top-down grid planning remains essential for coordinating these private investments in complex systems. The development of grid-scale renewables, driven by tax credits and state standards, has prioritized low-cost, carbon-free power without fully considering operational reliability. Effective coordination of decentralized incentives with system-level policies can lower costs and accelerate the path to full grid decarbonization.

Some Policy Approaches, All with Trade-Offs

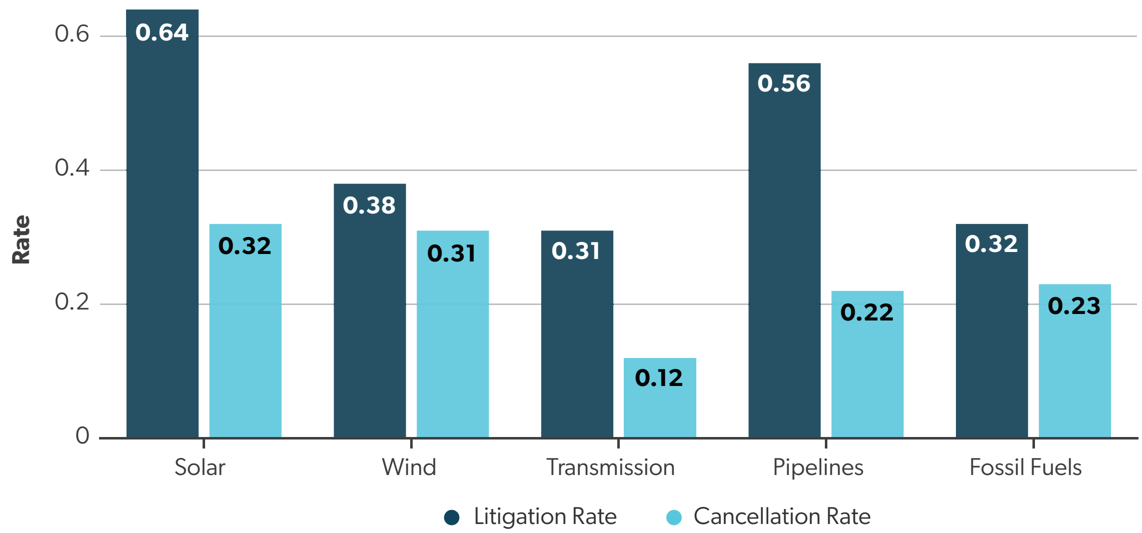
Government policy is critical in facilitating decarbonization at all levels. Effective policies should minimize transaction and administrative costs while maximizing environmental and economic benefits. Federal Environmental Protection Agency regulations and the current patchwork of state policies, such as renewable portfolio standards, have often hindered innovation by creating inconsistent and conflicting requirements. Carbon pricing mechanisms like revenue-neutral carbon taxes offer efficient solutions but have proved politically challenging and vulnerable to manipulation, as revenue-constrained governments have incentives to reduce or eliminate revenue neutrality.

Performance-based emissions regulations offer a compelling alternative to prescriptive rules. These set clear emissions targets, allowing flexibility in how to achieve them. For example, utilities could be required to reduce CO_2 emissions per megawatt-hour, incentivizing investment in cleaner technologies and operational efficiencies. By focusing on outcomes rather than specific technologies, regulations could promote competition and innovation in an environment where the best solutions can emerge.

Implementing stringent federal emissions standards for power plants is a different approach to driving significant reductions in greenhouse gas emissions. Such standards ensure a consistent regulatory framework that can promote long-term investments in clean-energy infrastructure and technologies. A limitation facing emissions standards is the impossibility of establishing an optimal standard and the difficulty of determining an effective standard that is also cost-effective for industry to implement and regulators to monitor.

Policies should avoid favoring specific technologies and focus on emissions outcomes. This approach ensures diverse clean-energy technologies can compete, allowing for decentralized innovation and consumer choice. Policies should test capital-intensive bulk system investments against the potential

Figure 19. Litigation and Cancellation Rates for Energy Projects That Received an EIS



Source: Michael Bennon and Devon Wilson, "NEPA Litigation over Large Energy and Transport Infrastructure Projects," *Environmental Law Reporter* (2023), https://papers.ssrn.com/abstract=4498938.

for decentralized solutions, enabling flexibility as clean-energy technologies evolve.[87]

Another regulation that hampers decarbonization is the National Environmental Policy Act (NEPA). The Inflation Reduction Act subsidized clean-energy projects, but NEPA-required environmental impact statements (EIS) are a substantial barrier to building the requisite infrastructure for such projects. The National Association of Environmental Professionals found that in 2022, a typical federal agency took more than four years on average to complete an EIS, although some recent reforms focus on reducing this time.[88] Once the EIS is completed, a project can still be held up in litigation (Figure 19).[89] Several states, too, have their own versions of NEPA. Demand for clean-energy projects is high, but the complex and multifaceted regulatory apparatus makes building these projects exceedingly difficult.[90]

Potential NEPA reforms include creating time limits on the use of injunctions that halt construction and preventing states from blocking federally approved projects.[91] Recent draft legislation from the House Committee on Natural Resources proposes streamlining NEPA by limiting the number of agencies involved in the permitting process, creating a 120-day statute of limitations for lawsuits that challenge NEPA decisions, and curtailing the court's ability to halt projects; for a court to issue an injunction, the proposed project must create "proximate and substantial environmental harm."[92]

These policy alternatives foster innovation, flexibility, and the adoption of clean technologies, advancing the decarbonization of the US electric system while supporting economic growth.

A Future Both Clean and Prosperous

Decarbonization is essential to building a clean, prosperous future that fosters economic growth and human well-being. Transitioning to low-carbon energy sources mitigates climate disruption, reduces pollution, and can create dependable power systems.

The shale revolution, Holy Cross Energy's goals, advancements in geothermal energy, and new nuclear strategies highlight diverse pathways to decarbonization, with more to emerge in an innovation-driven future. Technology-agnostic policies can accelerate this transition, minimizing costs, maximizing benefits, and fostering innovation.

Decarbonization is about more than reducing emissions; it is about building a future where clean energy drives economic prosperity and enhances quality of life. Aligning decarbonization with economic growth requires forward-thinking policies that balance environmental sustainability with economic resilience, ensuring the benefits of a low-carbon economy are broadly shared and contribute to long-term prosperity.

Justice

Energy justice is a key element of any vision of the future grid. Incorporating justice into this vision involves thinking about the distribution of the benefits and burdens embedded in our energy system. Who has access to the technologies? Who has access to jobs? Who has the opportunity to build wealth from investments in these systems?

At the same time, energy justice involves ensuring that decisions include a wide range of voices. This focus is particularly important because the current incumbents have an enormous voice and substantial political influence that can diminish the influence of other individuals and communities.

Energy justice involves four key concepts: distributive, procedural, universal, and commutative justice. While all four concepts are intertwined in practice, recognizing these distinctions strengthens our framework.

Distributive justice addresses the fair allocation of benefits and burdens across sociodemographic groups. In the energy transition, this means ensuring all communities, especially marginalized ones, have access to clean energy, affordable electricity, and economic opportunities. Current policies, like tax credits, often favor wealthier homeowners, leaving low-income and minority groups unable to participate in energy programs.[93]

In his 1971 book, *A Theory of Justice*, philosopher John Rawls proposed the famous "original position" and "veil of ignorance" as a thought experiment to derive principles of justice. The "original position" is a hypothetical scenario in which individuals decide on principles of justice for society from behind a "veil of ignorance," which conceals their own social status, abilities, and personal characteristics to ensure fairness and impartiality in their choices. In a Rawlsian framework, decarbonization or grid expansion must prioritize equitable outcomes, particularly for those who are least advantaged and who have historically been left behind.[94]

Procedural justice emphasizes fairness and transparency in decision-making and the legitimacy of institutions. It ensures all stakeholders have a voice in shaping energy policies. Rooted in legal theory and social psychology, procedural justice holds that fair processes build trust, even when outcomes are unfavorable.

Robert Folger and Russell Cropanzano build on procedural justice theories by integrating them with accountability and moral judgments.[95] They argue that fairness is about not only how decisions are made but also how decision-makers are held accountable. This concept is critical in the energy context, fostering legitimacy and cooperation as our energy systems evolve.

Distributive and procedural justice exist on a foundation of other fundamental justice concepts. The most fundamental concept is *universal justice*, rooted in the Aristotelian notion of justice as fairness and equality before the law. In *Nicomachean Ethics*, Aristotle elaborated on justice as a virtue and distinguished between particular justice (such as distributive and procedural justice concepts) and universal justice.[96] Aristotle's concept of universal justice, also known as *general* or *legal* justice, is rooted in his broader ethical framework, in which justice is seen as the complete virtue expressed in relation to others. For Aristotle, laws aim to foster virtuous behavior in a society, so universal justice becomes the overarching principle that ensures the community's harmonious functioning by aligning personal virtues with the collective good. This concept reflects his belief that a just individual not only abides by laws but also contributes to the moral fabric of society, thus integrating personal ethics with civic responsibility. Any improvements to the electric grid must focus on universal justice; while the grid is designed to provide reliable energy services to all, it fails to achieve this ideal, disproportionately affecting marginalized communities with blackouts and lack of resilience.

The related concept of *commutative justice* refers to requirements not to harm others, often understood as negatively defined rights to freedom from harm to one's life, liberty, and property. Incorporating commutative justice includes respecting individuals' rights and ensuring that policies do not infringe on the negatively defined rights of individuals or groups. This concept of justice is best illustrated by Adam Smith's discussion in *The Theory of Moral Sentiments*.[97] Both universal and commutative justice are foundational concepts in modern legal codes and are pillars on which a broader conception of energy justice rests.

Incorporating these concepts into changing energy systems respects and enhances the rights and well-being of all individuals. Achieving energy justice requires reimagining institutions, decision-making processes, and priorities to create a more just and inclusive system.

Inequities

Inequities in the electric grid affect access to energy resources and community resilience during power disruptions. In California, underserved communities face significant barriers to adopting DERs like solar panels and battery storage due to outdated grid infrastructure and uneven policy support.[98] Low-income and rural areas often lack the grid capacity to integrate DERs that could provide resilience, while wealthier communities with better infrastructure benefit more from clean-energy sources. State incentives, such as rebates and tax credits, disproportionately favor those who can afford the upfront costs, leaving disadvantaged communities reliant on fossil fuels and further exacerbating environmental and health disparities.

Low-income and minority communities are more likely to live near polluting fossil fuel plants, experience longer power outages, and have less access to clean energy.[99] These inequalities are rooted in decades of underinvestment in grid infrastructure in marginalized areas.[100]

Weather-induced power outages disproportionately affect socially vulnerable communities. A one-decile increase in socioeconomic vulnerability corresponds to a 6 percent increase in outage duration, equating to an average 170-minute delay in power restoration.[101] Southeastern US communities with higher vulnerability face significantly longer outages than less vulnerable areas.

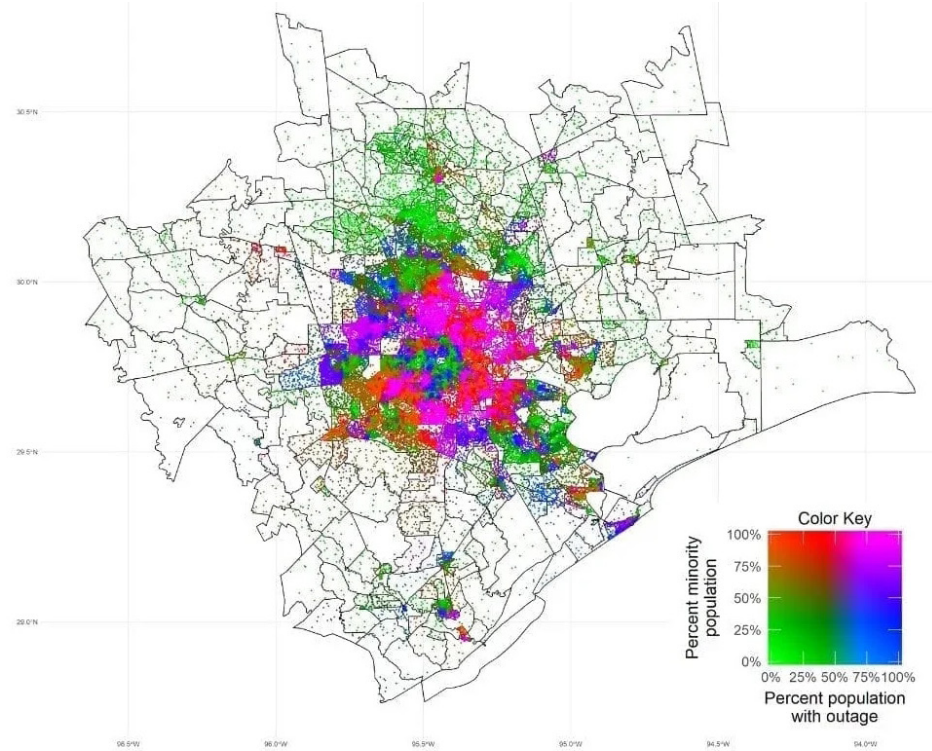
During Winter Storm Uri in Texas in 2021, over 4.5 million people lost power. Minority communities were four times more likely to experience blackouts than were predominantly white neighborhoods, which had an 11 percent chance of outages compared with 47 percent for communities of color (Figure 20).[102]

Low-income and traditionally disadvantaged households in the US have the lowest rates of adoption of residential solar or EVs while also receiving the least amount of tax credits toward these technologies,[103] and they are the most likely to be exposed to air pollution from power plants and mobile sources.[104] Studies on US energy insecurity and poverty have also found that low-income residents pay a significantly higher share of one's household income on energy services compared with the average US household,[105] and they are more likely to struggle to pay their energy bills,[106] engage in risky behavior and financial coping strategies,[107] and be disconnected from their service provider.[108] Such situations represent failures of all four concepts of justice.

Examples of Energy Justice

A wide range of potential actions can support energy justice. While these examples represent only a limited set of programs, they offer useful perspectives on how to support the changes suggested by our framework in a just way. There is a need for deliberate action to ensure, for example, that people across diverse geographies and demographics have equal access to receive and deliver services to the grid. Communities suffering from pollution and grid vulnerabilities can benefit from resilient, distributed infrastructure, improving local wealth, service quality, and overall economic vitality.

Figure 20. Map of the Blackouts in the Houston Metropolitan Statistical Area During the Winter Storms in February 2021



Source: Benjamin K. Sovacool et al., "Energy Justice Beyond the Wire: Exploring the Multidimensional Inequities of the Electrical Power Grid in the United States," *Energy Research & Social Science* 111 (May 2024): 103474, https://doi.org/10.1016/j.erss.2024.103474.

Microgrids

Microgrids advance energy justice by providing localized, reliable, and affordable power, especially in underserved or remote communities. They promote procedural justice by involving communities in decision-making and mitigating energy inequities caused by centralized grids.

ComEd's Bronzeville microgrid in Chicago, developed with local input and in partnership with the microgrid company Enchanted Rock, is in a historically underserved neighborhood. It enhances community resilience and empowers the community by providing reliable, locally generated electricity during grid outages.[109]

Similarly, the Viejas Microgrid on the Viejas Band of Kumeyaay Indians' lands in California provides sustainable energy for tribal operations, reduces costs, and promotes energy sovereignty, showing how microgrids can foster independence and cultural respect.[110] The project allows the tribe's reduced energy costs to be reinvested in critical services such as education and infrastructure. It was developed in collaboration with tribal members, ensuring their participation in decision-making, and allows the tribe to control its energy resources.

Solar for All

The Inflation Reduction Act's Greenhouse Gas Reduction Fund allocated $7 billion in April 2024 to support solar programs for low-income communities. The Solar for All program provides grants and financing for solar deployment in disadvantaged areas, enhancing energy affordability and reliability.[111]

Justice40 Initiative

Established by executive order in 2021, the Justice40 Initiative ensures at least 40 percent of certain federal investment benefits go to disadvantaged communities. As part of the Justice40 Initiative, the Department of Transportation uses a mapping tool to identify vulnerable populations and ensure investments in health, energy access, and climate resilience.

Justice in a Clean and Prosperous Future

Digitalization and decentralized technologies can benefit disadvantaged communities by enabling democratization, dependability, and decarbonization, but only if structural barriers are addressed. Attention to justice requires community engagement, financial incentives, technical support, and expanded market opportunities for customers across the economic spectrum. Reducing barriers to innovation will also make energy technologies more affordable and accessible.

Innovations in digitalization, decentralization, democratization, dependability, and decarbonization will affect how benefits and burdens are distributed and the procedures for determining such distributions. These decisions will have implications that must be grounded in principles of universal and commutative justice. If these advancements increase energy costs, households with tight budgets and high energy burdens will be disproportionately affected, especially in regions where climate change drives higher energy consumption. Mitigating these effects requires incorporating all four justice concepts into strategies for future power systems.

Connecting the Dots to Create a Framework

The evolving landscape of power systems is characterized by a convergence of digitalization, decentralization, democratization, dependability, decarbonization, and justice. This framework is designed to capture the substantial potential of these elements, each contributing to transforming the electricity sector in significant ways.

Digitalization serves as the foundational layer, enabling a more interconnected, responsive, flexible, and adaptable grid. It expands the possibilities for greater economic and environmental value by making data-driven decisions and real-time management more accessible and effective and enabling changes to grid architecture.

Decentralization builds on this foundation, shifting control from centralized authorities to the grid edge, where consumers and smaller-scale producers play increasingly significant roles. This shift not only enhances efficiency and resilience but also fosters *democratization*, giving individuals and communities greater agency over their energy choices.

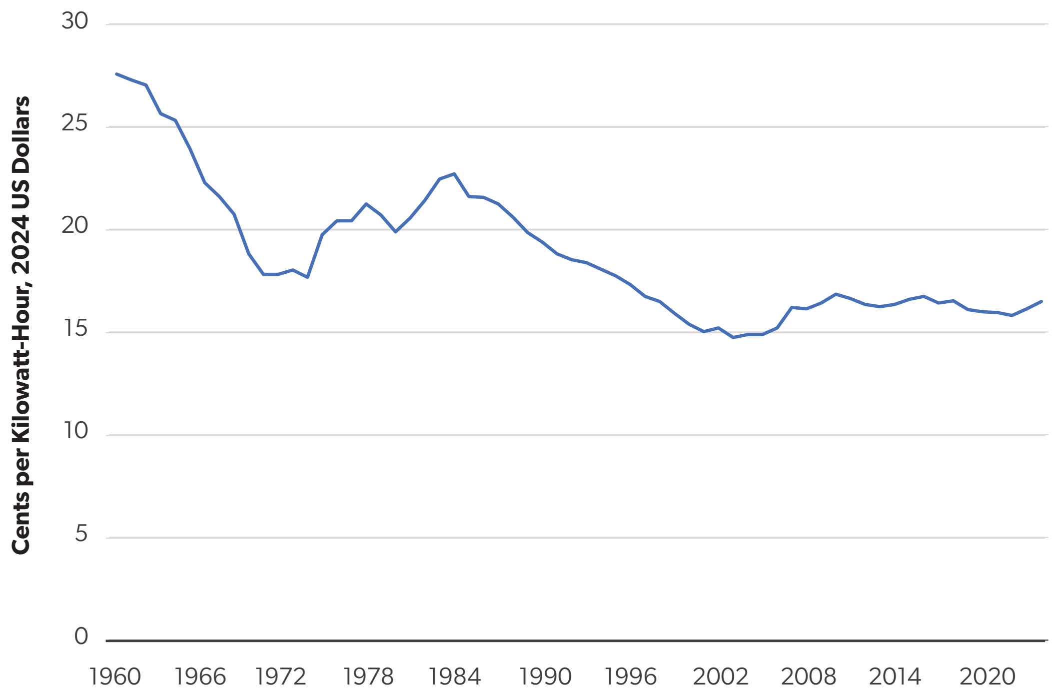
However, as the grid becomes more decentralized and democratized, maintaining *dependability* becomes more complex. Integrating a broader array of energy sources and management systems challenges traditional models of reliability, resilience, and resource adequacy that are incorporated in dependability. Achieving *decarbonization*, the reduction of carbon emissions, is a critical objective that intersects with all these elements, demanding innovative approaches to policy and technology.

Finally, the pursuit of *justice* ensures that these transformations' benefits and costs are equitably distributed and that individuals are treated equally under the law. This principle means addressing disparities in access and affordability while ensuring that the costs and benefits of the common, network aspects of energy systems are shared fairly across all segments of society.

While these transformations present significant challenges, they also offer unprecedented opportunities. The traditional paradigm of the electricity industry, characterized by centralized control and rate-base regulated monopolies, is outdated. Advances in technology and economic dynamism are eroding the assumptions that justified this model and its preeminence for over a century.

Historically, the centralized, monopoly-driven model—based on a single company sending power from a few large generators over transmission and distribution networks to captive, passive consumers under a monopoly franchise—was justified by

Figure 21. Annual Average US Residential Electricity Price



Source: Edward Kahn, *Electric Utility Planning and Regulation* (American Council for an Energy-Efficient Economy, 1991), 11.

the economies of scale and technological limitations that made it the most efficient way to meet the growing demand for electricity. Even those who tend to favor limited regulation, entrepreneurial innovation, consumer choice, individual empowerment, and self-reliance in other sectors of the economy broadly acquiesced to, and even strongly supported, the centrally planned and operated vertical monopoly model for utilities. This model was governed by an interdependent and self-perpetuating tandem of technocrats and regulators, who in turn were strongly influenced by what utility shareholders and bondholders have long been conditioned to expect.[112] Similarly, aspects of the regulatory paradigm and how it is implemented are also outdated, although its consumer-protection mission remains essential.

This paradoxical posture made sense as long as economies of scale and technology limitations dictated that this model was the best way to meet the growing demand for electricity from households and businesses reliably and affordably. However, since the 1970s, when the decades-long trend of steadily declining real electricity prices ended, these assumptions have been increasingly called into question (Figure 21).[113]

Unexpected cost and system integration issues for large new plants in the 1970s; the rise of smaller, more dispersed generation technologies in the 1980s; and the introduction of competition in the generation segment through regulatory restructuring in the 1990s marked the beginning of a shift away from the centralized model. Yet networks carried on as centrally planned and operated regulated monopolies, in most cases including monopoly retail service territories, although some regions extended competition to retail service with varying degrees of effectiveness.

The opportunity for even more fundamental change had to await the revolution that has occurred over the past few decades in the cost and performance of highly distributed information and communication technology and, more recently, highly distributed production and storage of energy. Those productive innovations have accelerated this shift, making it possible for customers and businesses to take greater control over their energy use.

Digitalization and innovative energy service offerings are exposing a rapidly expanding range of easy and convenient ways for customers and businesses to save money and make their own decisions about what constitutes dependable electric service, by taking greater control over how and when they obtain the electricity they need. This decentralization not only offers cost savings and improved resilience but also enhances democratization by giving consumers greater agency over the many ways they could and do interact with an essential service.

Looking forward, the cost of failing to embrace these opportunities will escalate. As the energy transition progresses, the industry, regulators, and policymakers must adapt to a new reality where digitalization, decentralization, and democratization are central to achieving dependability, decarbonization, and justice. The traditional industry model, with its reliance on regulated, rate-based utility capital investments and an increasingly outdated model for assessing system reliability, is increasingly seen as a barrier to innovation and progress.

Innovation in this context requires fair market access, a level playing field vis-à-vis incumbent service providers, and regulatory transparency. It also relies on an expectation of protection from abrupt, arbitrary, or capricious market interventions. Barriers to innovation under the legacy industry model affect the entire value chain. These barriers are evident across the value chain, particularly in the transmission infrastructure investments that have favored reinforcing outdated assets over exploring new, more cost-effective solutions. Since 2010, an average of 80 percent or more of investments in transmission infrastructure in most regions have been in reinforcing or replacing aging local rate-based assets with no competition and little or no oversight.[114] In many cases these investments may no longer be cost-effective or even useful when compared with employing innovative grid-enhancing technologies or when coupled with "smart" distributed resources and customer empowerment.

Meanwhile, only 20 percent or less of those investments have been in the regionally and interregionally planned network investments that increasingly constitute the digitalized grid's unique value proposition.[115] In other words, enlightened planning and oversight—adequately reflecting the potential of decentralized grid-edge actions—retains an important role.

As we look to the future, the roles of the bulk and distribution grids will need to adapt. Devolving greater information and control to the grid edge not only is increasingly feasible but also offers a valuable complement to the traditional reliance on top-down, capital-intensive investments in bulk generation, transmission, and distribution assets. By incorporating this approach, we can reduce the risk of overinvesting in infrastructure that may become underutilized over time.

The grid is not only a continued source of key benefits but also a single-point source of vulnerability. The inexorable march of digitalization from bus bar to meter has added cybersecurity to the growing list of threats to the bulk system, including increasing intensity and frequency of climatic events. We must embrace the potential of decentralized, digitalized solutions that offer greater flexibility, adaptability, and resilience. These solutions not only mitigate the risks associated with traditional grid infrastructure but also empower consumers and communities to play a more active role in managing their energy needs.

The benefits of digitalization go beyond operational innovation. New tools like digital twins can help decision-makers more productively use network investment, particularly in distribution networks. Network engineers can simulate the deployment of new distributed technology across their networks without risking security of supply. The hosting capacity of distribution networks can be expanded by not just adopting new grid-enhancing technologies but also employing new digital tools such as dynamic operating envelopes.

By embracing these new tools, we can avoid unnecessary restrictions and costs imposed on the adoption of new technologies. We can spare customers the costs of underutilizing network assets out of an overabundance of caution. Regulators can embrace more productivity-focused, less capital-biased incentives for monopoly network operators without fear of compromising reliability.

The bulk and distribution grids will continue to play a critical role, but they no longer need to be all things to all people, nor can they be. It is in the interest of all customers, especially in vulnerable and underserved communities, that the grid's role—and the institutional framework required to maintain its vitality—evolves to drive innovation and accommodate advances in technology and services in the distributed management of energy services. Customers and communities can and should have greater agency to lower costs, increase resilience, and improve the quality of their lives.

The energy transition presents both challenges and opportunities. By embracing digitalization, decentralization, and democratization, we can build a more dependable, decarbonized, and just energy future.

III. Implications of the Innovation Framework

In the foregoing chapters, we have set out a vision for the future of power systems, centered on the imperative of harnessing innovation across multiple dimensions, and we have proposed a framework that would enable us to achieve that vision. We put forward the following vision as the guiding objective of the report:

> We should strive toward an energy system that seeks to remove barriers to innovation and enable vibrant ecosystems to accelerate opportunities for consumers to have access to affordable and dependable power systems, decide how and when they consume (and produce) the electricity they want and need, and invest in the solutions that bring them the greatest value.

The implication behind this vision statement is that, to meet the demands of a decarbonizing electric supply and the beneficial electrification of energy services reliably and affordably, we must amplify innovation in new and creative ways, including institutional innovation. The level of uncertainty about the future of the electricity sector, on both the demand side and the supply side, is greater than at any time since Thomas Edison and George Westinghouse battled over direct versus alternating current. As a result, rewarding innovation and expanding the institutional and commercial ability to leverage emerging products and services is more important than ever. Some aspects of the technologies, regulatory institutions, and industry business models in electricity have become obsolete and in some cases have become obstacles to achieving the vision we have articulated.

We put forward a framework for reforming the legacy electric industry ecosystem in service of this innovation-centric vision. That framework leverages the revolution in recent decades in information and communication technologies—in a word, digitalization—to enable a shift toward greater decentralization and democratization in providing electrified energy services to customers.

A framework favoring greater decentralization and democratization recognizes that, as digital technologies have progressed, the legacy industry ecosystem of a centralized, top-down, unidirectional flow of information, energy, and services from monopoly producers to captive customers no longer represents the only, or best, structure for ensuring the provision of electrified energy services is dependable, decarbonized, affordable, and just. Instead, the proposed framework seeks a more dynamic balance between the value that innovators and empowered consumers can create by enabling information and control at the grid edge and the value of the still-critical roles that only centralized large-scale network infrastructure can play.

The vision and framework articulated here have implications for multiple actors in the electricity ecosystem. These actors include regulators, policymakers, legislators, incumbent industry players, startup innovators, and customers. These actors all have opportunities to reduce or remove barriers to innovation, especially innovation to provide customers with more information and control.

Regulators

The changes driving this report's vision also carry important implications for utility regulators. Utility regulators for most of the past 100 years have had the unique role of economic regulation of activities that serve the public interest. While the history of defining what that means is extensive and complicated, in the simplest terms, it refers to the cost-based regulation of a virtual or natural monopoly in providing an essential good.

While electricity is as essential a good and service as ever, arguably only the wires infrastructure for transmitting and distributing power remains a natural monopoly. This is the expected outcome for natural monopoly markets facing technology innovation—the footprint of the natural monopoly will inevitably shrink as new, advanced technologies are more and more capable of reducing transactions costs and providing direct customer value. In short, the technology innovation changes the economies of scale that characterize natural monopoly markets. This means that regulators must be even more attuned to the need to limit (or, perhaps, quarantine) the incumbent monopoly to those areas of the system where the economies of scale remain and orient regulation toward enabling open access to the energy infrastructure operated by the regulated monopoly.

Furthermore, the service provided by that monopoly activity now includes moving power both to and from the edge of the grid, with traditional grid-supplied electricity increasingly competing with distributed alternatives. The electricity-consuming public has an increasing interest in activities beyond the monopoly wires, such as ensuring access to innovative methods for delivering reliable energy services and opportunities to use their own resources to provide grid services, if they choose.

Electricity regulators have three basic roles in leveraging innovation:

1. Ensuring that innovators have a fair opportunity to use grids as open platforms to interact with potential customers without compromising reliability

2. Incentivizing monopoly grid operators to employ innovation in optimizing the value, reliability, and resilience of the services they provide

3. Embracing and encouraging innovation in the pricing and service options available to consumers under their jurisdiction, including designing appropriate safeguards

The first role implies striking a balance between preventing grid operators from leveraging their cost-of-service-regulated core business model to disadvantage competitive entry in activities beyond the provision of platform services while empowering grid operators to take necessary actions to maintain reliability. The traditional regulatory interest in reliability remains—indeed, it becomes even more demanding as reliability-adjacent investment and operations become more dispersed—but the nature of reliability evolves as more customers gain more agency over what they're willing to pay for on-demand electricity for different end-use energy services at different times and in different places.

The second role implies adapting regulatory incentives to shift monopoly grid operators away from legacy business models and toward business models more suited to the rapidly changing electricity landscape. Historically, electric industry regulation operated from a presumption that, because of favorable economies of scale, it should incentivize a business model based on investment in capital-intensive, supply-side, centrally planned and operated capacity, irrespective of how much or how little it is expected to be used, which was deemed necessary to support an "obligation to serve" on-demand, around-the-clock consumption at a flat rate. With the transformations already well underway at the center and on the periphery of the grid, that model will become increasingly unaffordable.

The optimal business model for regulated grid operators going forward will need to reflect two-way flows of electricity and information and expect superior financial results. It should recruit and appropriately reward flexible grid-edge resources that improve network productivity and resilience and lower electric bills for all customers, including (to a lesser extent) those who choose not to participate. This model means targeting regulatory incentives to the productive, transparent, and reliable operation of distribution systems as open platforms (a "distribution system operator" model). It calls for regulatory incentives more meaningfully tied to grid operators' performance against relevant service-driven objectives, rather than simply rewarding reliability-driven additions to regulated asset bases.

The third role calls for regulators themselves to accept the challenge of being more innovative and entrepreneurial. With advances in technology over recent decades, especially over the past 20 years, regulators now have many ways to ensure safe, reliable delivery of essential energy services while ensuring revenue sufficiency for prudent grid operators. More and more customers have alternatives to their historical passive reliance on grid-supplied electricity, and more and more customers are in a position to offer important value to grid operators and the wider population of grid stakeholders.

It is no longer enough for regulators to simply protect electricity consumers and provide for revenue sufficiency. They will be challenged to explore regulatory strategies that incentivize customers to not only remain connected to—and contribute equitably to the cost of—the monopoly networks but also engage with the grid in ways that lower the cost of reliable service for all. At the same time, regulators will be challenged to adopt more interactive definitions of grid reliability and more dynamic and creative approaches to safeguarding customers, especially the most vulnerable.

Policymakers

The vision we have articulated has implications also for state and federal policymakers. Dependability will of course remain paramount to energy policymakers, but new challenges are arising as they consider the equally important objectives of decarbonization and affordability. Customer empowerment and access to innovative disruption must become priorities alongside consumer protection. Energy policy should seek to address market failures in the deployment of new products and services, through consumer education and, where appropriate, support for technology deployment.

Beyond energy policy, this framework has implications for tax policy. Legacy tax policies often unintentionally penalize emerging alternatives that would otherwise increase social welfare, such as tax policies meant to address affordability that end up favoring traditional capital-intensive options over more innovative service-intensive approaches. Where such biases are observed, tax policy should be adapted to clear barriers to a more decentralized, more democratized electricity sector.

Support for innovation within and around the monopoly networks to raise the productivity of rate-based investment should become a cornerstone of policies targeting affordability and energy justice. This implies that energy policy should promote interoperability and compatibility of equipment standards. Energy and resource planning should be leveraged to consider the full range of alternatives available to ensure reliability through and beyond the current period of transition, with a proactive focus on the relative net benefits of nontraditional, non-supply-side alternatives.

Legislators

The most straightforward implication for legislators is the need to draft and adopt legislation enabling the achievement of the policy objectives described above. In some states, legislators will need to remove legal barriers that restrict access to customers for nontraditional suppliers of energy services. Where customers have a legal right to access innovative providers of energy services, legislators will need to address questions about data privacy, including the ownership of, storage of, and access to customer data.

Legislators should also pass legislation to expand and clarify the statutory mandate for regulators, empowering them to innovate in their pursuit of reliability and affordability and directing them to actively consider nontraditional, non-supply-side solutions and solution providers. The pursuit of decarbonization has broad implications for state and federal energy regulators. Yet regulators have often struggled with the extent to which their statutory authority empowers them to account for the direct and indirect impacts of decarbonization policies on their core economic mandates for reliability and affordability. An implication for legislators, therefore, is that to realize the full benefits of the framework we propose here, regulators should be given a more explicit statutory mandate to consider how current and reasonably foreseeable decarbonization policies are likely to shape a dependable and affordable future electricity system.

Incumbent Industry Players

Our vision has significant implications for incumbent industry players. Customers continue to explore alternatives to passive reliance on grid-supplied electricity, alternatives that are only growing more attractive as threats to the resilience of the bulk power system proliferate. "Smart" end-use electric devices and systems, with the potential to either exacerbate or mitigate the challenges facing grid operators, are proliferating exponentially, soon to be counted in the billions. The economics of energy resources, both utility scale and distributed, continue to be turned upside down. The resulting stresses and opportunities call into question the business model of monolithic, centrally planned and operated grids and their continued ability to serve all customers at an affordable cost.

The sector framework proposed here offers a vision of a future for incumbent utilities that supports a wide range of robust energy futures and is inherently more responsive to customers' needs and desires. Unfortunately, the current business model is the product of 20th-century economies of scale and natural monopoly dynamics that favored large investment of ratepayer capital. Those dynamics have changed. Moving forward, regulated monopoly utilities can embrace a transition to an open-access network model that empowers everyone connected to the network to participate as they choose and ensures that essential energy services that are both dependable and decarbonized are available to all customers at an affordable cost. Monopoly transmission network operators would be even more important than ever in this future, but their role would be complementary with a growing distribution of information and control to the periphery of the network. Distribution system operators in some cases might retain some form of the vertical roles of a traditional distribution utility, but a distribution system operator's profitability would be driven overwhelmingly by its effectiveness in providing a multidirectional platform for stakeholders at both ends of the network.

The implications of such a transition are admittedly broad. Farsighted utilities would be proactive in managing investor expectations in anticipation of a different but more future-proof model of profitability (or in the case of municipal and cooperative utilities, a different service and revenue model). Network operators would be incentivized to work with regulators to explore more innovative revenue models and service offerings. Network operators could in many cases even be the ones to take the lead in helping state regulators and legislators understand the benefits of enabling such a transition.

Innovators

Implications for innovators revolve around the need to become trusted partners in delivering essential services while providing a transparent and responsible balance between customer risks and rewards.

Innovators can and should take the lead in working with regulators to craft risk-mitigation strategies that foster beneficial risk-taking within socially acceptable limits. While removing or lowering barriers to entry will be important, healthy competition will in the long run rely on enforcing certain minimum requirements for service providers, including maintaining credit capacity and capital requirements sufficient to meet their obligations under a reasonable range of possible contingencies. Innovators in providing services directly to network operators may find the platform model a more welcoming environment, but they may also find a more rapid pace of change in what their customers need from them. Experienced innovators know that innovation can be a two-edged sword.

Customers

The vision and framework articulated here is about giving customers of all shapes and sizes more agency over how they get their electricity, when they get their electricity, what they pay for their electricity, and what they get paid for sending electricity back to the grid (or to their neighbors). For that reason, customers would choose for themselves what the implications of the proposed vision and framework would be.

There is no question that customers will be confronted with the double-edged sword of more choices. Their ability to evaluate an expanding range of choices will rely on the diligence exercised by network operators, regulators, innovators, and legislators in ensuring transparency, gatekeeping entry appropriately but not excessively, and providing ample opportunities for customer education. Undoubtedly, one of those choices will likely remain a traditional flat-rate service, recognizing that such an option is a premium, risk-managed product with costs that must be either reflected in the rates charged for it or, in the case of vulnerable customers, subsidized in some form through social policies other than regulated rates.

But the ultimate implication of the vision and framework articulated here will be to lower electricity bills for all customers and significantly lower bills for those customers willing and able, directly or through service providers, to consume grid-supplied electricity or supply electricity to the grid when and where it creates the greatest value for them and their neighbors.

IV. Action Plans for Implementation

This group has coalesced around a compelling vision of the future that includes innovation-enabled clean and abundant energy supporting prosperous communities. In this future, consumer-focused energy solutions that enable self-determination form the foundation of a flourishing and vibrant economy with strong governance models. As we have noted in this report, true innovation requires broad diffusion of technology and widespread adoption.

Implementing practical changes using the framework we have outlined is critical to the transformation envisioned. This is no simple feat, and unfortunately, there is no single prescription for how that can take place. Each state or jurisdiction has a unique mix of agencies, authorities, and other stakeholders that compose the regulatory ecosystem surrounding the utility industry. Still, transformative change clearly requires some executive leadership that supports coordinated action and collaborative discussion.

In our federalist system, no single prescriptive model will work in all cases. Rather, we outline and rely on a series of principles that can guide both near-term and long-term decisions and that work toward a larger vision, including changes to the layered regulatory systems and physical architecture of power systems. In this way, we believe that building blocks (including, for example, microgrids and flexible loads) can be aggregated into the existing systems and offer a pathway to transformative change.

The implementation principles laid out here focus on policy actors. In some cases, state energy offices might serve as the primary entities responsible for shaping and implementing energy policies in individual US states. In other cases, the public utility commission (PUC) may be best positioned for leadership. In still other cases, the governor or legislature might create a new office or administrative leader that can coordinate the actions and visions of state agencies, industry, academia, and community stakeholders outside of litigated or contested proceeding.

Whatever the vehicle, qualities embodied in this leadership role and principles of change are worth highlighting. Their scope must span a wide range of activities, including energy planning, regulatory compliance, promotion of energy efficiency, and support for clean and distributed renewable energy development. The leader must work closely with other state agencies, local governments, and the private sector to ensure that state energy strategies align with broader economic, environmental, and social goals.

Their responsibilities are often directly influenced by legislative statutes, which provide the legal framework and specific mandates for action in the state or jurisdiction. Recognizing the legislative intent is critical to translate this into actionable policies and programs. The relationship with regulators, state energy offices, and other agencies will be instrumental in translating the larger intent into actionable policies and programs that facilitate innovation's ability to address the state's unique energy needs and the broader national objectives related to energy security, sustainability, and resilience.

In this manner, the leadership role within the state must strive to implement the vision of a digitalized, decentralized, and democratized electricity system. By leveraging their jurisdiction and role in translating legislative statutes into actionable policies, this agent of transformation can foster the necessary innovation and entrepreneurship required to achieve greater dependability, decarbonization, and justice in the energy transition.

Primary Actors of Energy Policy

Building on the discussion of policy actors in Chapter III, here we suggest some implementation pathways within the diverse policy contexts across the United States. Each state or jurisdiction has several classes of policy actors; to apply this report's framework to power systems, these state players can play a pivotal role in enabling these changes through several concrete actions. Note that technological innovation and entrepreneurship are driving forces behind power system transformation, leading to outcomes such as increased decarbonization, greater dependability, and a more significant emphasis on justice.

Executive Branch

Typically, the executive branch (whether that is the president at the federal level, the governor at the state level, or the mayor at the municipal level) will help form a vision for the future, establish a multiagency plan, and convene leaders across government, industry, and civil society. In this way, the executive can align and influence agency activities and legislative proposals along a set vision.

Legislative Branch

The legislature may enact the executive's vision or take its own actions, including exerting influence in and issuing mandates for agencies and regulatory bodies. State legislatures have broad jurisdiction over a range of policy areas, including taxation, public safety, health care, and energy regulation. The legislature typically also controls funding allocations and authorizations.

In the context of the electricity industry, state legislatures enact laws that regulate utilities, set energy policy goals (such as renewable energy mandates or efficiency standards), and oversee state regulatory bodies like PUCs. They often influence decisions about electricity generation, transmission, and distribution, shaping the state's energy mix, market structure, and grid modernization initiatives. State legislatures also control budgets and appropriations that can affect energy programs and incentives. Their relationship with the electricity industry is thus one of governance and oversight, as they set the legal and regulatory framework within which utilities and other market participants operate.

Regulatory Bodies

The Federal Energy Regulatory Commission (FERC) is an independent federal agency responsible for regulating the interstate transmission of electricity, natural gas, and oil. FERC's jurisdiction covers wholesale electricity markets, interstate electric transmission, natural gas pipelines, and hydropower projects. One of its core responsibilities is ensuring that energy rates, terms, and conditions are just and reasonable, as mandated by legislative statutes like the Federal Power Act. The Federal Power Act empowers FERC to regulate wholesale electricity markets and interstate transmission to prevent discrimination and promote competition.

FERC's decisions must align with federal laws, such as the Natural Gas Act and the Energy Policy Act, which guide its regulatory authority. While FERC operates independently, its relationship with these statutes means it is bound to interpret and enforce energy laws passed by Congress.

Nevertheless, FERC plays a central role in shaping the regulatory framework for the future energy system—one that emphasizes digitalization, decentralization, democratization, dependability, decarbonization, and justice. FERC's authority to regulate interstate transmission and wholesale electricity markets provides a key lever for implementing many of these changes.

State PUCs are regulatory agencies responsible for overseeing and regulating essential utility services, including electricity, natural gas, water, and telecommunications. Their primary jurisdiction includes ensuring that utilities provide reliable services at reasonable rates while maintaining financial stability and service quality.

PUCs operate under the authority of state laws and legislative statutes, which define their scope of regulation and decision-making power. These statutes often mandate PUCs to balance the interests of consumers, utilities, and broader policy goals, such as environmental sustainability or energy reliability. PUCs implement and enforce state laws by creating regulations, setting utility rates, reviewing infrastructure investments, and adjudicating disputes. Their decisions are closely aligned with state legislative priorities, making them key decision-makers in translating energy and utility policy into practice within the regulatory framework.

Agencies

State energy offices and the US Department of Energy have vital roles to play. They often manage research programs and distribute funding for energy incentives and support programs, and they complement regulatory actions in advancing executive visions and legislative priorities. These agencies are also often tasked with implementing studies, roadmaps, and task forces that serve as guiding documents for a state's or jurisdiction's energy strategy.

Stakeholders

A wide range of industry actors, consumers, and communities surround power systems and play essential roles in shaping energy policy, participating in the legislative and regulatory processes, and driving innovation.

The Guiding Vision

This report is guided by the following vision statement:

> We should strive toward an energy system that seeks to remove barriers to innovation and enable vibrant ecosystems to accelerate opportunities for consumers to have access to affordable and dependable electric systems, decide how and when they consume (and produce) the electricity they want and need, and invest in the solutions that bring them the greatest value.

We recognize, as do many industry professionals, policy experts, and academics, that aspects of the technologies, regulatory institutions, and industry business models in electricity have become obsolete and in some ways have become obstacles to achieving the vision we have articulated. In this report, we propose a holistic framework for reflecting on and analyzing the current changes in our technologies, economies, and expectations and for articulating the dimensions of this vision. We also suggest some actionable steps that policy actors can take to address institutional obsolescence and make this vision of a dynamic, clean, prosperous future a reality.

We see a different path ahead. This framework is based on a vision of the future that is a state change from where we are today. But that future requires changing policy, regulation, and culture. We recognize this will not occur overnight, but we also are encouraged by the many examples where technological change and market transformations can come more quickly than we sometimes think possible. We believe this may prove the case with power systems. Toward that end, we offer this framework to inform the vision outlined in this report.

The framework seeks both rapid and longer-run change that can transform the industry and its regulation, leading to greater energy abundance. We believe this involves enabling systems that encourage a greater diversity of capital, customer solutions, and open-access models to both physical and digital infrastructures. Fundamentally, these changes will allow customers to organize their energy

Table 2. Characteristics of the Framework Components

Digitalized	• Data rich • Automated • Visible and accessible platforms
Decentralized	• Local • Small • Resilient • Coordinated across scales • Allows multidirectional flows
Democratized	• Participatory • Open • Community led • Encourages and leverages private and community investments • Encompasses multilateral economic activity
Dependable	• Reliable • Resilient • Understood
Decarbonized	• Clean • Abundant • Supply responsive • Allows flexible loads
Just	• Equal • Priced fairly • Open • Vigilant • Accountable

Source: Authors.

technologies and transactions in the most effective ways to meet their needs.

This process involves applying and operationalizing several key and essential systems theory concepts: layered systems, loose coupling, and interoperability. Layered systems organize the grid by function for easier management. Loose coupling allows components to operate independently. Interoperability ensures different technologies work together, even if from different manufacturers. These principles make the grid more adaptable and dependable.

Some of the proposals may seem radical, but we see them as inevitable outcomes that are entirely consistent with the economic theory underlying this vision. Technological innovation and entrepreneurship are key to bringing transformative change to the grid, and in this action plan, we outline the different opportunities for various actors to move forward immediately.

We need to move away from centrally controlled, top-down, supply-focused approaches that have worked well in the past but now stand in the way of a more distributed, flexible, diverse, and inclusive energy system. Some utilities and policy actors in some regions have moved away from the vertically integrated, regulated utility model, and some functions and technologies are better operated with a centralized yet layered perspective (e.g., transmission). No single prescription can be applied across every jurisdiction, but in each case, opportunities to implement the offered framework can be seen as aligning with strategic principles that

1. Encourage collaboration,
2. Reduce barriers from legacy systems,
3. Accelerate deployment of new technology, and
4. Foster innovation and transformation.

A New Framework

The framework encompasses six broad dimensions: digitalized, decentralized, democratic, dependable, decarbonized, and just energy systems. Table 2 summarizes the key characteristics of these dimensions, developed in Chapter II.

At an architectural level, we see the grid as transforming into an open platform that allows multidirectional power flows and multilateral economic transactions. These new models incorporate elements that reorganize the consumer value propositions, the structural changes to regulatory models and the boundaries of the firms involved, and the fundamental architecture of the grid from a unidirectional distribution system to a multidimensional platform.

In this context, we recognize that regulatory models and conceptions of the regulated utility are also intimately tied to foundational concepts of democracy, justice, and community. These concepts all have deep roots in our society, dating back in many cases to classical origins.

Implementation

All actors have opportunities to move toward the vision with "no regrets" early actions, where there are obvious and immediate benefits that can be realized. Understanding where any jurisdiction or authority resides along a simplified market model is valuable. The framework we propose describes a simple pathway with six parallel, but heavily overlapping, lanes of activity leading toward a final state outlined in the overall vision. We see these actions as well suited to support technology innovation, environmental outcomes, increased equity, and enhanced resilience (especially in the face of increasingly disruptive climate, weather, and geopolitical events).

Expecting immediate change is unrealistic; many aspects of the current system may feel permanent and unable to evolve. We challenge ourselves to question these assumptions. It is valuable to characterize the path ahead into three broad phases:

1. **Early Action.** Early actions include holding meetings to establish a vision, creating "no regrets" incentives for early adoption, articulating capabilities and requirements, and establishing new leadership roles.

2. **Accelerating Transformation**. The next phase accelerates transformation through aligned action, community and industry engagement, and increased agency funding.

3. **End-State Transformation.** The final transformation reflects this report's vision statement.

Figure 22 visualizes this progression from the status quo through the phases of change for each dimension.

Categories of Action

Recommended actions include

- Encouraging collaboration,

- Reducing existing barriers,

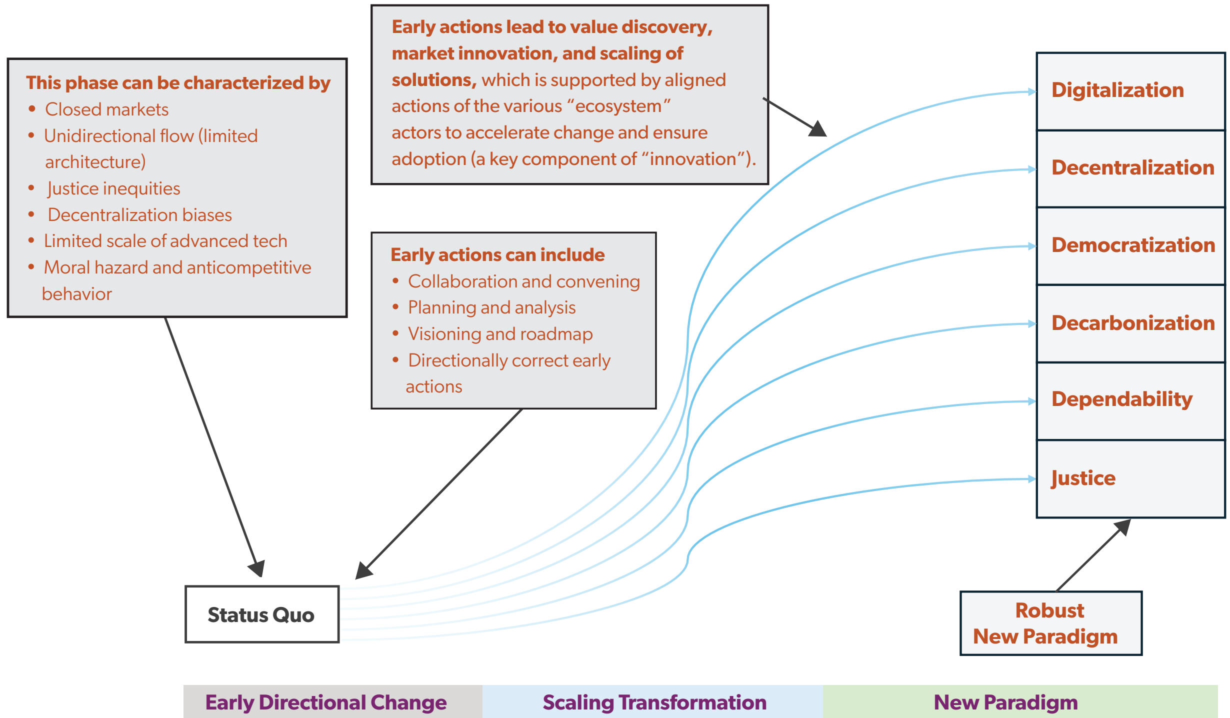
- Accelerating deployment of new technology, and

- Fostering innovation and transformation.

Building from these guiding principles, potential actions can be organized along a continuum to include a wide range of potential next steps. As noted earlier, while few prescriptive strategies work in all cases, there are also opportunities for each class of policy actors (executives, legislatures, regulators, agencies, and other stakeholders) to begin to implement aspects of this framework.

A variety of approaches might be appropriate for states. Typically, these actions will benefit from a clearly designated role that has or is granted sufficient authority to convene parties and implement policy and market changes. For example, having a state energy office convene a standing, official working group on emerging electricity technologies and their opportunities would be a powerful strategy to drive the implementation of the outlined vision, if a state isn't already doing so. It might also include establishing a new office focused on deployment or creating an executive-level officer or "czar" for the state. Working groups can serve as dynamic platforms for interdisciplinary collaboration, bringing together experts from state agencies, industry, academia, and community

Figure 22. Annotated Grid Transformation Journey



Source: Authors.

organizations to continuously assess and guide the state's energy transition.

In all cases, identifying the near-term, achievable objectives that align with long-term, strategic outcomes is important. Ensuring that the first steps taken are aligned with a comprehensive vision of an energy system that is resilient, supports open access, and recognizes the value of robust data sharing among all parties will be critical to implement the larger framework.

To be clear, and as we've highlighted, nothing is simple. Institutional rigidity and entrenched incumbents will work to subvert change. Leadership and imagination will be required. Nevertheless, we believe there are actions available to operationalize the framework in the six dimensions outlined, accelerating innovation and opening pathways for a new energy ecosystem that is centered on consumers and capable of addressing the pressing challenges we face.

The implementation plan provides a roadmap for each actor to contribute effectively to a clean and prosperous energy future. By taking these recommended actions, state and federal entities can collaborate to remove barriers to innovation, empower consumers, and ensure that power systems become more digitized, decentralized, democratized, decarbonized, dependable, and just. While some actions can be taken quickly and with relative ease, others will require sustained effort and structural changes. All are crucial for achieving the holistic transformation envisioned in this framework.

Moving Forward

In nearly all cases, convening political, industry, intellectual, and community leaders in established task forces, innovation centers, and working groups can be one of the most valuable ways to begin to identify the barriers and potential pathways for the following topics, among others:

- Energy transition goals and strategies
- Open-access and distribution system operator models
- Grid architecture including bidirectional flow
- Market-based rates
- Performance-based rates
- Modeling and economics (including the value of lost load)
- Data access and privacy
- Interoperability and standardization

Example Actions

Digitalization

- Promote grid modernization, including deploying sensors and controls and advanced metering infrastructure, to allow real-time access to consumer information, resource performance, and grid conditions.
- Enable demand-side management through digital platforms, including creating data platforms, exchanges, and warehouses.
- Encourage integration of digital technology and distributed energy resources, expanding on orders like FERC Order 2222.
- Ensure that enabling technologies are deployed and digital platforms such as advanced meters and demand response are fully used.
- Seek to encourage, accelerate, and fund investments in advanced technologies, including sensor automation and controls.

Decentralization

- Create market incentives to reward demand flexibility, including demand-response and time-based rates that correlate with actual operating conditions.
- Support deployment and adoption of distributed energy resources and microgrids to create rebates and tax incentives for accelerated adoption.
- Pursue interconnection reform and standardization.
- Promote community energy resources for efficiency upgrades to reduce peak demand and emissions.
- Deploy microgrids and supplemental utility services.
- Develop markets for grid services.
- Fund research and development.
- Integrate distributed energy into integrated resource plans and distribution system plans.
- Enable community solar, load flexibility, virtual power plants, microgrids, demand aggregation, and supplemental utility service.

Democratization

- Establish direct access to energy markets.
- Develop distribution-level markets for grid services and distributed energy aggregations.
- Ensure fair access to grid infrastructure.
- Expand fair value for exports in tariffs and net metering.
- Enable community solar and microgrids.

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- Encourage new market entrants, including local co-ops and third-party service providers.
- Accelerate community solar panels and virtual power plants and load flexibility.
- Introduce open-market models, competition, and transparency.
- Balance freedom and accountability in energy technology.

Dependability

- Invest in grid hardening and cybersecurity.
- Encourage incentives for customer solutions such as energy storage and batteries.
- Accelerate sophisticated backup power and resilience solutions that leverage fair export rates to attract private capital.
- Establish resilience performance metrics.
- Prioritize critical facilities.
- Establish formal resilience planning procedures and requirements.
- Reduce barriers to resilience solutions that can only come from distributed energy (mostly owned by consumers, not the grid operator).

Decarbonization

- Establish clean-energy requirements and legislation.
- Create markets for carbon pricing.
- Fund technology development, commercialization, and research and development.

Justice

- Enact specific requirements and considerations for distributive, procedural, universal, and commutative justice.
- Ensure distributed energy is widely accessible.
- Enable access to decision-making.
- Protect vulnerable communities from harm.
- Support low-income adoption of new technologies.
- Establish consumer and disconnection protections.

For example, industry representatives could provide insights on the latest innovations, while academic experts could offer research-driven analysis on potential impacts and benefits. Including community organizations in the working group would help ensure that the benefits of new technologies are equitably distributed and that the voices of all communities are heard. The working groups could produce regular reports and recommendations for the broad range of potential actions, offering strategic guidance on how best to leverage emerging technologies. This guidance would include identifying priority areas for investment, proposing new regulatory frameworks, and suggesting legislative changes needed to support innovation.

And, in nearly all cases, it will be critical to establish credible and reliable models of governance and oversight that limit the political influence of incumbent parties and introduce the competitive discipline of open markets (which has always been a foundational goal of regulation). By focusing on these areas, federal, state, and other leaders can translate the vision of a decentralized, digitalized, and democratized electricity system into reality, driving progress toward a more dependable, decarbonized, and just energy future. This process will require close collaboration with industry stakeholders, policymakers, and communities to ensure these efforts are inclusive and effective.

We are at a pivotal moment when reconsidering the possibilities that lie ahead is essential—technologically, economically, and culturally. This rethinking must encompass not only desirable outcomes but also necessary actions to ensure systems function productively for all participants. The lines between individual- and system-level actions are increasingly blurred, as technologies enable more tasks to be performed individually that once required collective efforts. We must also reassess which aspects of our technological, regulatory, and business models are obsolete and why they no longer serve us.

This process involves a clear understanding of the costs and benefits of both inaction and change, along with a critical examination of the assumptions that underpin our mindsets, analytical approaches, modeling techniques, and institutional designs. This deep reflection and adaptation are crucial for the continued evolution of power systems and the structures that support them.

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