U.S. DEPARTMENT OF
ENERGY

Pathways to Commercial Liftoff: **Innovative Grid Deployment**

APRIL | 2024

Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff Report. Please direct all inquiries and input to liftoff@hq.doe.gov. Input and feedback should not include business sensitive information, trade secrets, proprietary, or otherwise confidential information. Please note that input and feedback provided is subject to the Freedom of Information Act.

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Acknowledgements

Cross-cutting Department of Energy leadership for the Pathways to Commercial Liftoff effort:

Under Secretary for Infrastructure: David Crane

Under Secretary for Science and Innovation: Dr. Geraldine Richmond

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Office of Energy Justice and Equity: Dr. Shalanda Baker

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Acknowledgements *(continued)*

Department of Energy advisory and support for the Innovative Grid Deployment Liftoff report:

Office of Technology Transitions: Julius Goldberg-Lewis, Isabella Ragazzi, Katheryn Scott

Grid Deployment Office: Nina Peluso, Elizabeth O'Connell

Office of Clean Energy Demonstrations: Dr. Theresa Christian

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Loan Programs Office: Jen Downing, Adam Wallen, Yonatan Abebe, Anastasia Shylnov, Amy Peterson, Elizabeth Perera

Office of Policy: Ryan Wiser, Dr. Nicholas Johnson, Betony Jones, Zoe Lipman

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Analytical support provided by Guidehouse.

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Preface

Purpose of Liftoff Reports

Liftoff reports describe the market opportunity, current challenges, and potential solutions for the commercialization of a portfolio of technologies to serve society's energy needs. Liftoff reports are an ongoing Department of Energy (DOE) led effort to engage directly with energy communities and the private sector across the entire clean energy landscape. Their goal is to catalyze rapid and coordinated action across the full technology ecosystem. Reports will be updated regularly as living documents and are based on best-available information at the time of publication. For more information, see liftoff.energy.gov.

Scope of the Innovative Grid Deployment Liftoff report

This *Innovative Grid Deployment* Liftoff report is focused on identifying pathways to accelerate the near-term (3-5 years) deployment of key commercially available but underutilized advanced grid technologies and applications on existing rights-of-way transmission and distribution systems. This scope was developed based on the need for greater deployment of available solutions that can quickly respond to accelerating grid pressures, including the need to cost-effectively expand transmission and distribution capacity to support demand growth, enhance system reliability and resilience, and support integration of utility-scale and distributed clean energy resources. This Liftoff report is focused on achieving substantially greater capacity and value within the existing transmission and distribution system and does not detract from the DOE's multi-layered and parallel efforts to expand the grid. The Liftoff focus is a reflection that the issues pertinent to scaling these advanced grid technologies and applications are meaningfully different from the priorities of grid expansion and thus merit their own focus.

The advanced grid technologies and applications in scope (referred to as "advanced grid solutions" throughout this report for simplicity) are summarized in Table 1 below.

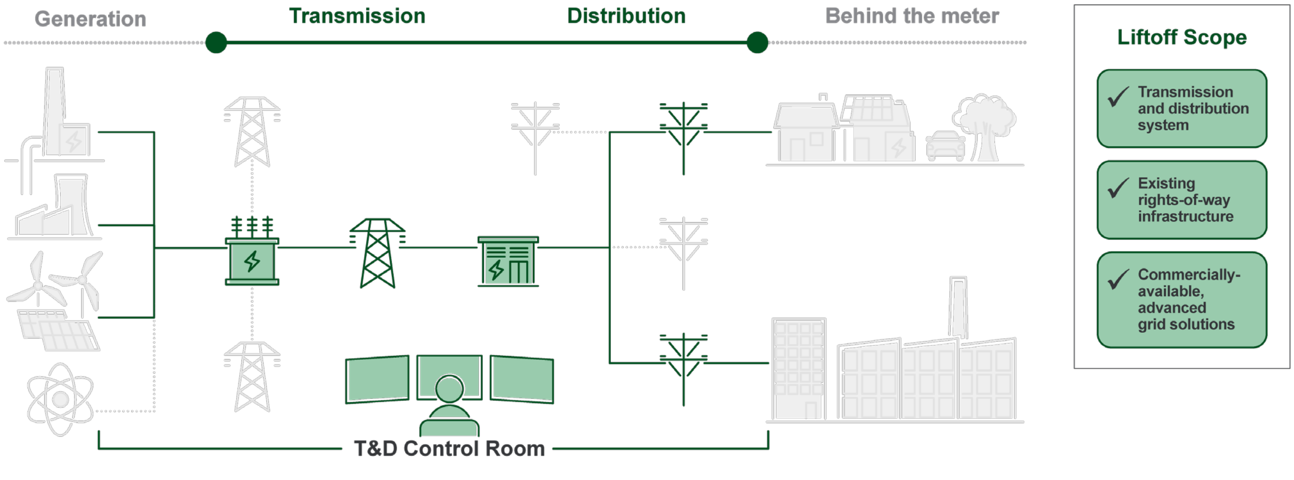


Figure 1. Summary of Innovative Grid Deployment Liftoff Report Scope

Note: Important future grid technologies currently in pre-commercial stages, deployment challenges associated with new rights-of-way (e.g., permitting and siting), and applications specific to generation and behind-the-meter resources are not addressed in this effort.

Table 1. Summary of advanced grid technologies and applications ("advanced grid solutions") in report scope

Category	Advanced Grid Solutions
Advanced Transmission Technologies	Advanced Conductors Point-to-point High Voltage Direct Current (HVDC)
Situational Awareness and System Automation Solutions	Advanced Distribution Management Systems (ADMS) and ADMS applications Distributed Energy Resource Management System (DERMS) Advanced Fault Location, Isolation, Service Restoration (FLISR) Volt/VAR Optimization (VVO) Smart Reclosers Power Factor Corrections Substation Automation & Digitization Advanced Sensors
Grid-Enhancing Technologies and Applications	Dynamic Line Rating (DLR) Advanced Power Flow Control (APFC) Topology Optimization Virtual Power Plants (VPPs)[1] Energy Storage (as a T&D asset)[2] Advanced Flexible Transformers
Foundational Systems	Communications Technologies Data Management Systems System Digitization and Visualization Alternate Timing and Synchronization

Note: This list is not exhaustive of all important grid solutions. Technologies were identified and prioritized based on commercial readiness but are not comprehensive of all DOE transmission and distribution grid priorities (i.e., technologies not commercially available today are not included).

Recognizing the imperative to expand and advance grid modernization in the near term, DOE has dozens of initiatives and funding programs to support the electric industry across grid research, development, demonstration, and deployment, including technology, regulatory, policy, and commercialization support. This Liftoff report is one part of this broader suite of DOE efforts[3] and is specifically focused on accelerating deployment of commercially available and underutilized advanced grid solutions that can address near-term hotspots and modernize the grid to prepare for a wide range of energy futures. The aim is to catalyze and organize a dialogue around the path to liftoff.

See Appendix A for additional information on DOE deployment-focused funding and technical assistance opportunities and Appendix B for an overview of several DOE grid programs.

1 See the Pathways to Commercial Liftoff: Virtual Power Plants (2023) report for a deeper dive on VPPs.

2 The focus in this report is on energy storage used as a transmission and distribution (T&D) asset to defer or offset T&D capacity expansion, support peak load management, and/or provide other grid services to enhance system resilience and reliability. For additional information on this and other storage use cases, see the Pathways to Commercial Liftoff: Long Duration Energy Storage (2023) report.

3 This commercial deployment focus is supported by DOE's history of sustained investments into the research and development of grid technologies. For example, DOE made early investments to develop dynamic line rating in 2010. See the DOE's Grid Modernization Initiative for more information on research and development efforts.

Executive Summary

Deploying the advanced grid solutions[4] available today could cost effectively increase the capacity of the existing grid to support 20-100 GW of incremental peak demand when installed individually, while improving grid reliability, resilience, and affordability. The grid[5] is becoming a bottleneck to greater economic development, decarbonization, and equity priorities. Customers are demanding more grid capacity as regional electricity demand grows substantially for the first time in decades to serve a rapid uptick in data center and manufacturing needs and broader end-use electrification. At the same time, heightened threats and increased dependence on electricity increase the importance of reliability and resilience of existing and new grid infrastructure. The existing transmission and distribution system has untapped potential to help meet these challenges, which can be unlocked with a set of available technologies that are dramatically under-deployed relative to their potential value. These technologies can help serve as a bridge to address near-term capacity needs as critically needed new transmission, distribution, and generation is built out, while supporting grid reliability, resilience, and affordability. Grid operators[6] and regulators should consider a new growth-oriented and proactive grid investment strategy to capture the value of these advanced technologies to meet customer needs within a changing energy future.

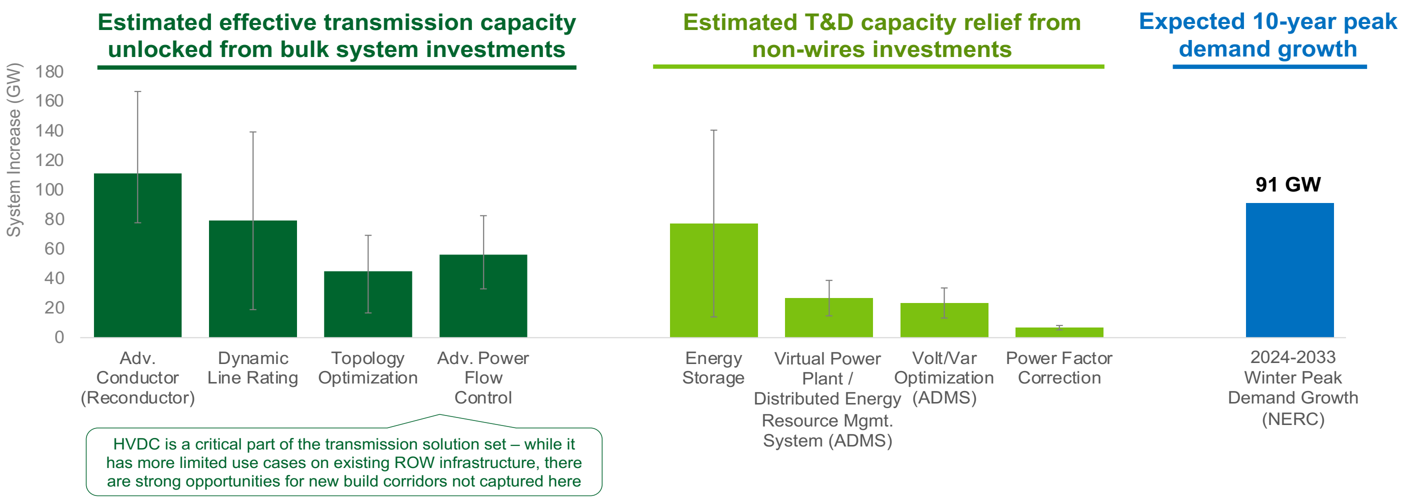


Figure 2. Estimated transmission and distribution (T&D) capacity impact from full potential deployment[7]

Multiple advanced technologies and applications are commercially available today that grid operators and regulators can use to help address near-term hotspots and modernize the grid to prepare for a wide range of energy futures. These technologies and applications (referred to as "advanced grid solutions" throughout this report) include four categories that apply across the transmission and distribution system: a) *advanced transmission technologies* that expand firm line capacity, b) *situational awareness and system automation* solutions that improve visibility and decision-making, c) *grid-enhancing technologies (GETs) and applications* that improve system utilization and performance, and d) the *foundational systems* necessary to enable advanced technologies and a modern grid.

4 "Advanced grid solutions" is used throughout this report to refer to the twenty advanced grid technologies and applications in scope, as summarized in the Preface.

5 Throughout this report, the term "grid" is used to refer specifically to transmission and distribution (T&D) infrastructure (not bulk power generation or behind-the-meter assets) unless otherwise noted.

6 "Grid operators" is used throughout this report to refer to utilities that own and/or operate transmission and distribution systems (including investor, municipally, and cooperatively owned utilities), transmission system operators (e.g., Regional Transmission Operators, Independent System Operators), and merchant transmission and distribution companies.

7 Represents estimated full potential of deploying grid solutions at scale in technically and economically feasible locations overnight on the existing grid as of 2023. See footnote 33 for detail."

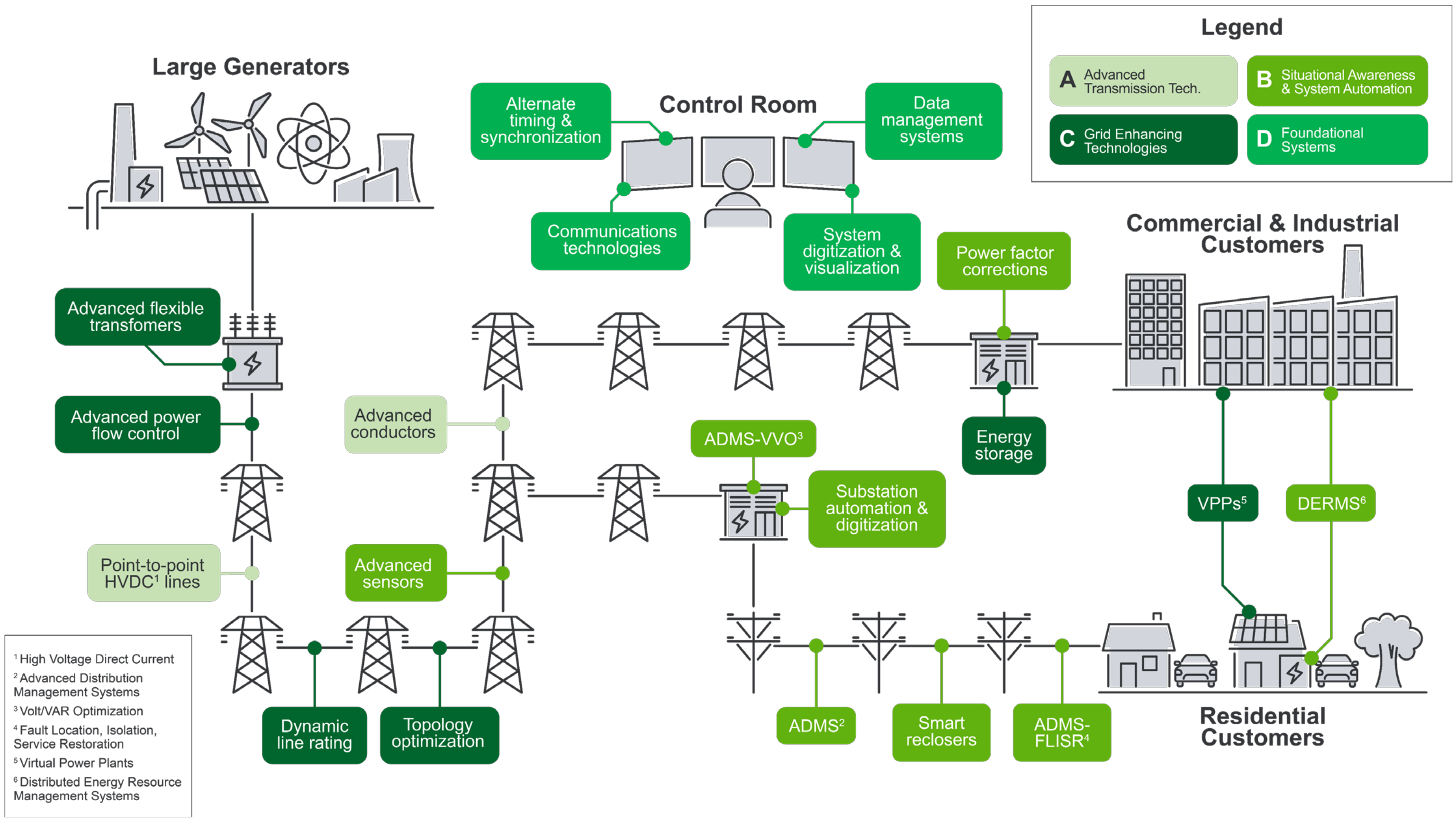


Figure 3. Overview of advanced technologies and applications in Liftoff scope (illustrative)

Collectively, these technologies—if deployed at scale—can provide a step change in grid operators' ability to efficiently and effectively manage the grid. Grid operators can deploy these solutions in a variety of strategic combinations to address local needs; no one single solution will suffice. A strategic, long-term (e.g., 10-15+ years) investment approach is necessary to realize the optimized benefits between many of these technologies and to determine today's foundational infrastructure investments that can fully unlock the benefits of future technology deployments.

Advanced Grid Solutions			T&D capacity impact	Affordability	Reliability	Resilience	Sustainability
Advanced Transmission Technologies	Advanced Conductors		Primary	Significant	Significant	Significant	Significant
	Point-to-Point HVDC systems		Primary	Significant	Significant	Primary	Significant
Situational Awareness and System Automation Solutions	Advanced Sensors		Low	Significant	Primary	Significant	Significant
	Power Factor Correction		Significant	Primary	Significant	Moderate	Significant
	Smart Reclosers		Low	Low	Primary	Significant	Low
	Substation Automation & Digitization		Low	Low	Significant	Primary	Low
	ADMS	*Base ADMS (*D-SCADA, OMS)	Low	Moderate	Significant	Significant	Moderate
	ADMS	*System efficiency:* VVO	Primary	Primary	Moderate	Moderate	Primary
	ADMS	*DER integration:* DERMS	Primary	Low	Moderate	Moderate	Primary
	ADMS	*Reliability*: FLISR	Low	Moderate	Primary	Primary	Low
Grid Enhancing Technologies and Applications	Dynamic Line Ratings (DLR)		Primary	Primary	Significant	Moderate	Significant
	Adv. Power Flow Control (PFC)		Primary	Primary	Significant	Moderate	Significant
	Topology Optimization		Primary	Primary	Primary	Significant	Significant
	Energy Storage		Primary	Significant	Primary	Primary	Significant
	Advanced Flexible Transformers		Low	Moderate	Primary	Moderate	Moderate
	Virtual Power Plants (VPPs)		Primary	Significant	Moderate	Moderate	Significant

Low	Moderate	Significant	Primary
Indirect, limited impact	Direct, moderate impact	Direct, operationally significant impact	Direct, primary impact

Note: Foundational technologies are excluded since they have limited direct impact on outcomes. Benefits representative of relative impact for a specific technology (within each row) and not for comparison between technologies (between rows).

Figure 4. Advanced grid solutions' value proposition for key grid outcomes

Most of these solutions could be deployed on the existing grid in under three to five years and are lower cost, greater value, or both when compared to conventional technologies or approaches. For example, dynamic line rating (DLR) can be scaled in fewer than three months after initial implementation to increase effective transmission capacity by an average of 10-30% at less than five percent of the cost of rebuilding the line to expand capacity. The applicability of these technologies varies based on local climates, operating contexts, and grid objectives. In some situations, deployment of advanced grid solutions can replace or indefinitely defer traditional grid investments; in others, these technologies serve as a "bridge to wires", allowing better alignment between near-term customer needs and the cadence of grid capital planning. Several example use cases are developed in this report to illustrate this nuance (see Chapter 3).

These advanced grid solutions are already being used today to drive system benefits. Many utilities—from large investor-owned utilities (IOUs) to small co-ops—are investing in and relying on these solutions for day-to-day grid operations. Adoption to date has largely been driven by policy or regulatory mandates, reactions to external pressures (e.g., wildfire risk, distributed energy resource adoption), or individual technology champions.

Yet deployment at scale is lagging across the United States. Traditional cost-of-service IOU business models have not sufficiently incentivized these solutions to warrant the significant upfront planning, engineering, operational, and organizational effort required to deploy advanced technologies at scale. For smaller municipal utilities and electric cooperatives in particular, the upfront cost and organizational resources necessary to drive effective investment can be a particular challenge.

Liftoff will be achieved when utilities and regulators comprehensively value and integrate advanced solutions as part of core grid investment, planning, and operations. When these technologies are fairly evaluated and compensated—alongside the conventional options used today—utilities and regulators can ensure the most efficient and effective solution is used to meet customer needs.

Achieving liftoff within three to five years is possible by deploying 6-12 large operational, no regrets deployments across a diverse set of utility contexts for each advanced grid technology—deployed individually or in combination. Four priorities should be simultaneously addressed during these deployments to derisk and drive adoption at scale.

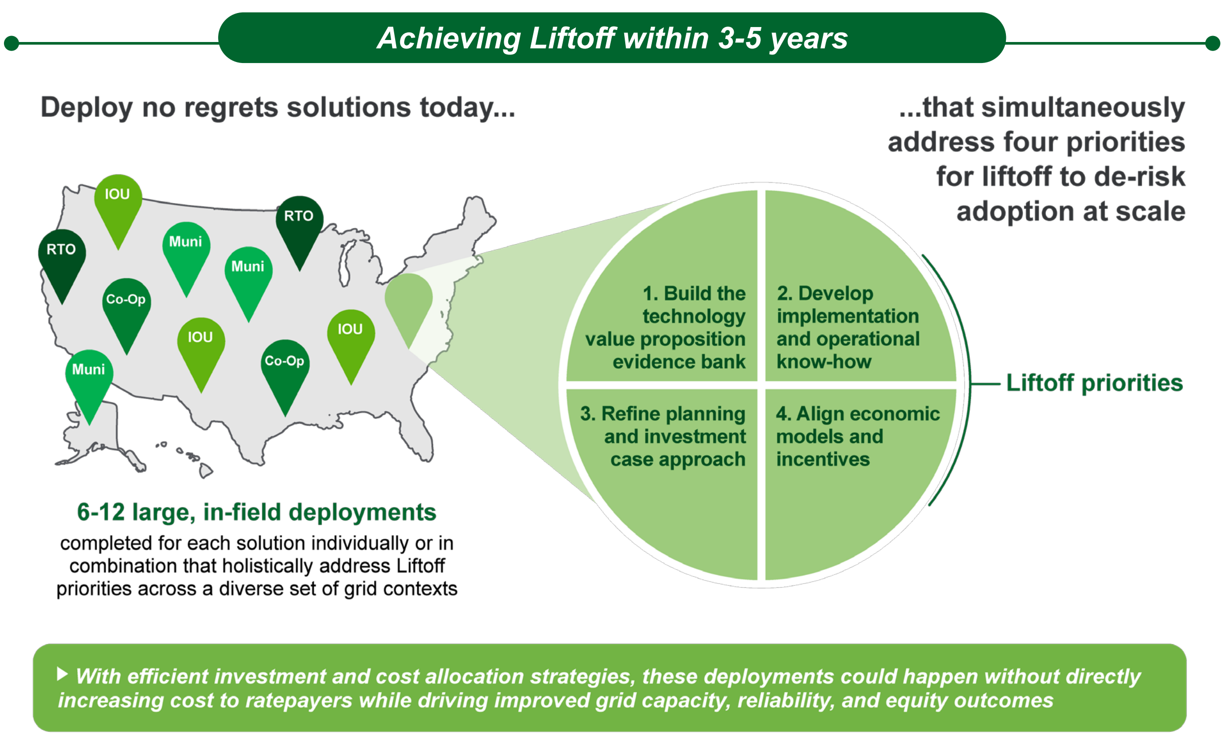


Figure 5. Achieving liftoff for advanced grid technologies and applications

1. **Build and share the bank of industry evidence for the technology value proposition:** Building widespread understanding and confidence in advanced technologies as viable alternatives to conventional solutions is critical to ensuring broader acceptance among utilities and regulators in core grid processes. Outcomes from these deployments should be transparently shared across industry players and regulators—including lessons learned from successes *and* failures—to build industry familiarity and confidence in these technologies' capabilities, operational impacts, and value propositions.

2. **Develop implementation and operational know-how:** Grid operators need to know how to procure, install, operate, and maintain advanced technologies. Key processes underpinning deployment at a greater scale include standardized and interoperable technical specifications, installation and inspection checklists, workforce partnerships and training, and operational guidance and best practices. Utility peer-sharing reduces information asymmetry between jurisdictions and service territories and accelerates overall uptake by reducing barriers to adoption.

3. **Refine planning and investment case approaches:** During system planning, grid operators must be able to effectively evaluate and prioritize advanced technology solutions for investment (including against conventional alternatives). To prudently oversee utility proposals, regulators need to have visibility into and understand the cost-effectiveness of these technologies and how they should be strategically pursued. This requires a robust understanding of and methods for comprehensively evaluating the benefits and costs of these technologies, including benefits that are expected to occur but may be hard to value in traditional frameworks.

4. **Align economic models and incentives:** Grid operators and utilities are looking for certainty on how solutions will be paid for and, for profit-motivated operators, if they can generate sufficient financial returns to warrant investment. For regulated utilities, incentivizing adoption requires that regulators lead in aligning utility compensation models with the value generated from advanced grid solutions (e.g., performance-based regulation, capitalizing some operational expenses). New mechanisms can help allocate costs in ways that better align with beneficiaries and equitably share benefits, such as shared savings mechanisms.

All four priorities are essential pillars of success. Learnings from each step should inform each other, which necessitates collaboration across industry stakeholders to address these priorities.

Addressing these four priorities and transparently sharing the outcomes through 6–12 deployments can de-risk and help build repeatable operational and investment models for technology adoption at scale. This can help overcome the perpetual piloting that new grid technologies are often stuck in across utilities today. The individual technologies covered in this report are at different stages of progress across these liftoff priorities, so resources should focus on closing outstanding gaps. The DOE is already investing in supporting advanced technology deployments through programs like the Grid Resilience & Innovation Partnerships (GRIP) program. Beyond technology deployments, additional resources—from the DOE and other grid stakeholders—for technical assistance and capacity building can advance industry execution know how, more robust planning and investment case approaches, and economic model innovation.

Through more efficient and equitable investment approaches, grid operators and regulators can start deploying these advanced grid solutions without increasing costs for residential ratepayers. For example, using just one-fifth of the current conventional asset replacement investments to proactively upgrade assets with advanced grid solutions would double industry-wide investment in advanced solutions while improving grid capacity and reliability outcomes without adding costs to ratepayers.[8] This represents an important opportunity to bring in new sources of capital by leveraging existing investments more efficiently and pursuing innovative cost allocation strategies. All utilities, states, and regions can begin developing

8 Data is based on Edison Electric Institute's (EEI) transmission and distribution capital expenditure data ($26B spent on conventional transmission and distribution replacement and $5.8B on advanced transmission and distribution technologies in 2023). See footnote 41 for additional detail.

proactive, forward-looking grid modernization strategies to enable better prioritization of and investment in the grid solutions that can best serve customers amidst a changing energy future.

Utilities, regulators, policymakers, solutions providers, and other key stakeholders can start acting today—taking advantage of unprecedented federal investment and policy incentives—to accelerate deployment of advanced grid solutions that unlock meaningful near-term value and long-term compounding benefits.

Table 2. Example priority actions by stakeholder (not exhaustive)
(See Chapter 4 for additional priority actions and discussion for other key stakeholders)

Stakeholders	Potential priority actions to pursue today	
Grid operators *(IOUs, co-ops, public power, RTO/ISOs)*	• Deploy no regrets solutions to address grid hotspots and support liftoff • Transparently share deployment outcomes and best practices • Develop modernization strategies using emerging best practices	***Leverage federal funding opportunities***
Regulators and governance boards *(PUCs, FERC, City Councils, Co-op boards, Tribal authorities)*	• Revamp grid modernization strategies and planning processes by adopting current best practices • Require grid operators to consider advanced grid solutions in current planning and asset replacement processes • Align utility incentive structures with the value of advanced grid solutions (for regulated utilities) • Develop appropriate cost recovery mechanisms	
Policymakers *(federal and state legislators, governors, state energy offices)*	• Collaborate with regulators to ensure advanced solutions are considered in current processes • Establish clear policy goals to inform grid investments • Coordinate multi-stakeholder collaborations that accelerate equitable grid modernization	
Solutions Providers *(technology providers, engineering firms, consultants)*	• Proactively articulate and value technology benefits • Share performance risk for proven but sub-scale solutions • Integrate advanced grid solutions into core services (planning model platforms, engineering projects)	
DOE *(HQ, National Labs)*	• Support large operational deployments and the sharing of performance data and best practices • Explore opportunities to collaborate with external stakeholders on a publicly available and easily accessible library of advanced grid solutions • Expand technical assistance resources to support planning and investment approaches and regulatory innovation • Encourage and/or require applicants to incorporate advanced grid solutions in DOE funding programs	
Additional potential actions for other key stakeholder groups—including trade and labor organizations, communities and intervenors—are discussed in Chapter 4		

This report highlights the near-term opportunity to unlock untapped grid capacity opportunities and progress modernization priorities with available advanced grid solutions on existing infrastructure. It is meant to inform and advance partnerships between DOE, other public sector stakeholders, and the private sector to accelerate near-term investment in these grid technologies and applications. Sustained action will be required to simultaneously scale up the adoption of commercially available advanced grid solutions, build new grid infrastructure, and deploy next-generation grid technologies.

Glossary

AAR	Ambient adjusted rating
ADMS	Advanced Distribution Management System
AFL-CIO	American Federation of Labor and Congress of Industrial Organizations
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
APFC	Advanced Power Flow Control
ATS	Alternative Timing and Synchronization
BA	Balancing Authority
BCA	Benefit-Cost Assessment
CAIDI	Customer Average Interruption Duration Index
CAPEX	Capital Expenditures
CMI	Customer Minutes Interrupted
DA	Distribution Automation
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DLR	Dynamic Line Rating
DOE	U.S. Department of Energy
EEI	Edison Electric Institute
EPC	Engineering, Procurement, and Construction
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
FLISR	Fault Location, Isolation, and Service Restoration
GDO	DOE Grid Deployment Office
GET	Grid-Enhancing Technology
GRIP	Grid Resilience and Innovation Partnerships Program
GW	Gigawatts
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IBEW	International Brotherhood of Electrical Workers
IBR	Inverter-Based Resource
IDSP	Integrated Distribution System Plan
ISO	Independent System Operator
IOU	Investor-Owned Utility
IT/OT	Informational technology/operational technology
MW	Megawatts
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Offices
NERC	North American Electric Reliability Corporation
NTO	Network Topology Optimization
OPEX	Operating Expenditures
PBR	Performance-Based Regulation
PUC	Public Utilities Commission
PSC	Public Service Commission
ROW	Rights-of-Way
RTO	Regional Transmission Organization
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
T&D	Transmission and Distribution
VPP	Virtual Power Plant
VSC	Voltage Source Converter
VVO	Volt/VAR Optimization

Chapter 1: Overview and Value Proposition

Key takeaways

- The North American Electric Reliability Corporation (NERC) projects electricity peak demand to grow an estimated 91 GW over the next decade, which is equivalent to 12% of current U.S. peak demand.[9] A path consistent with achieving net-zero emissions economy-wide by 2050 would require even greater peak demand growth from electrification and domestic manufacturing.
- With electricity demand growing significantly for the first time in decades, grid operators and regulators are faced with the need to pursue a new, growth-oriented grid investment strategy.
- Twenty advanced technologies and applications are available today that can be deployed across the transmission and distribution grid to help respond to near-term pressures while modernizing the system for a range of energy futures.
- Deploying these technologies overnight could increase the capacity of the existing grid to support 20-100 GW of incremental peak demand when installed individually, with significant additional capacity potential when installed in strategic combinations. This could help defer an estimated $5-35B in transmission and distribution infrastructure costs over the next five years.
- Many of these solutions can be deployed within three to five years on the existing system and at a lower cost than conventional technologies, providing a bridge to address near-term capacity needs while critical new transmission capacity is developed in parallel.
- Properly designed, implemented, and regulated deployments of advanced grid solutions can advance equity and energy justice by improving the affordability and reliability of the grid in disadvantaged communities, reducing system-wide emissions, and enhancing system visibility to improve measurement of equity metrics and outcomes.

9 91 GW represents the winter peak demand growth expected from 2024-2033 from the North American Electric Reliability Corporation (NERC) forecast as of December 2023.

Section 1.a. Introduction

The mandate of the United States electric grid and of its operators is to provide safe, reliable, and affordable power to customers. Grid operators have always provided electric service based on customer need, extending and augmenting the electric grid if necessary to enable energy consumption and generation. While the need to modify the electric grid in response to customer demands is not new, recent changes in technology, policy, and customer behavior are placing significant pressures on the existing system. Customers are seeking to use and generate power in new ways, with new types of devices, in different physical locations, and with different temporal patterns. In some jurisdictions, certain changes are already widespread (for example, residential rooftop solar adoption at scale). Other shifts, such as electrification of medium- and heavy-duty vehicles, are in their nascence. Overall, grid operators expect that customers will seek to add nearly a hundred gigawatts of new load and hundreds of gigawatts of new generation resources to the grid within the next decade.[i] Meeting net zero emissions economy wide targets could increase this growth in electricity demand and generation and storage needs even further.[10,ii]

The U.S. transmission and distribution grid requires significant investment to address these accelerating trends and pressures. Safely managing and integrating additions of electric loads (e.g., electric

10 An NREL analysis shows that a 100%-by-2035 clean electricity future could require 2,000 GW of new generation capacity. Electric generating capacity is expected to grow more rapidly than peak demand, given the capacity factors and capacity contributions of new generation assets as well as the need to replace aging existing generating capacity.

vehicles, heat pumps), other distributed energy resources (e.g., energy storage, rooftop solar), industrial load (e.g., manufacturing, data centers), and renewable generation at the bulk scale requires a larger grid with greater capacity and more flexibility—by some estimates, the grid must double or even triple in capacity in order to accommodate these changes.[iii] As many of these new resources will be digital and inverter-based themselves, the grid must also become more data-rich and flexible to enable grid operators to accommodate these resources and ensure stability of power flowing through the grid.

Spending on new infrastructure and new capabilities is only one of several investment imperatives to modernize the grid. Grid operators must also pursue investments needed to maintain an aging asset base and to continue to provide reliable service in the face of increasing threats from severe weather events. Grid operators are being challenged today by their customers and their regulators with the need to simultaneously pursue investments that manage a more complex customer environment at the distribution level, provide greater reach and transfer capability at the bulk power level, and improve system resilience—and to do so quickly, at scale, equitably, and affordably.

The process of updating and maintaining the electric grid is continuous, and today represents nearly $170B of new capital investment on an annual basis (including generation).[iv] Yet much of this investment is focused on system maintenance, with grid operators performing like-for-like replacements or pursuing incremental updates to the thousands of individual assets that make up the electric grid. While utility spending is often targeted at minimizing risk of wasted spending, the sector now faces significant risk from *inaction*: without aggressive investment in near-term growth, customers will be unable to add the load and generation resources necessary to meet their needs and policy priorities.

As such, grid operators and regulators are faced with the need to pursue a new, growth-oriented investment strategy. To protect customers and serve their interests, grid operators can seek to maximize capital efficiency and serve multiple goals with the same investment, for example ensuring both greater resilience and greater capacity when replacing an aging asset at the end of its life. The technologies discussed below are key to this strategy and can enable grid operators to ensure the grid continues to be fit for purpose, serving the needs of customers now and into the future.

Section 1.b. Technology definitions

The advanced grid technologies and applications (referred to as "advanced grid solutions" throughout this report for simplicity) in scope work across the transmission and distribution system and control rooms to enhance and modernize the existing grid. The solutions in scope fall across four categories:

A. **Advanced transmission technologies** that can increase physical line capacity;

B. **Situational awareness and system automation solutions** that improve visibility of the existing grid and automate key processes;

C. **Grid-enhancing technologies (GETs) and applications** that better optimize and adaptively control a dynamic grid; and

D. **Foundational systems** that are necessary to deploy and use advanced grid solutions.

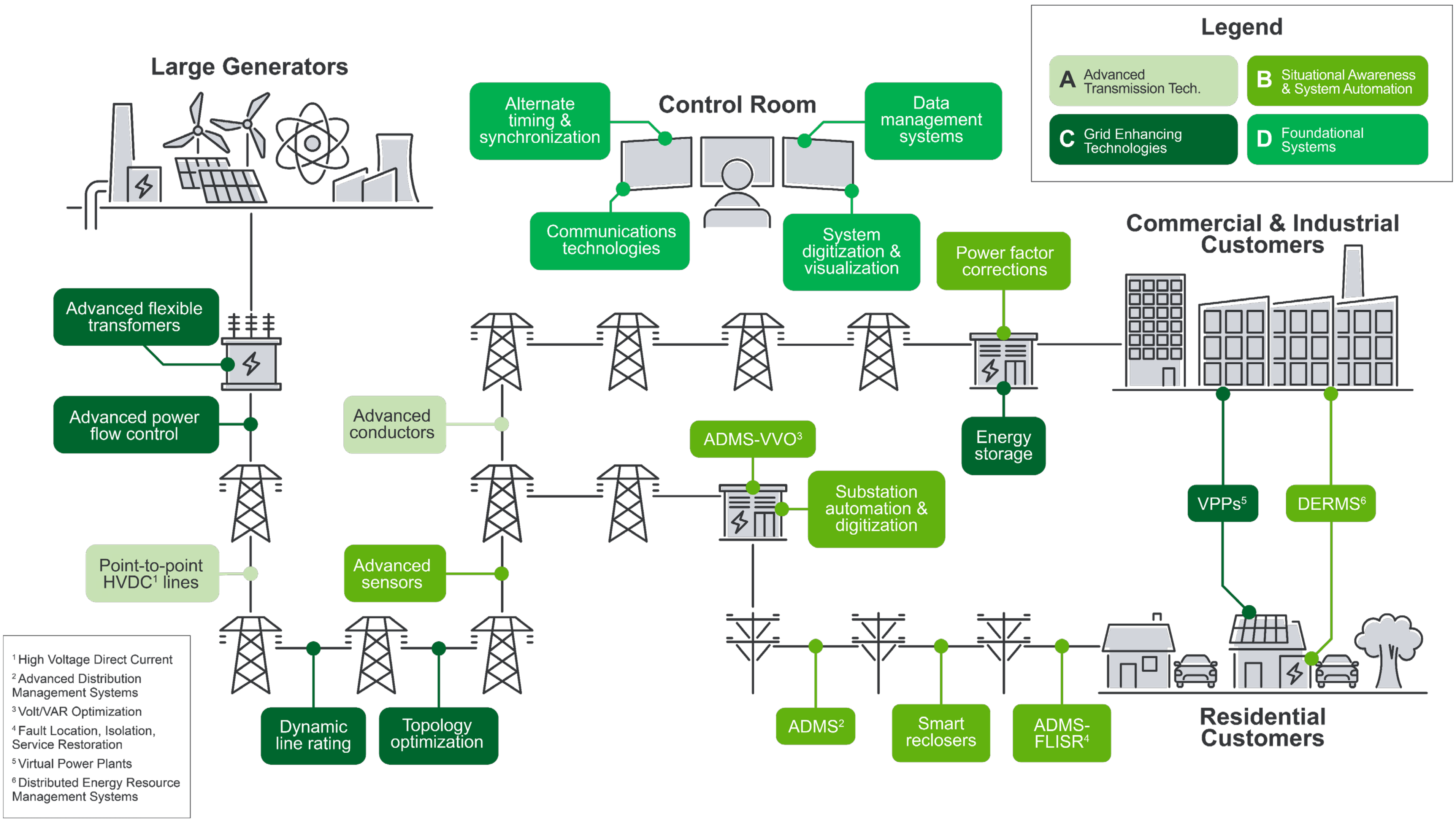


Figure 6. Illustrative overview of advanced technologies and applications in Liftoff scope

Table 3. Definitions of advanced grid solutions in Liftoff scope

Grid category		Advanced Grid Solution	Definition	T&D Use		Type	
				T	D	Hardw.	Softw.
Advanced Transmission Technologies		Advanced and Enhanced Conductors *(referred to as "advanced conductors" throughout report for simplicity)*	Conductors that increase line capacity by >1.5x (at a similar weight per foot); advanced conductors use composite core (instead of traditional steel cores) to improve efficiency and increase capacity with limited sag; enhanced steel core conductors have capacity and efficiency benefits, but reconductoring usability varies based on sag clearance requirements; *in Liftoff report, as "advanced conductors" includes both conductor types for reconductoring use cases on existing rights-of-way*	X	X*	X	
Advanced Transmission Technologies		Point-to-point High Voltage Direct Current (HVDC) systems	HVDC systems include efficient and high-capacity direct current (DC) transmission links and converter stations connecting the DC system to the larger alternating current (AC) grid.	X		X	X
Situational awareness and system automation		Advanced Sensors	Includes both physical sensors to detect environmental conditions and electrical sensors to detect system current (e.g. merging units, AMI 2.0), providing granular, real-time data on grid conditions.	X	X	X	
Situational awareness and system automation		Power factor corrections	Devices/systems designed to align voltage and current on the distribution network, reducing energy losses.		X	X	X
Situational awareness and system automation		Smart reclosers	Protective switches that can automatically restore power to as many customers as possible by clearing temporary faults and quickly isolating permanent faults on the grid.		X	X	
Situational awareness and system automation		Substation automation and digitization	Technology solutions to streamline the process of monitoring and controlling substations and their essential equipment as well as converting binary status and analog measured data to digital data.	X	X	X	X
Situational awareness and system automation	***ADMS Advanced Applications***	Base Adv. Distribution Management System (ADMS)	Software platform that supports a wide range of distribution management and optimization. ADMS integrates various distribution grid functionalities (e.g., outage management, asset management, demand response).		X	X	X
Situational awareness and system automation	***ADMS Advanced Applications***	Distributed Energy Resource Management System (DERMS)	Manages integration and use of distributed energy resources (i.e. solar panels, energy storage) on the distribution and/or bulk power system; an advanced ADMS capability.		X	X	X
Situational awareness and system automation	***ADMS Advanced Applications***	Volt VAR Optimization (VVO)	Enables integrated optimization of voltage and reactive power levels across the distribution network which reduces power losses on distribution lines, increasing energy efficiency; an advanced ADMS capability.		X	X	X
Situational awareness and system automation	***ADMS Advanced Applications***	Fault Location, Isolation, and Service Restoration (FLISR)	Grid sensors and software that integrate with ADMS to quickly locate and isolate faults on the grid and automatically restore power to as many customers as possible.		X	X	X
Grid-Enhancing Technologies and Applications		Dynamic line rating (DLR)	Real-time calculation of a transmission line's thermal capacity (i.e., power carrying capacity) based on local conditions (conductor temperature, ambient weather conditions, line sag); dynamic rating helps increase effective capacity versus more conservative static and ambient adjusted line ratings.	X	X*	X	X

Grid category	Advanced Grid Solution	Definition	T&D Use		Type	
			T	D	Hardw.	Softw.
Grid-Enhancing Technologies and Applications ***(continued)***	Advanced Power Flow Control (APFC)	Change power flow direction through adjusting line reactance. In a meshed network, this can redirect power from overloaded lines to lines with available capacity; advanced PFCs are more compact, faster, and efficient than older PFCs.	X		X	
	Topology optimization	Software that can identify optimal reconfiguration of the system when there is a change in transmission assets to more flexibly and efficiently operate the grid.	X	X*		X
	Energy storage (as a T&D asset)[11]	Storage solutions sited within the transmission or distribution systems with the use case to defer or offset transmission and distribution capacity expansion, support peak load management, and/or provide other grid services to enhance system resilience and reliability.	X	X	X	
	Advanced Flexible Transformers	Transformers that can alter their voltage or impedance while energized, through integrated electromechanical or power electronic mechanisms, which improves system efficiency and provides power flow control capabilities. Some flexible designs also enable a single transformer to replace multiple transformers within a utility's footprint, lowering overall costs and enhancing resiliency.	X	X	X	
	Virtual Power Plants (VPPs)	Platforms that aggregate distributed energy resources to provide flexible supply and demand resources to the grid.		X		X
Foundational Systems	Communications technologies	Robust communication infrastructures for seamless data transfer across grid components. This includes Field Area Network (FAN), Wide Area Network (WAN), and fiber technologies.	X	X	X	X
	Data management systems	Systems that handle and convert large quantities of data to usable values that grid operators and asset owners can aggregate and synthesize (e.g., supervisory control and data acquisition system).	X	X	X	X
	Alternate Timing and Synchronization	Category of solutions that augment the capabilities of Global Navigation Satellite System (GNSS) infrastructure in the grid to ensure infrastructure resilience in the face of possible time-signal disruption.	X	X	X	X
	System digitization and visualization	Systems that create digital replicas of physical grid components and system interactions based on inputs from advanced sensors and communications networks.	X	X		X

** Technologies that could be used on the distribution system but have not been deployed widely yet. As adoption grows on the transmission system, distribution applications are expected to grow.*

Note: These grid technologies and applications are not exhaustive of the solutions that grid operators and regulators need to pursue to expand and modernize the grid. For example, new transmission and distribution infrastructure is still needed to serve long-term load growth, improve system reliability and resilience, and achieve national decarbonization objectives. Research and development into next generation grid technologies will be important as grid characteristics and needs evolve. Advancements in system modeling and planning are needed to address interconnection queue issues, improve understanding of grid needs, and inform better investment decisions amidst a rapidly changing energy future.

11 Today, lithium-ion batteries are the most commercially available energy storage solution; other storage technologies are becoming increasingly available (such as flow batteries, mechanical solutions, metal-anode batteries, and others). Industry operators can identify the optimal storage size and type to best serve their needs and use cases. For additional information on this use case, see the Pathways to Commercial Liftoff: Long Duration Energy Storage (2023) report.

Section 1.c. Value proposition

Individual technology value proposition

These grid solutions each have distinct and complementary value propositions to drive modern grid objectives and support transmission and distribution capacity expansion. No one technology is sufficient. Utilities can leverage these solutions in a variety of combinations to advance their specific grid modernization objectives.

Figure 7 summarizes the impact of these technologies across five dimensions: transmission and distribution (T&D) capacity impact, customer affordability outcomes, reliability, resilience, and sustainability (specifically decarbonization in the context of this report).[12,v] This summary and the discussion below are not exhaustive of all the benefits these technologies provide, but rather highlight some of the core value propositions across this diverse solution set.

Advanced Grid Solutions			T&D capacity impact	Affordability	Reliability	Resilience	Sustainability
Advanced Transmission Technologies	Advanced Conductors		Primary	Significant	Significant	Significant	Significant
	Point-to-Point HVDC systems		Primary	Significant	Significant	Primary	Significant
Situational Awareness and System Automation Solutions	Advanced Sensors		Low	Significant	Primary	Significant	Significant
	Power Factor Correction		Significant	Primary	Significant	Moderate	Significant
	Smart Reclosers		Low	Low	Primary	Significant	Low
	Substation Automation & Digitization		Low	Low	Significant	Primary	Low
	ADMS	*Base ADMS* (D-SCADA, OMS)	Low	Moderate	Significant	Significant	Moderate
		System efficiency: VVO	Primary	Primary	Moderate	Moderate	Primary
		DER integration: DERMS	Primary	Low	Moderate	Moderate	Primary
		Reliability: FLISR	Low	Moderate	Primary	Primary	Low
Grid Enhancing Technologies and Applications	Dynamic Line Ratings (DLR)		Primary	Primary	Significant	Moderate	Significant
	Adv. Power Flow Control (PFC)		Primary	Primary	Significant	Moderate	Significant
	Topology Optimization		Primary	Primary	Primary	Significant	Significant
	Energy Storage		Primary	Significant	Primary	Primary	Significant
	Advanced Flexible Transformers		Low	Moderate	Primary	Moderate	Moderate
	Virtual Power Plants (VPPs)		Primary	Significant	Moderate	Moderate	Significant

Low	Moderate	Significant	Primary
Indirect, limited impact	Direct, moderate impact	Direct, operationally significant impact	Direct, primary impact

Note: Foundational technologies are excluded since they have limited direct impact on outcomes. Benefits representative of relative impact for a specific technology (within each row) and not for comparison between technologies (between rows).

Figure 7. Advanced grid solutions' value proposition for key grid outcomes

Transmission and distribution (T&D) capacity impact

The U.S. grid may need to double in size by 2035 to accommodate expected demand and generation growth and meet decarbonization objectives. Regional transmission capacity would need to increase by 20-128% by 2035 to accommodate expected growth in clean energy demand with an additional 25-412% increase in interregional transfer capacity needed to improve system reliability and resilience.[vi] However, with siting, permitting, and construction of new transmission infrastructure taking up to 10 years to build out in some past cases, pressures are compounding on the existing transmission system.[vii] The U.S. transmission system has historically expanded at a rate of ~1% per year; this rate would need to nearly double to achieve

12 Transmission and distribution (T&D) capacity impact is defined as increasing physical system transfer capacity, improving the utilization of the grid system to increase effective capacity, and deferring the need for transmission and distribution infrastructure (e.g., by leveraging distributed energy assets, managing demand, improving efficiency). Affordability is defined as reducing energy costs for consumers; energy affordability is the idea that consumers can pay for their home electricity use while also paying for other basic living expenses, such as food and medication, without having to choose or feel overburdened (DOE). Reliability in this context refers to the ability of system operators to prevent outages and restore power quickly when outages do occur under expected conditions on the transmission and distribution grid. Resilience is the ability of the grid to withstand instability and unexpected conditions or faults then gracefully return to predictable–but possibly degraded–performance (NIST). Sustainability in this context is specifically focused on reducing greenhouse gas emissions from the power sector to support the United States' clean electricity goals (The White House). See citation for sources.

the projected transmission needs by 2035.[13,viii] Expanding distribution capacity and bidirectional power flow capabilities (particularly in areas where distribution constraints exist) is also critical to support transmission expansion and demand growth.

While new transmission infrastructure has been slow to come online to connect new generation, electricity demand is growing. In December of 2023, the North American Electric Reliability Corporation (NERC) nearly tripled its 9-year electricity demand forecast from the prior year, from 200 to 550 gigawatt hours of growth. NERC reported that these energy growth forecasts "were higher than at any point in the last decade" with "a growing number of areas in North America facing resource capacity or energy risks."[ix] Within the last year, several U.S. utilities and ISO/RTOs significantly increased their peak demand forecasts, largely driven by a surge in data centers, manufacturing, and long-term electrification trends.[14,x] Achieving net-zero emission economy-wide by 2050 would drive even greater peak demand growth—potentially hundreds of gigawatts—from electrification and domestic manufacturing.[xi]

Several advanced grid solutions can help address grid pressures by expanding and enhancing the existing transmission and distribution system. Transmission and distribution capacity can be enhanced on existing rights-of-way by expanding the physical capacity of existing infrastructure, improving the utilization of the current system, improving efficiency, and relieving the need for capacity altogether.

Advanced conductors can increase physical transmission capacity between 1.5-3 times conventional steel core conductors.[xii] Point-to-point HVDC systems can increase line capacity anywhere from 40% to over 200% (which can be useful in dense urban areas) and improve line efficiency.[xiii] Other solutions such as dynamic line rating (DLR), topology optimization, and advanced power flow control (APFC) can increase system utilization by allowing for transmission lines to increase power flow while still operating within safe capacity margins.[15] The effectiveness of these technologies varies based on where and how they are deployed, but they can unlock up to 10-50% additional effective carrying capacity on average.[16, xiv] Additionally, technologies such as ADMS-Volt/Var Optimization (VVO) and power factor correction can alleviate transmission capacity needs by improving downstream system efficiency through reducing line losses, with studies finding a 6.4% efficiency improvement.[xv] Finally, some technologies and applications like energy storage, Virtual Power Plants (VPP), and Distributed Energy Management Systems (DERMS) can relieve transmission and distribution capacity demands by providing dispatchable energy in the distribution system and behind the meter, avoiding the need for transmission infrastructure all together.

Affordability

As of May 2023, 26% of U.S. households reported experiencing energy insecurity for at least 1-2 months within the last year.[17,xvi] Communities of color and Tribal nations in particular experience energy insecurity at disproportionately high rates.[xvii] At the same time, the need to expand and replace aging grid infrastructure could place additional burdens on ratepayers, with consulting firm Marsh McLennan estimating that it would cost $700B just to replace aging transmission lines, in addition to the cost of expanding the grid.[xviii]

13 According to Princeton University's Project REPEAT analysis, the recent historical U.S. transmission expansion rate of ~1% a year would need to grow to 2.3% to maximize the carbon emissions reduction potential from the Inflation Reduction Act. Princeton cites this rate of growth is comparable to the average transmission additions from 1978-2020. To achieve the 20% increase in regional transmission capacity by 2035 the DOE's National Transmission Needs Study found was needed to maintain system reliability would imply needing ~1.7% annual increase (almost double recent historical rates).

14 Utilities include: Puget Sound Energy: Puget Sound Energy Demand Forecast; CAISO: 2022 Integrated Energy Policy Report Update; Arizona Public Service: 2023 Integrated Resource Plan; NYISO: 2022 and 2023 Load & Capacity Data; Georgia Power: Integrated Resource Plan; Duke: Carolina Resource Plan; PJM: Energy Transition in PJM; and ERCOT: 2022 and 2023 Long-Term Load Forecast

15 By providing a real time rating, DLR can also result in lowering transmission capacity when a line is above its safe operating limit; while this would inform grid operators to reduce power flow over that line and result in lower capacity, it improves grid safety and reliability.

16 Average GETs capacity impacts: Topology optimization can increase effective transmission capacity by 5-50%; DLR can increase transmission capacity by 10-30% upwards of 90% of the time; APFC can increase transmission capacity by 10-25%. See endnote for citations.

17 Energy insecurity – as defined by the U.S. Census Bureau – includes three conditions: (1) a difficulty paying energy bills (2) reduced or forewent basic necessities like food and medicine to pay an energy bill, or (3) kept home at an unsafe temperature because of energy cost concerns.

Meanwhile, transmission capacity constraints are driving up customer energy bills.[18] These costs, referred to as congestion costs, adversely impact ratepayer energy bills and are estimated to have increased over fifty percent in one year to reach ~$21B in 2022.[xix]

Given the significant investment that is already required to upgrade and expand the grid, deploying advanced grid solutions on the existing system can help alleviate upward cost pressures for ratepayers and utilities. There are several ways these grid tools can improve affordability outcomes. If managed intentionally, these benefits can specifically help alleviate energy burdens in disadvantaged communities.

Upgrading and better utilizing the existing system—including by leveraging demand-side resources—can **defer and/or avoid some of the cost of rebuilding or adding new transmission and distribution infrastructure.** If deployed at scale by 2030, VPPs are estimated to be able to serve 10-20% of peak demand, avoiding ~$10B in annual grid costs.[xx] A 2023 transmission study by ISO-NE found that reducing 2050 peak load through demand response and energy efficiency programs (which leverage solutions like VPP and DERMS), could reduce transmission costs by $9B.[xxi]

Additionally, some grid-enhancing technologies can **lower customer energy costs by reducing congestion and improving system efficiency**. PPL Electric Utility deployed DLR on two congested lines for an expected $23M in reduced congestion costs.[xxii] In PJM, one study found that deploying a $0.5 million DLR system could save $4 million[xxiii] and deploying various numbers of APFCs could save $39-196 million in annual congestion costs.[xxiv] Alliant Energy used topology optimization reconfigurations to identify $40.3 million in achievable congestion cost reductions (54% of total system congestion costs).[xxv] In addition to ADMS-VVO and power factor corrections discussed before, advanced conductors increase system efficiency by reducing the electrical resistivity of lines, with studies finding efficiency improvements of 20-40% which can translate into lower energy costs for ratepayers.[19,xxvi]

Finally, utilities can **reduce operations and maintenance costs** by utilizing advanced solutions that improve reliability by enabling predictive maintenance, reducing overall truck rolls, and reducing outages. Those technologies are discussed further in the next section.

Reliability

The reliability of the electric grid refers to the ability of system operators to prevent outages and restore power quickly when outages do occur under expected conditions. The standard reliability metrics[20] used in industry measure the average response over a range of outage events, which means the resulting values help utilities and regulators understand system performance to common outages. Grid reliability is not equal—disadvantaged communities often have lower reliability than higher income areas and Tribal nations have reported experiencing outages at a rate over six times higher than the national average.[21,xxvii] This demonstrates the need for greater investment in reliability improvements specifically in these communities to advance energy justice outcomes.

Technologies like ADMS, advanced sensors, and digital substations can improve reliability by **increasing situational awareness to reduce restoration time**, which allows operators to locate faults and power outages more quickly. FLISR and smart reclosers can **automatically reconfigure the system to minimize**

18 Congestion costs occur when the lowest-cost resource that is available cannot be used to meet demand because of transmission constraints. A higher-cost resource must then be used to serve demand, increasing costs to customers. This additional cost is referred to as "congestion costs".

19 This efficiency improvement is when the advanced conductors are operated at the same temperature as a standard conductor; if operating at maximum capacity, net losses can be higher because of the greater amount of power being transmitted.

20 These metrics include **System Average Interruption Duration Index (SAIDI)**: the average duration in minutes a customer is interrupted considering the full system during a reporting period (the average includes all customers, those who lost power and those who did not); **System Average Interruption Frequency Index (SAIFI)**: the average number of customers who lost power during a reporting period; **Customer Average Interruption Duration Index (CAIDI):** the average duration in minutes a customer is interrupted considering only the customers who lost power during a reporting period.

21 For example, in Texas during Winter Storm Uri in February 2021, communities with a large minority population were more than four times as likely to suffer blackouts than those without a large minority population, even taking income into account.

the number of customers that experience an interruption on the distribution system. For example, FLISR has been found to reduce the number of customers suffering interruptions of greater than 5 minutes by up to 45% per outage event.[xxviii] Additionally, advanced conductors can **prevent potential outages altogether through system hardening.** Lastly, solutions like DERMS and energy storage can **provide contingency power** support when outages do occur by leveraging available distributed energy resources.

Advanced grid solutions can also support system reliability as the generation mix shifts from fossil assets to inverter-based renewables and storage, which can impact conventional grid physical dynamics. [22] Wind and solar capacity could increase by 6-10x if the U.S. were to achieve 100% clean electricity by 2035.[xxix] This growth is already being seen today. Following historical success rates, if only 15 percent of the solar, wind, and storage capacity currently in the interconnection queue was connected, this would represent ~300 GW of inverter-based resources (IBRs) on the grid within the next several years—more than double the existing solar and wind capacity as of early 2023.[xxx] An additional 100-175 GW of distributed generation could come online by 2030.[xxxi] This increase further accelerates a shift in the fundamental dynamics of the grid away from centralized bulk-power generation to a dynamic, distributed generation fleet.[xxxii]

Several advanced technologies can facilitate integration and management of these new resources while maintaining system reliability. For example, ADMS-DERMS can manage the grid supporting capabilities of modern IBRs to increase system awareness of distributed assets and improve distribution system power quality. When additional support is needed, ADMS-VVO and power factor corrections can manage voltage and improve system stability. Together these technologies help **facilitate safe and efficient integration of distributed resources** that are a significant part of emerging grid capacity.

Resilience

Grid resilience is the ability of the system to withstand instability and unexpected conditions or faults then gracefully return to predictable—but possibly degraded—performance.[xxxiii] This is different from reliability in which normal services are provided. Resilience includes the ability to prepare for and adapt to changing circumstances, and to withstand and recover rapidly from disruption regardless of the source. More frequent and severe weather events,[23,xxxiv] rising physical and cyber-attacks on the system,[24,xxxv] and the uncertainty associated with variable generation/load[25,xxxvi] can each introduce disruption which can be mitigated through resilience measures that maintain service through the event and accelerate a return to normal operations.

Technologies that can **provide contingency power and reduce restoration time** for common disruptions improve system resilience.[xxxvii] Point-to-point HVDC systems provide the grid with black start and system restoration capabilities, and when interconnected with neighboring systems, HVDC can import emergency energy without impacting the stability of the source system.

Other resilience benefits include **reducing strain on the system and increasing flexibility**. For example, power factor correction reduces strain on transformers and other distribution network equipment, thereby providing additional operational flexibility while reducing wear and operational costs. Advanced flexible transformers can also provide operational flexibility to match line voltages to system needs without adding wear to physical switches, thereby efficiently mitigating system stresses during disruption. Additionally, the ability to change its impedance also provides power flow control capability to route power during a disruption. Other flexible transformer designs can be used to replace a large subset of transformers within a utility's footprint, reducing equipment supply, repair, and replacement times to enhance system resilience.[xxxviii]

22 Inverter-based resources (IBR) do not have the same inertia properties as thermal -based synchronous generation (e.g., fossil fuel plants, geothermal), which impacts conventional grid dynamics that were based on these large inertia resources.

23 Between 2011 and 2021, the average annual number of weather-related power outages in the U.S. increased by roughly 78% compared to 2000-2010.

24 NERC cited a 10% increase in physical attacks on the grid between 2022 and 2023.

25 Uncertainty and forecasting errors around both supply and demand can create resource adequacy concerns and event potential outages. Resilience solutions can shore up resource adequacy and overcome the delta between forecasts and reality.

Sustainability (decarbonization)

As discussed above, the grid will need to expand and modernize to enable power sector decarbonization. These advanced grid solutions can help decarbonize the grid through three main avenues:

1. **Reduce curtailment of existing renewable generation** through either grid enhancements (e.g., DLR, APFC, topology optimization) or physical capacity additions (e.g., HVDC, advanced conductors) on already congested lines.

2. **Enable the interconnection of new clean energy generation** to the bulk power system in cases where transmission upgrades are needed. These technologies could potentially reduce both time and cost to upgrade lines to be able to accommodate more renewables.

3. **Reduce emissions from fossil fuel energy generation** by reducing upstream greenhouse gas emissions, particularly emissions from fossil fuel peaking plants, through improved system efficiency with advanced conductors and ADMS-VVO and leveraging clean distributed generation through VPPs to serve load. This has important energy justice and equity implications as over two-thirds of fossil fuel-powered peaker plants in the U.S. are located near communities with a higher percentage of low-income households than the national average.[xxxix]

This report specifically focuses on the impact of these technologies on greenhouse gas emissions. Other important sustainability impacts these technologies unlock through enabling the transition to a modernized and more efficient grid include reducing air pollution and water consumption associated with conventional thermal power generation.

Additional benefits

Implementation of these technologies provides a host of other benefits that can lay foundations for further grid modernization and technology adoption, including improvements to grid safety, security, flexibility, and customer satisfaction. System digitization and improved data collection from these advanced technologies can enable Artificial Intelligence and advanced analytics applications (e.g., predictive maintenance, improved modeling) and improve grid planning and operations. Additionally, having greater data on and visibility into system performance and outcomes can unlock new opportunities to identify and capture the value created by these technologies to better allocate benefits and costs (e.g., enabling performance incentive mechanisms, sharing costs based on asset use).

These grid technologies have the potential to advance energy justice and equity outcomes if properly and intentionally deployed. Deploying advanced grid solutions (e.g., VPPs, FLISR, DERMS) in areas that directly benefit disadvantaged communities can meaningfully improve affordability, reliability, and resilience outcomes while reducing air emissions. Several solutions (e.g., DERs and storage) can also support greater energy independence for Tribal and other communities seeking more control over local energy choices. These benefits are particularly important for disadvantaged communities that are hit first and hardest by and often the last to recover from natural disasters, grid outages, and other physical infrastructure challenges. Having more granular system data through these technologies can enhance utilities and regulators' ability to establish and track metrics at a sub-system level to enable more equitable grid planning and investment decisions. Additional implications for energy justice and equity are discussed in Section 3.c.

Value in combination

Beyond their individual value proposition, these technologies in combination unlock meaningful additional system value. Fully understanding these grid solutions requires viewing them as part of larger systems to identify and value their interacting effects and shared dependencies.

The benefits that flow from many of these technology investments are complementary and can stack. For example, a study by think tank RMI (formerly Rocky Mountain Institute) of dynamic line rating, topology optimization, and advanced power flow control found that deploying these three solutions together drives a ~20-25% greater capacity impact to enable new generation interconnection than any of the solutions individually.[xl] On the distribution side, for example, smart reclosers are able to improve reliability on an individual circuit, but when deployed with an ADMS-FLISR system, the same reclosers can be coordinated and optimized across an entire distribution network, which enables whole groups of customers to be served by an alternative feeder. This avoids customer outages entirely or shortens restoration times. Integrating reclosers with an ADMS-FLISR system therefore enhances system reliability on a much larger scale than is possible through the basic function of automated reclosers.

ADMS and digital substations are among the technologies that are key enablers and amplifiers of other technology benefits despite having limited standalone value. ADMS is a critical foundational technology for DERMS (which likewise underpins VPPs) as well as a key amplifier of many other distribution-level technologies, such as FLISR and VVO. FLISR and VVO can provide value on a standalone basis, but their most meaningful benefits rely on the existence of a central ADMS platform that can enable more sophisticated use-cases. Moreover, most foreseeable new or improved technologies that emerge as potential distribution grid modernization investments in the next decade are likely to rely on the existence of a central ADMS platform, as they are becoming the industry standard for smart grid operation and grid-edge situational awareness. Digital substations have some limited standalone reliability value but can significantly enhance the value of other solutions (e.g., ADMS-VVO, DLR, energy storage, advanced transformers).

These technologies share dependencies on many common foundational technologies. This creates opportunity to both realize cost synergies across multiple technology deployments and unlock access to future advanced technologies from foundational investments today. For example, investing in high-quality of service communications can support ADMS today, and then enable grid protection schemes and next-generation solutions in the future. Capturing future system value requires a strategic approach to right-size foundational infrastructure investment to best support expected future technology deployments. As an example, the figure below shows how various sophistication levels of communications technologies unlock access to different advanced grid solutions.

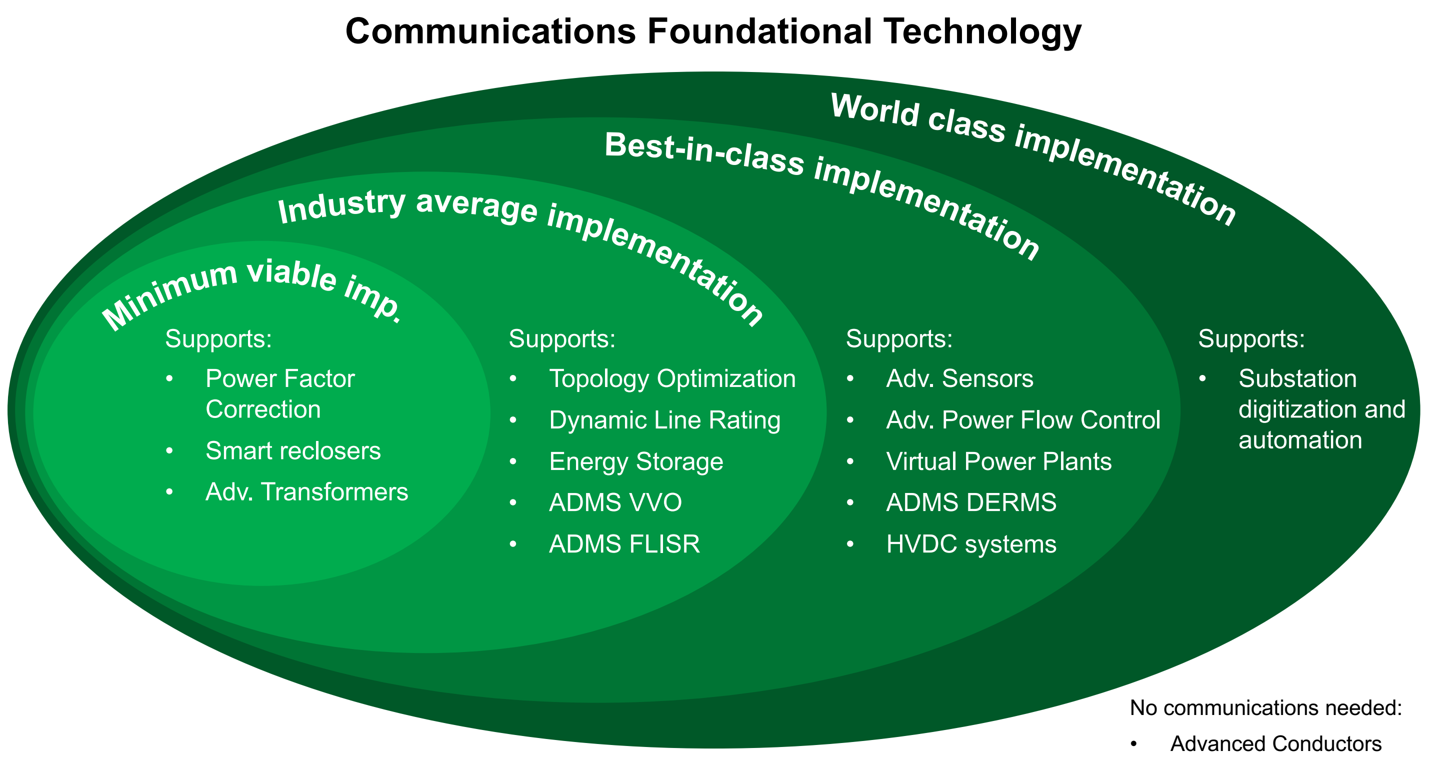


Figure 8. Communications technology quality-of-service needs for advanced grid solutions

See Appendix D for additional information on the foundational systems underpinning advanced grid solutions. See Chapter 3.b. and Appendix C for additional discussion and examples of technologies in combination in example utility contexts.

Deployment costs

Many of these solutions are a fraction of the cost of conventional technologies. For example, on the transmission side, a recent DOE study of DLR and advanced PFC applications in New York found these advanced technologies cost less than 25% of traditional upgrades.[xli] PPL Electric recently deployed a DLR solution for less than $1M on two transmission lines, which avoided having to reconductor or rebuild those lines at a cost of $0.5-4M/mile (or an estimated total of ~$13-68M).[26,xlii]

On the distribution side, a Wood Mackenzie analysis of fifty major IOU rate cases found that the average project cost of DER management (e.g., DERMS) was 100 times cheaper than average physical infrastructure project costs.[xliii] While physical infrastructure will still be needed to enhance the grid, alternate solutions that can be more cost-effective should be considered.

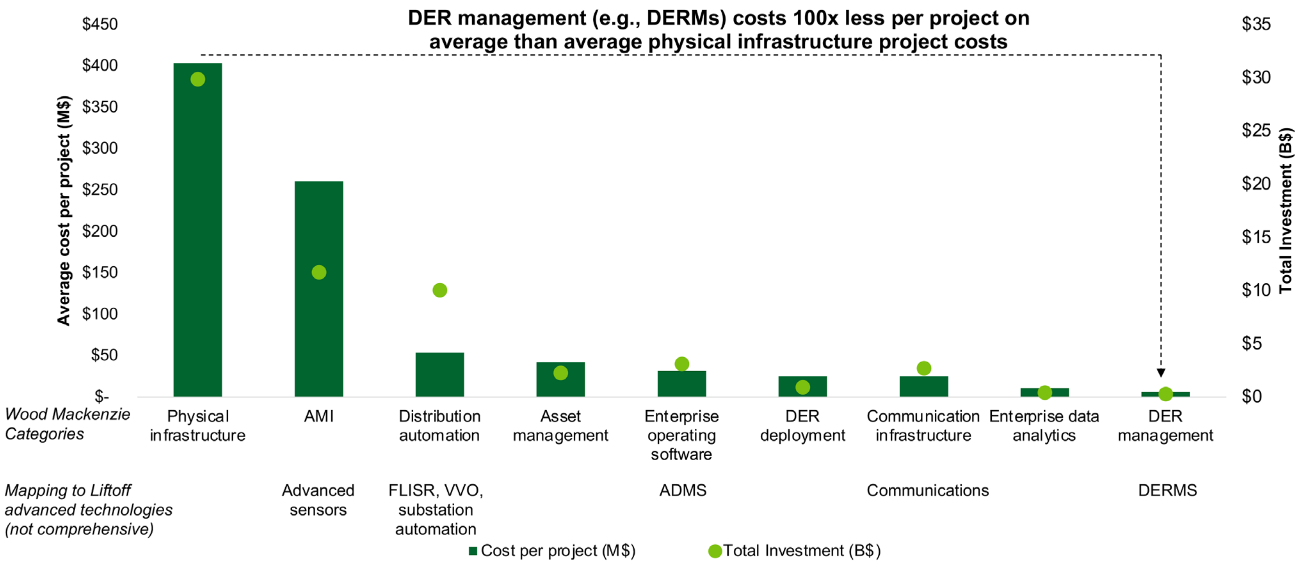


Figure 9. Average project costs and total investments of IOU distribution grid modernization investments by technology category

While low cost to scale, initial advanced technology deployments often have higher upfront costs associated with building necessary foundational infrastructure and capabilities (e.g., workforce training, systems integration). These early investments often reduce the costs of future deployments—both for scaling that same technology and enabling other advanced technologies with shared system and capability requirements—and enable compounding benefits to be captured.

Some of these solutions are still expensive physical assets, including advanced conductors, point-to-point HVDC, energy storage, and advanced flexible transformers. For example, while reconductoring with advanced conductors is estimated to cost less than half the price of a new build, advanced conductors can be 1.5-2x the cost of conventional steel core conductors.[27,xliv] While the efficiency benefits of advanced conductors often quickly outweighs the higher upfront costs of these solutions, grid operators and utilities will need to evaluate the cost effectiveness of advanced reconductoring and optimal cost allocation method in

26 The total cost is estimated based on cost per mile reported by PPL and lengths of lines (~27 miles total), assuming entire line would be reconductored and/or rebuilt.

27 Project costs on a dollar per mile basis. Costs estimated from MISO's Transmission Cost Estimation Guide and industry interviews. Additional costs for reconductoring may be required to upgrade substations or other system capacity constraints to maximize capacity impact. If needed or desired, grid operators may be able to reconductor with an advanced conductor today and defer a substation upgrade until later to realize the full capacity benefit.

particular contexts.[28,xlv] Additionally, energy storage today costs ~$1,000-3,300/kW for 2 to 10-hour lithium-ion storage.[xlvi] While storage can be a high-impact solution to defer grid capacity needs, increase reliability and resilience, and provide ancillary grid services, grid operators will need to evaluate the optimal storage solution in specific use cases to cost-effectively maximize system value for ratepayers.

Lastly, some technologies may individually have higher operational expenditures than conventional hardware assets. These operational expenditures can include costs associated with data management or software subscriptions (which are sometimes counted as operational expenditures), higher utilization of assets (higher wear and tear), and necessary workforce training. Overall, advanced grid solutions can reduce operating costs (as discussed above) through improved operational efficiencies, preventative maintenance, and reduced truck rolls. Minimizing operational costs and realizing efficiencies may require intentional approaches to ensure the advanced grid solutions are fully leveraged.

Grid operators and regulators will need to determine the most efficient use of capital investment to drive the greatest system value and customer outcomes—including a combination of cost-effective advanced technologies alongside conventional asset replacement and expansion investments.

Deployment timeline

These technologies can be deployed quickly on the existing grid, making the most of existing rights-of-way. While new transmission infrastructure is needed, average new build timelines are exceeding 7-10+ years due to complex system planning, siting, and permitting challenges. These capacity enhancements and relief solutions can be faster alternatives to relieve near-term transmission and distribution capacity constraints as a bridge until new infrastructure can be brought online.

Initial deployments typically take ~1–3 years to complete. After the initial infrastructure is in place, scaling the technology across a utilities' operations often takes less than 3–6 months. Initial deployment set up includes completing pre-requisite infrastructure investments (e.g., data uplift, communications installations), identifying and procuring solutions providers, securing regulatory approvals if applicable, training the workforce, and other necessary processes. Importantly, however, these upfront investments can also be used to support faster deployments of other technologies with shared subsystems.

In this Liftoff report, the focus on existing rights-of-way (ROW) is on existing transmission and distribution electricity infrastructure. Opportunities to leverage existing transportation ROW (e.g., highways) to co-locate power with transport is another high-impact opportunity. See the National Transmission Needs Study (2023) for additional discussion about opportunities to accelerate electric system build out on existing transport ROW.[29, xlvi]

Because these initial deployments come with several years of lead time, grid operators will need to proactively anticipate and plan for these investments. Waiting until an urgent grid need arises may be too late to leverage these advanced technologies.

28 A forthcoming DOE tool is in development to support cost effectiveness evaluations for various conductor types and is expected for release in 2024.

29 For additional discussion on highway and transmission co-location opportunities, see the White House's United States Innovation to Meet 2050 Climate Goals report and a joint initiative by The Ray and ESRI on Hidden in Plain Sight overview.

Table 4. Average deployment timelines for grid solutions impacting transmission capacity[xlviii]

Advanced Grid Technologies and Applications		Initial deployment timeline for a utility (years)			Subsequent deployment timeline
		1-3	4-7	7+	
Bulk system solutions (on existing ROW)	Advanced Conductors				1–3 years
	Point-to-point HVDC				~2–5 years
	Dynamic Line Ratings (DLR)				<3–6 months
	Adv. Power Flow Control (PFC)				<3–6 months
	Topology Optimization				<3–6 months
T&D Capacity Relief solutions	ADMS-VVO				<1 year
	ADMS-DERMS				*Varies based on functions added*
	Energy Storage (as a T&D asset)				<1–2 years
	Virtual Power Plants (VPP)				*Varies based on market and VPP type*
	Power factor correction				<3–6 months
Conventional alternatives	New transmission build				*N/A*
	Utility-scale generation[30,xlix]				*N/A*

Deployment flexibility

Most of these innovative technologies can be flexibly adapted to meet an individual utility's needs and context. Many of these solutions have a wide range of sophistication levels, with considerable benefits still being possible with more basic technology investments (Table 5 summarizes an example capability progression of an ADMS-FLISR application). Grid operators can identify the appropriate level of innovation and supporting technical requirements based on their grid objectives and capabilities.

30 Timelines for deployments can vary widely for utility-scale generation, particularly depending on interconnection timelines. As of 2022, average time projects spent in the interconnection queue was 5 years.

Table 5. Example Capability Progression of ADMS-FLISR[l]

ADMS-FLISR Implementation Progression					
	0 – Initiating	**1 – Enabling**	**2 – Integrating**	**3 – Optimizing**	**4 – Pioneering**
FLISR Type	Manual switching	SCADA switching	ADMS Advisory FLISR	ADMS Autonomous FLISR	ADMS model-based including DER
Competing Tech			DA FLISR open loop		
Sensors	None	Low – Portable testing equipment	Med – Local & line fault detection	Med – Communicating sensors installed on feeders to detect faults	High – Permanent equipment at substations and operation centers to detect faults
Communications	None	Low	Med – Partial link with ADMS	High – Integration and automatization within ADMS	High – Integration and automatization within ADMS
Data management	None	Low	Med – Determine fault locations via waveform data	High – Leverage AMI, SCADA and other sensor data to determine faults	High – Leverage AMI, SCADA and other sensor data to determine faults
Reliability improvement benefit	None	Baseline	~30%	~40%	~50%
Estimated industry adoption today	100%	95%	15%	2%	0%

Many of these technologies can also be scaled up and/or down over time to meet utility contexts and priorities. For example, on the distribution side, a typical progression of technology deployments ranges from manual systems to individual automation at a technology unit level to more advanced system-wide optimization and ultimate dynamic controllability. Basic DERMS can be installed today to integrate distributed resources passively and then scaled up to more a sophisticated controllability solution, such as a VPP application.

Applicability across the grid

The specific use case and application of these systems are highly location- and context-specific. Grid operators can individually determine the appropriate viability of these solutions in their own operations.

Technologies with generally wide technical and economic applicability on the existing grid include most situational awareness and system automation solutions—including advanced sensors, smart reclosers, digital substations, ADMS base, ADMS VVO, and ADMS FLISR—as well as grid-enhancing solutions like topology optimization.

Technologies with more specific applicability on the existing system (as of 2023) include:

- **Advanced conductors (moderate applicability)**: Reconductoring is typically most economically viable on lines that are approaching end of life (or if capacity increase is so significant to warrant early replacement); advanced reconductoring for capacity benefits is most applicable on lines that are thermally limited (primarily short lines <30 miles and at voltages <500kV); advanced reconductoring for efficiency improvements is broadly applicable. For reconductoring to be economically viable, the supporting structures and poles must have sufficient remaining life and structural integrity (if structure is near end of life, will need to be rebuilt).[31, li]

31 Idaho National Laboratory estimated ~20% of U.S. transmission lines could be viable candidates for reconductoring.

- **Advanced power flow control (moderate applicability)**: Advanced power flow control is most applicable on meshed networks with multiple transmission ties; on radial lines, these are most applicable to longer lines (30-45 miles for voltages <230kV, 60 miles for 230-500kv), which represent a minority of U.S. transmission lines.[lii]
- **Dynamic line rating (moderate applicability):** DLR is most applicable on shorter lines that are thermally limited, facing congestion, and/or operate at or near their rated capacity. Due to its features of using real time environmental conditions to calculate additional capacity headroom, DLR has the greatest impact (and thus economic viability) in climates with meaningful temperature changes and/or high wind speeds.[liii]
- **Point-to-point HVDC (limited applicability):** HVDC retrofits on existing ROW are largely limited to either replacements of existing aging HVDC lines or HVAC conversions, which is typically only economic when greater than ~60% capacity increase is required and the rights-of-way cannot be expanded (i.e., high-capacity in-feeds to city centers).[liv]

As the grid expands and modernizes, the applicability of these solutions is expected to likewise grow as additional grid services and value propositions are enabled. Building on efforts to date,[32] further research could support identifying optimal locational applicability and use cases for specific technologies across the U.S. grid and within a utility's own operating context.

Section 1.d. Opportunity at stake

Deploying these technologies to their full potential overnight could increase the capacity of the existing grid to support 20-100 GW of incremental peak demand when installed individually, with significant additional capacity potential when installed in strategic combinations. This impact is on the order of magnitude of the additional 91 GW of incremental winter peak demand growth expected through 2033, according to NERC forecasts as of December 2023.[lv] As the grid enters a period of rapid demand growth in several regions, advanced technologies that can be quickly and cost effectively deployed to increase grid capacity in the near term are increasingly important to maintain system reliability and serve customer needs. This analysis suggests that grid operators have multiple high-impact technology options available that could start being evaluated individually or in combination in existing investment plans to identify the potential applicability and impact of these solutions in their own operations.

32 See Table 6 for additional resources on example studies evaluating the applicability of advanced technologies.

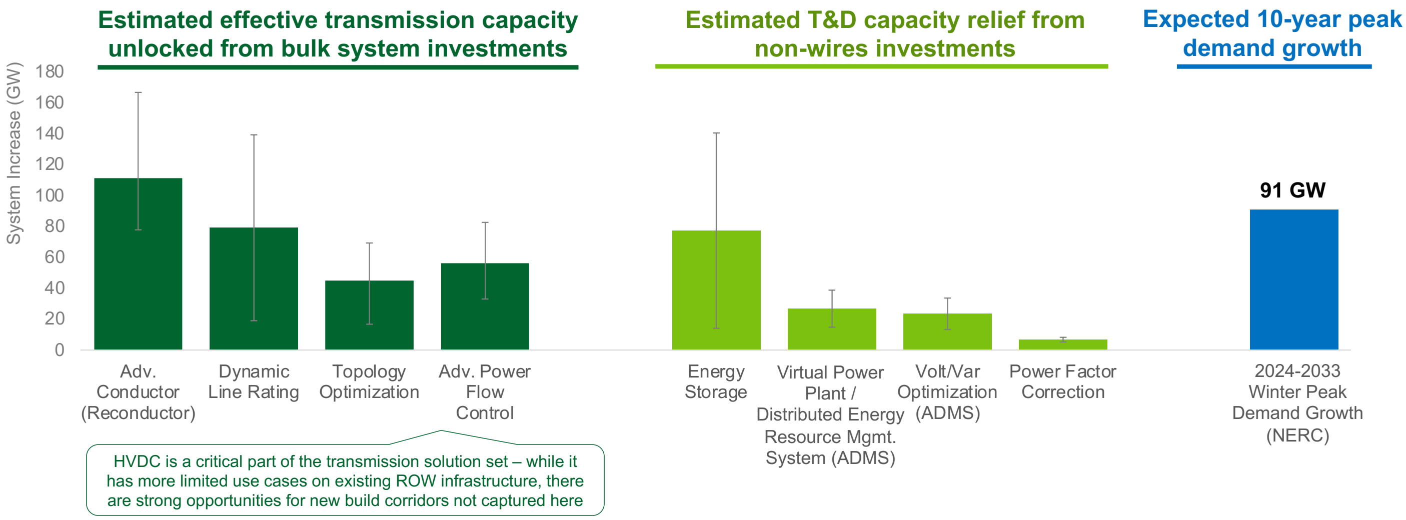


Figure 10. Estimated Transmission and distribution (T&D) capacity impact from full potential deployment of transmission enhancing and relieving technologies on the existing T&D footprint (as of 2023)[33]

Notes: Represents estimated full potential of deploying grid solutions at scale in technically and economically feasible locations overnight on the existing grid as of 2023 (does not consider actual deployment timelines). The grey bar represents the range of potential outcomes based on technology impact (e.g., DLR can increase effective capacity between ~5-40%) and illustrates the uncertainty associated with limited data availability, wide range of deployment scenarios, and locational and topological differences.

Deploying advanced conductors and grid-enhancing technologies like dynamic line rating (DLR), topology optimization, and advanced power flow control (APFC) in viable locations across the U.S. transmission system suggests unlocking enough incremental transmission capacity to support 5-15% higher peak load from 2023 levels when installed individually. These technologies can support this higher peak load by increasing transmission capacity and improving utilization to reduce curtailment of existing resources and facilitate new generation interconnection. Additional grid capacity relief is possible through improved use of distributed energy resources (e.g., VPPs), energy storage, and distribution system efficiency solutions like ADMS-VVO that could have each addressed ~5–10% of 2023 peak load if they had been widely deployed.[34]

New transmission capacity is still critically needed to interconnect new generation and increase transfer capabilities between regions to improve system resilience and reliability. However, alongside this capacity expansion, these advanced grid solutions are a near-term option that can help serve as a bridge to fill interim gaps as new transmission infrastructure is developed and to help reduce overall new build needs in the long-term. As the grid is expanded, these solutions can be incorporated in new expansion to further enhance the system in the long term.

Deploying these solutions to their full potential suggests deferring an estimated $5–35B in transmission and distribution infrastructure costs over a five-year period. This could provide important cost relief to customers, helping offset the additional costs from new system capacity expansion and replacements that will still have to happen. Additionally, these technologies could further help reduce rising congestion costs. If deployed to their full potential, grid-enhancing technologies like DLR, advanced PFC, and network topology optimization could each individually reduce annual congestion costs by an estimated 25–50%, suggesting ~$5–10B in annual congestion cost relief for ratepayers. If deployed in combination, this might unlock additional congestion savings.

33 See Appendix F for detail on assumptions, sources, and inputs. Estimated capacity impacts based on analysis by Guidehouse, industry interviews, technology research studies, and historical deployment outcomes. Capacity impact estimates are based on impact to 2023 U.S. peak load based on where the technology is estimated to be economically and technically viable. This assumes that load is evenly distributed across the transmission and distribution system. Peak demand growth outlook represents the winter peak load outlook based on NERC'S Long Term Reliability Assessment as of December 2023. 'Bulk system" refers to the transmission system, which is part of the grid's bulk power system.

34 See Appendix F: Key Assumptions and Inputs for additional detail.

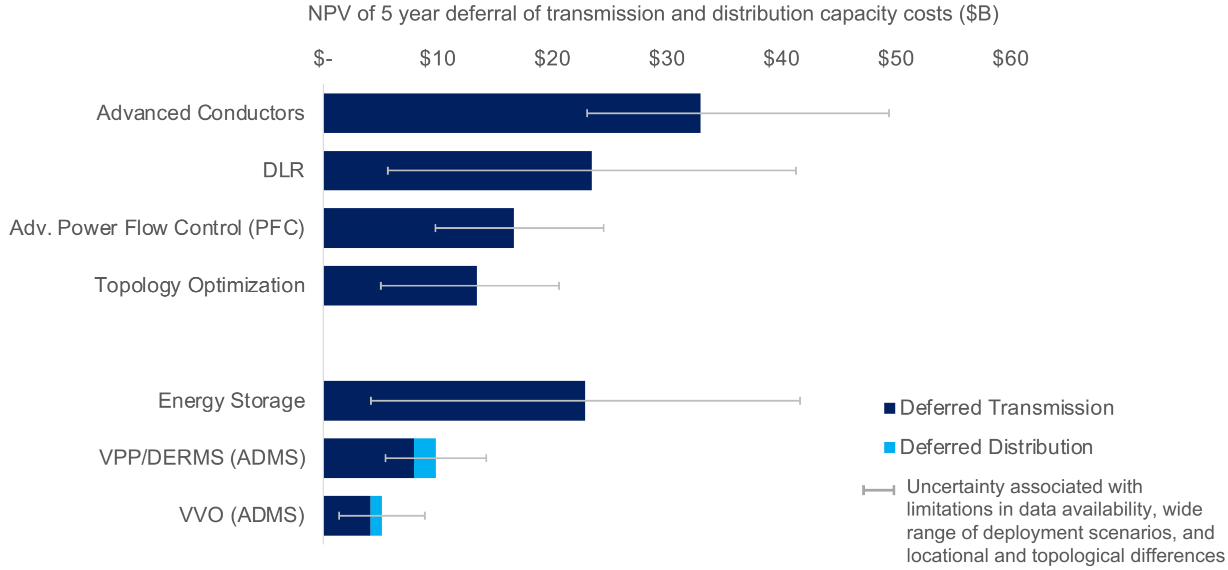


Figure 11. Estimated deferred transmission and distribution infrastructure costs from full potential deployment[35]

Deploying distribution automation solutions like FLISR and smart reclosers at scale could reduce customer outages experienced by an estimated ~10–20%—meaningfully improving system reliability and resilience outcomes.[36]

There are commercially available advanced technologies that can meaningfully enhance the value of the existing system in the near term. **These findings represent an urgent call to action for regulators, utilities, and all grid stakeholders to evaluate the opportunity to deploy these types of solutions to improve the reliability and affordability of the grid today.**

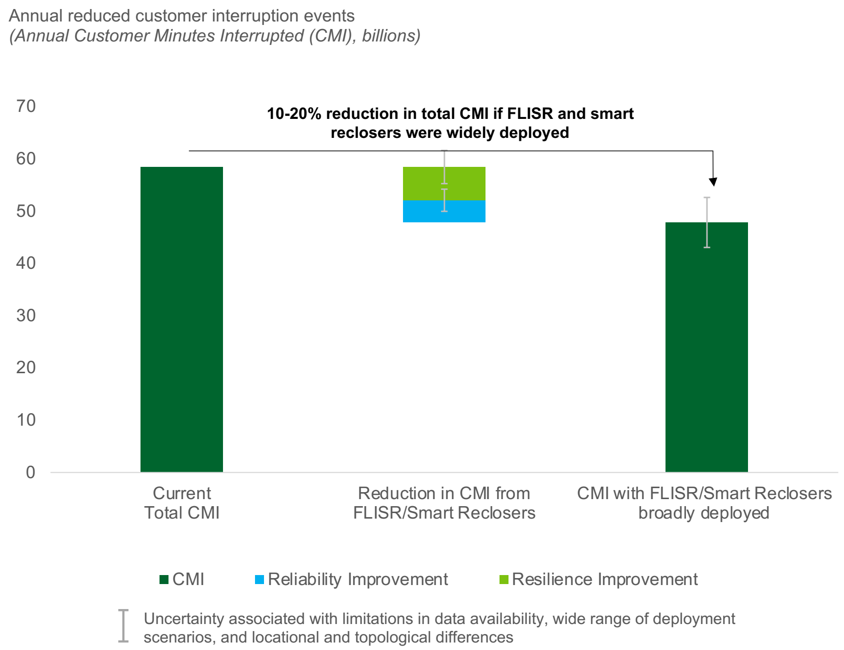


Figure 12. Estimated reliability and resilience improvement from full potential deployment of FLISR and Smart Reclosers

35 This estimate uses annual transmission and distribution deferral value ($/GW) and calculates the net present value (NPV) of over five years if the technology was deployed to its full potential based on the potential capacity impact (Figure 11). Industry practice of a five-year deferral period is used. The error bars represent the potential deferral value based on the capacity impact range achieved. See Appendix F: Key Assumptions and Inputs.

36 See Appendix F: Key Assumptions and Inputs. Estimates based on Guidehouse analysis, industry research, and case studies.

Several other studies have found similarly significant opportunities to apply these technologies to generate meaningful system impact.

Table 6. Summary of select studies covering advanced grid solutions

Study	Key findings
Virtual Power Plants: Pathways to Commercial Liftoff (DOE, 2023)[lvi]	Study found that VPPs could provide 80-160 GW of generation capacity, ~10-20% of peak capacity by 2030 (~3x current scale).
Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way (UC Berkeley, 2024) [lvii]	Study found that reconductoring could enable nearly four times as much transmission capacity to be added between 134 ReEDS zones by 2035.
GETting Interconnected in PJM (RMI, 2024)[lviii]	Study of impacts on applying dynamic line rating, topology optimization, and advanced power flow control to PJM found that these GETs could facilitate cost-effective interconnection of 6.6 GW of new solar, wind, and storage projects by 2027. The results found that the GETs and the new generation they enable could yield $1 billion annually in production cost savings.
Unlocking the Queue with Grid-Enhancing Technologies (Brattle, 2021)[lix]	Model of GETs applications in SPP found that twice the amount of additional new renewables could be integrated with dynamic line rating, topology optimization, and advanced power flow control. The estimated annual production cost savings were $175 million.
Advanced Conductor Scan Report (INL, 2024)[lx]	Study of advanced conductor types estimated approximately 20% of transmission lines could be viable candidates for reconductoring.
Grid-Enhancing Technologies: A Case Study on Ratepayer Impact (DOE, 2022) [lxi]	Modeling of dynamic line rating and advanced power flow control applications in NY found advanced power flow control reduced curtailment by 23–43% from additional capacity unlocked and a production cost savings of $1.7–4.6M
The Operational and Market Benefits of HVDC to System Operators (Brattle and DNV, 2023)[lxii]	Study that found converting AC overhead lines to HVDC can leverage existing rights-of-way to triple transfer capability; reduce transmission losses; mitigate AC stability constraints; gain VSC-enabled grid support functions; and achieve these benefits at one third to one half of the cost of building a new HVDC line.

Chapter 2: Current State of Technologies and Markets

Key Takeaways

- Of the nearly $90 billion invested in transmission and distribution infrastructure in 2023, only $6B (7%) was spent on advanced grid solutions.
- While grid modernization investment is increasing, the majority of transmission and distribution investment (93%) continued to go to conventional asset replacement, expansion, and physical hardening.
- As a result of conventional grid planning and investment processes that are reactionary and siloed in nature, advanced grid technology investments have likewise been reactive—largely driven in response to external legislative and regulatory mandates and/or significant physical pressures (e.g., extreme weather, distributed energy resource penetration, capacity constraints).
- While many utilities across the U.S. have started investing in advanced grid solutions, widescale adoption is lagging, particularly for transmission solutions including advanced conductors and several grid-enhancing technologies that can expand grid capacity without new rights-of-way.

Section 2.a. U.S. grid overview

The U.S. transmission and distribution grid is owned and operated by over 3,000 investor-owned utilities, publicly-owned utilities(e.g., municipalities), and electric cooperatives with oversight from a diverse array of regulatory and governing bodies. Across the United States, there are over 642,000 miles of high voltage transmission, 6.3 million miles of distribution lines, and 55,000 substations that serve over 170 million residential, commercial, and industrial customers.[lxiii] The average age of U.S. grid infrastructure is 40 years, with an estimated 30% of transmission lines needing to be replaced in the next decade and over 60% of distribution lines operating near or beyond their useful life.[lxiv]

Key grid stakeholders

Key grid stakeholders include:

- **Utilities:** There are three primary types of utilities in the United States, including investor-owned utilities (IOUs), public power utilities (including municipalities, federally owned electricity companies), and electric cooperatives.[37] IOUs serve ~72% of customers[lxv] and are profit-seeking, generating returns for shareholders primarily through an approved rate of return on capital expenditures approved by state and/or federal regulators. Public power utilities and co-ops—serving 16% and 13% of Americans, respectively[lxvi]—do not face a profit motive, but similarly are concerned with providing affordable and reliable service where elected local government officials or an elected board provide oversight into their operations and investment decisions.

37 There are a range of other utility types and grid asset owners including Tribal Utility Authorities, customer choice aggregators, and merchant operators, among others.

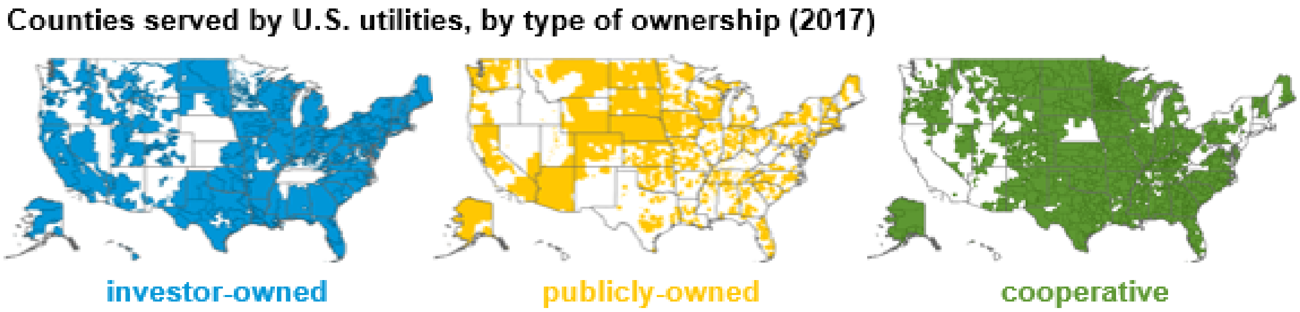


Figure 13. Counties served by U.S. utilities, by type of ownership (as of 2017)[lxvii]

- **Grid operators and balancing authorities**, including independent system operators (ISOs) and regional transmission organizations (RTOs), oversee overall grid and system reliability, security, and resilience, ensuring that supply and demand of electricity are constantly balanced.
- **Regulators**, including state public utility and state commissions (PUC/PSC), tribal authorities, and the Federal Energy Regulatory Commission (FERC), regulate utilities, developers, and grid operators based on statutory authority established under law, which often includes a focus on affordability, reliability, and security of electricity service.
- **Policymakers**, including state legislatures, tribal councils, and Congress, set policy direction and objectives impacting utility regulation decisions, impact state and tribal regulators by determining their statutory authority, and, for some states, establishing the PUC's budget and resource capacity.[38, lxviii]
- **Ratepayers, consumer advocates, and communities** typically prioritize minimizing electricity rates and energy bills to extent possible, weighing in on utility rate processes to support regulators and oversight boards in understanding if utility proposals are reasonable.

Other key stakeholders include trade, regulatory, and labor organizations, the Department of Energy and National Labs, and solutions providers (e.g., technology providers, consultants, and manufacturers). There are also a variety of civic society organizations (including academia, nonprofits, and think tanks) that produce thought leadership and directly or indirectly influence the design and implementation of policies and programs. These groups can engage during regulatory decision-making processes, such as by submitting comments on proposed rulemaking, regulatory requests for information, utility investment proposals ("rate cases"), and other key dockets.

Utilities, regulators, policymakers, and customers are consistently weighing the cost of grid investments next to a need for reliable power and broader policy goals. Figure 14 provides a simplified overview of the role and tradeoffs these players are balancing, with profit-motivated utilities as an example.

38 In most states, PUCs are funded based on fees and taxes paid by regulated utilities, but funding models vary.

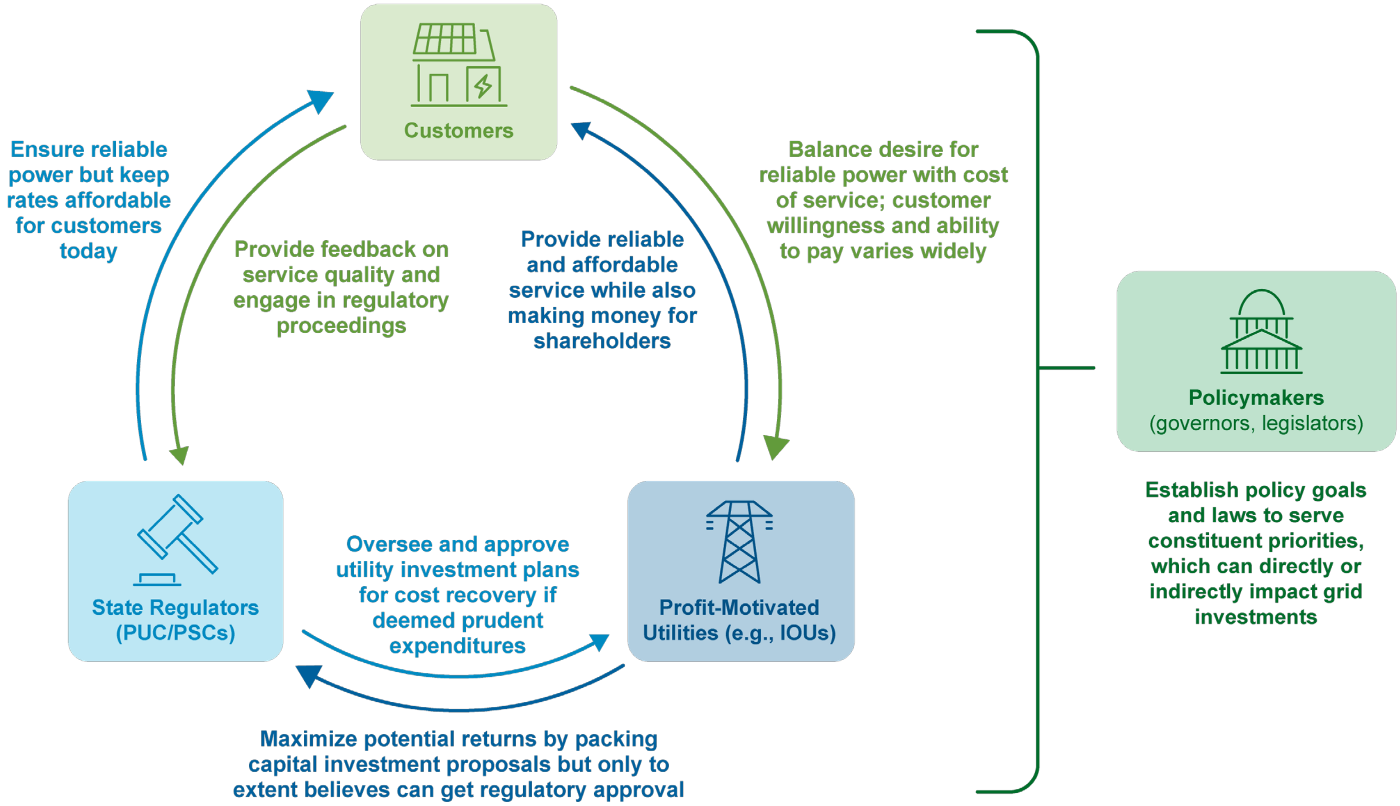


Figure 14. Example roles and motivations of grid stakeholders (profit-motivated utilities example)

Electricity market overview

The U.S. is geographically divided into vertically integrated markets and restructured markets.

- **Vertically integrated markets**: Utilities can own and operate generation, transmission, and distribution assets. Vertically integrated markets cover approximately one third of U.S. electricity demand.[lxix]
- **Restructured markets** (also referred to as 'deregulated markets'): Retail electricity suppliers, referred to as 'utilities' in this report, purchase power through wholesale markets or contractual arrangements rather than generate power with their own assets. Restructured markets serve approximately two-thirds of U.S. electricity demand.[lxx] Most utilities in restructured markets and some utilities in integrated markets belong to a nonprofit corporation called an Independent System Operator (ISO) or Regional Transmission Operator (RTO) that operates a regional bulk power system that balances demand with supply through a wholesale power marketplace.

States voluntarily allow their utilities to join ISOs/RTOs that are regulated by the Federal Electricity Reliability Corporation (FERC), while the state Public Utilities Commissions or Public Service Commissions (PUCs/PSCs) regulate the distribution systems and have oversight over transmission lines within their state. For vertically integrated markets, PUCs/PSCs also regulate generation. On Tribal lands, Tribal authorities often have sovereignty to regulate third party and tribally owned utilities, including distribution systems, transmission, and generation located within Tribal boundaries.

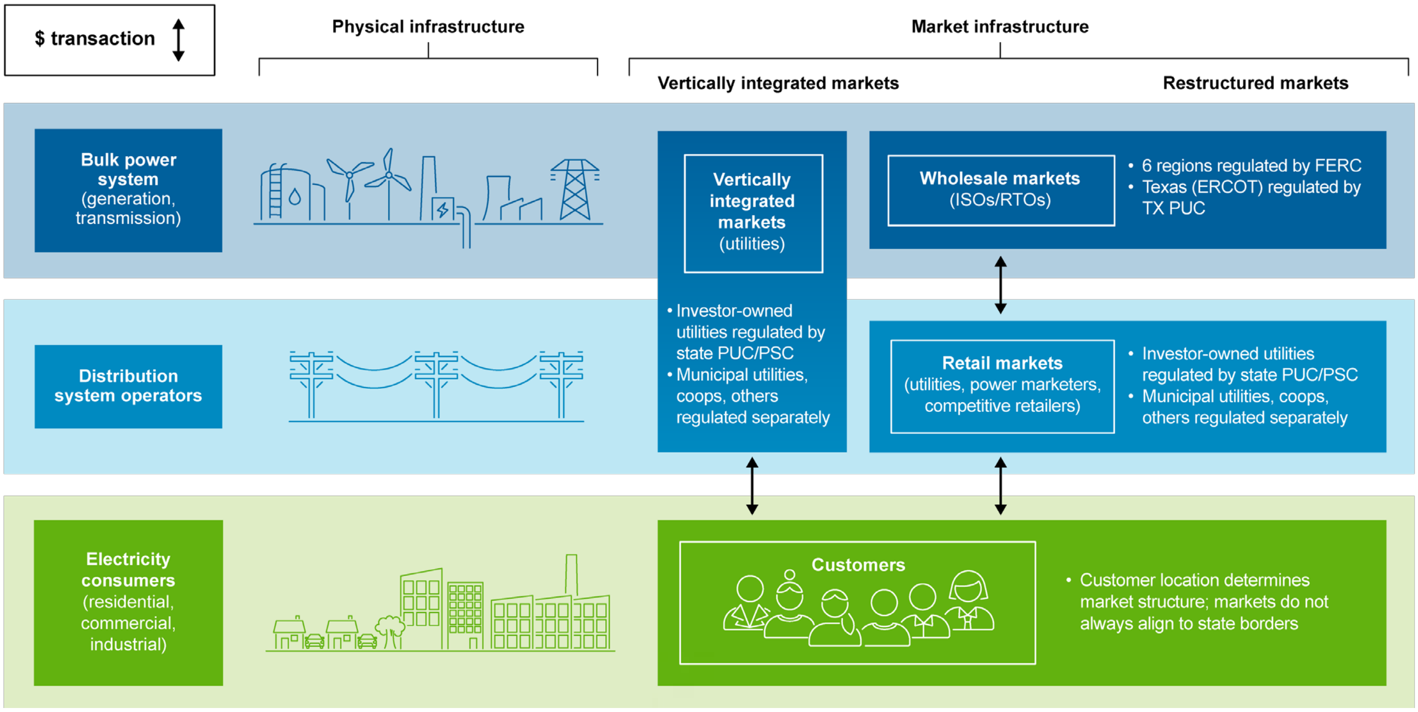


Figure 15. Electricity market overview

Grid planning and investment process overview

The grid planning process is divided between the distribution system and the bulk power system.

- **Distribution system**: Distribution investments are managed within state or Tribal boundaries by the local distribution system operator with the oversight of a state regulator or Tribal authority. Typically, distribution system investment decisions are made annually in response to a near-term reliability need (e.g., aging asset) or longer-term capacity expansion need in the form of an Integrated Resource Plan (IRP). As a result, distribution investments are often proposed and evaluated in separate planning processes, sometimes missing the benefits from a holistic, strategic approach to planning. Recognizing the need to bring together these disparate processes to drive greater ratepayer impacts, the DOE has developed Integrated Distribution System Planning (IDSP) resources to support regulators and grid operators in improving distribution system investment.[39] Nineteen states and the District of Columbia have started requiring regulated utilities to file some form of a distribution system plan (e.g., integrated distribution system plan, grid modernization plan, resilience plan) to manage investments, but this practice has not been uniformly adopted.[lxxi]
- **Bulk power system (including transmission)**: Transmission planning is a highly regulated process that involves engagement across a variety of utilities, state and federal regulators, ISO/RTOs and balancing authorities, and developers. Current transmission planning processes often tend to be siloed between regions, reactive to specific needs, and narrowly focused in terms of the benefits considered (focused on local area benefits instead of system-wide, quantifies only direct benefits based on the need considered).[lxxii] Transmission investments are often established in forward-looking ten-year plans that are developed by a variety of different regional forums that have limited interregional coordination and varying planning processes (e.g., ISO/RTO plans, WestConnect, and

39 Integrated Distribution System Planning provides a decision framework for developing holistic infrastructure investment strategies for local electricity grids. The planning process involves the determination of grid system requirements that are needed to achieve reliability, resilience, safety, affordability, and other objectives, such as equity and decarbonization. The process includes the development of a technology roadmap to modernize the grid and enable the integration, utilization, and orchestration of grid-edge technologies like storage, microgrids, and electric vehicles. Given the increasing complexity of demands on grid performance, IDSP provides a platform for holistic decision-making and the formulation of staged investment strategies. See the DOE's Distribution Grid Transformation site for additional information on Integrated Distribution System Planning and other distribution system resources including operational coordination and distribution system design.

sub-regional forums). New transmission or transmission upgrade investment decisions are typically focused on addressing a specific need in order to manage cost allocations, usually as a result either from an RTO/ISO or balancing authority (BA) that mandates transmission investment based on reliability concerns or from a utility/developer that proposes a project based on reliability and/or economic reasons.[40]

Within the distribution and bulk power planning processes, investment decisions are further siloed based on the type of investment. There are three general types of grid investments: 1) capacity expansion, 2) asset replacement (e.g., condition-based asset replacement for underperforming assets, aging infrastructure upgrade), or 3) grid hardening to respond to a reliability or resilience need.

1. **Changes in customer needs can trigger capacity expansion planning processes** (e.g., new generation interconnection request, growth in electricity demand). During a capacity expansion need, the grid operator will identify the necessary solutions to cost-effectively address that customer need while maintaining system reliability, such as by expanding or upgrading a transmission or distribution line or adding new generation capacity. This model is reactive to an existing or expected near-term need.
2. **Asset replacement planning is managed separately from this capacity expansion process.** When an asset is being replaced, whether due to age or underperformance, customer needs are already being met (or else a capacity expansion process would have been triggered). Since the system's needs are already addressed, grid operators will typically use a least-cost, like-for-like replacement process to replace or repair the asset back to its original performance standard. During an asset replacement, a utility does not typically proactively identify if there is potential value in upgrading that asset with an enhanced alternative that could effectively serve a future need. This could, indeed, face regulatory risk if seeking to perform a proactive upgrade to anticipate a need that, while foreseeable, falls outside of the utility's normal capacity planning timeframe.
3. **Grid hardening investments are often highly scrutinized by regulatory bodies and are often approved in reaction to extreme outage events.** Due to recent increases in the frequency and magnitude of extreme outage events, utilities are responding with climate resilience plans to harden infrastructure. These plans are often costly and sometimes lack sufficient evidence on the return on investment for regulators to approve, unless there are recent outage events that make customers willing to pay more for increased resilience.

Section 2.b. Current grid infrastructure investments

In 2023, utilities invested upwards of $170B across in the U.S. electric grid.[41, lxxiii] This included an estimated 18% spent on transmission infrastructure ($30.7B) and 34% spent on distribution infrastructure ($56.5B). Of this investment, the majority was spent on capacity expansion, conventional replacement, and hardening with only 7% of total transmission and distribution CAPEX going towards advanced technologies. This represents ~$1.8B in advanced transmission and $4B in advanced distribution solutions.[42, lxxiv]

40 Transmission upgrade processes vary based on drivers for investment. **New generation interconnection requests that requires transmission system upgrade:** In RTO regions, the RTO will conduct an interconnection impact study (recently shifting to a cluster study based on recent FERC order where requests are considered as a group instead of individually in the order in which they were received), tells the generator developer what the cost associated will be for the transmission upgrade, and the developer will pay for the cost of the transmission upgrade in order to interconnect to the grid. **Protect system reliability** (e.g., aging infrastructure, overloaded lines): In both RTO and non-RTO regions, utilities (or merchant developers) propose an upgrade to address the reliability concern identified by the RTO or utility (in vertically integrated markets). If proposals are approved, the utility/merchant developer can build the line and receive cost recovery at a set percentage based on FERC's return on equity parameters. **Economic rationale for investment** (e.g., reduce congestion costs, arbitrage opportunity): In RTO regions, the transmission owner submits a proposal to the RTO for a transmission upgrade. The RTO may study the proposal and either approve or reject it based on its system impact. If approved, the transmission owner can build the line, but accepts all economic risk (no approved cost recovery).

41 Data is based on Edison Electric Institute (EEI) and S&P Global data of public utilities. These utilities (EEI's members) represent about ~75% of Americans according to EEI. Additional investment from public power, co-ops, merchant developers, or others are not included in this estimate and would be incremental to IOU expenditure.

42 This "advanced technologies" category is defined by EEI and closely aligns with but may not overlap entirely with the advanced grid solutions covered in the scope of this Liftoff report.

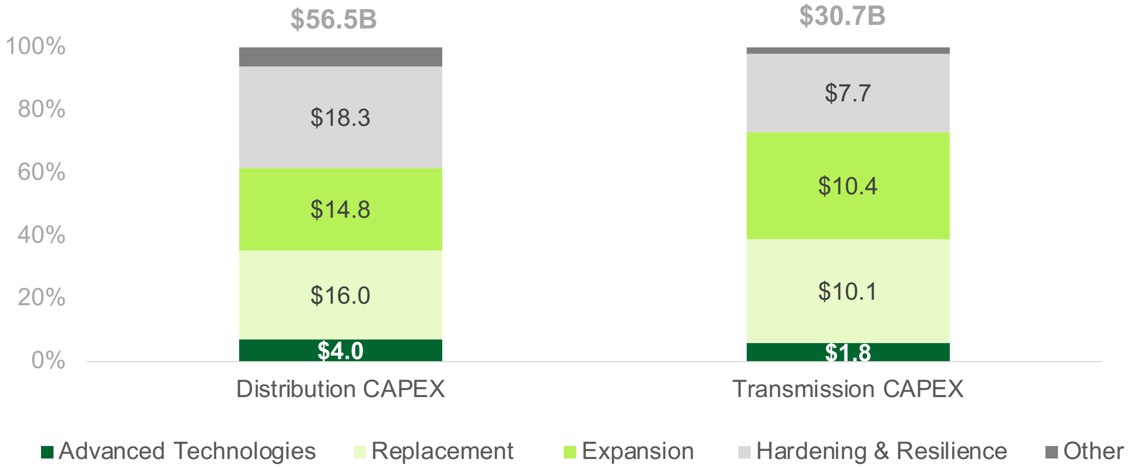


Figure 16. 2023 Investor-Owned Utility Transmission and Distribution CAPEX investment ($B) (Data Source: EEI, 2024)

Overall grid modernization investment has increased significantly in the last five years, with fifty major IOUs in the United States increasing annual investment in distribution grid modernization efforts by almost 10x from 2018 to 2023.[43, lxxv] Around 60% of these distribution investment proceedings were through traditional utility investment proposal processes (called "rate cases") or other regulator-approved grid modernization plans, where utilities earned an approved rate of return for investments (typically 10%). The remaining 40% were covered through various topic-specific proceedings (e.g., resilience plan, AMI plan) that may have been preapproved by a regulator for investment. [lxxvi] This illustrates the diversity of ways IOUs are pursuing grid modernization investments.

Section 2.c. Investment trends in advanced grid solutions

Several utilities across the United States have deployed a variety of advanced grid solutions to expand capacity and improve reliability and system affordability (see Appendix E for additional technology deployment examples).

Advanced grid solutions with greater industry interest include distribution automation and data management systems (e.g., ADMS), demand response and VPP solutions, and grid hardening investments.[44, lxxvii] IOUs drive the majority of investment in ADMS and advanced applications (VVO, DERMS, FLISR) with $1.2B in ADMS investments included in capital plans for fifty major IOUs as of 2023.[45, lxxviii] While public power utilities have exhibited interest in ADMS and DERMS solutions, many face cost and system integration barriers to adopting the advanced solutions. In a 2022 survey of sixty distribution utilities including many large IOUs, 21% had a fully operational ADMS system and another 49% were implementing some form of ADMS system, with 12% having an operational DERMS solution and 28% implementing a DERMS.[lxxix] Reflecting this industry trend, GDO's GRIP program saw a strong interest from IOUs, municipal utilities, and co-ops for ADMS and its related advanced applications. In the first round of funding, announced in October 2023, 16 ADMS projects were selected for $551.1M in federal support.

43 Wood Mackenzie's definition of grid modernization is more expansive than the twenty technologies in Liftoff scope and is broadly focused on physical hardening and modernization investments on the distribution system.

44 ADMS and advanced applications had ~30 proposed deployments across 19 states in 2023. Additionally, regulators approved several major investments in Michigan, New Jersey, North Carolina, Virgina, and California. VPPs and other demand response solutions have ~19 open proceedings across 8 states in 2023. In the face of nation-leading DER penetration in CA, the California Public Utilities Commission approved demand response pilot for three of its utilities: Pacific Gas & Electric, San Diego Gas and Electric, and Southern California Edison.

45 Interest and investment in VVO are increasing as it is now being viewed as a solution to manage DER impact through reactive power management capabilities. VVO along with other advanced applications are often deployed as the last modules of ADMS.

Other technologies have seen a more limited appetite for investment, particularly advanced transmission solutions. Transmission grid-enhancing technologies including DLR, advanced power flow control, and topology optimization have seen particularly limited utility interest at scale. Advanced conductors have had multiple deployments in the U.S. but largely remain a niche choice for select reconductoring applications when conventional steel core conductors (e.g., ACSR, basic ACSS) can't be used, such as when there are limited sag clearance allowances and thus a low-sag advanced conductor is required. Adoption of advanced conductors for their benefits in efficiency and capacity improvements has remained limited.[lxxx]

The application for storage as a transmission and distribution asset is emerging as a solution to meet system capacity needs. Most storage deployments to date have used storage as a generation asset. Energy storage of 4 hours or less has seen rapid market growth, representing more than 96% of deployments as of 2022, with much of this deployed alongside bulk power renewables and behind the meter customer-sited applications.[lxxxi] Investments in 6-10+ hour storage has remained limited due to a lack of sufficient market mechanisms to incentivize this level of capacity for its system reliability and resilience value.[lxxxii] Despite this strong uptick in storage as a generation asset, storage as a transmission and distribution asset is only recently starting to see greater interest. Several RTO/ISOs have started adjusting tariff and planning processes to better consider storage as a transmission solution.[lxxxiii] For example, the Midcontinent Independent System Operator (MISO) included a 20-hour energy storage project in 2020, finding it to be a cheaper alternative than rebuilding a transmission line.[lxxxiv]

Global investments in these transmission solutions have outpaced domestic adoption, despite many of these solution providers being headquartered and founded in the United States.[46] European transmission operators began piloting DLR in the late 2000s[lxxxv] and now have multiple scaled deployments. For example, Belgium's transmission operator, Elia, has over 30 active DLR deployments.[lxxxvi] Belgium has also widely deployed advanced conductors since 2009 to expand system capacity. China has used advanced conductors for a wide range of applications for decades, deploying over 370 miles of composite core conductors made in 2007 across a variety of projects using conductors by an American company (CTC Global).[lxxxvii]

Despite these advanced grid solutions' technical maturity and some growing industry interest, these advanced technologies remain underutilized at scale across the United States.

Section 2.d. Drivers of grid modernization investments

In the United States, grid modernization investment to date has largely been driven by reactions to legislative and regulatory mandates and significant external pressures (e.g., resilience and security threats, DER penetration). Industry stakeholders also cite the importance of individual technology champions within utilities and across the industry as a driver of advanced technology deployments.

Legislative and regulatory landscape

State-level grid modernization regulation and legislative yearly actions have increased approximately 2–3x since 2017.[lxxxviii] Across the United States, states and territories are exploring a range of options to advance grid modernization efforts. These include legislative actions such as (not exhaustive):

- Texas enacted H.B. 2555 allowing utilities to file three-year resilience plans for the transmission and distribution system.[lxxxix]
- Washington enacted S.B. 5165, extending IRP forecasts to 20 years and requiring consideration of grid modernization and demand response to use the existing system more effectively.[xc]
- Massachusetts passed a law mandating distribution utilities to prepare an Electric Sector

46 Example technology companies headquartered in the U.S. (not exhaustive): AutoGrid (ADMS); LineVision (DLR); SmartWires (DLR); SmartValves (APFC); NewGrid (topology optimization); CTC Global (advanced conductors); TS Conductor (advanced conductors).

Modernization Plan (ESMP) that motivates proactive upgrades to the distribution system.[xci]

- Montana passed H.B. 0729 that allowed advanced conductors with a certain efficiency improvement to be included in a utility's rate base with an incremental return-on-equity incentive.[xcii]

Regulators are also pursuing a variety of tactics. For example, nine states[47] have implemented performance-based regulation (PBR) to align utility incentives with key performance metrics,[48] while another twelve states are considering some form of PBR.[xciii] Twenty-two states and Puerto Rico have or are considering some sort of integrated distribution system planning or grid modernization plan requirement,[xciv] and several states require consideration of non-wires alternatives[49] when considering grid modernization objectives.

These actions correspond to increasing investment. For example, IOUs in New York and Massachusetts, states with regulator-mandated grid modernization plans, represented ~11% of total IOU grid modernization filings.[xcv] Additionally, Michigan and California have historically been active in creating grid modernization policies which has directly led to investment. In 2023, California utilities proposed $719 million in investments and Michigan utilities proposed ~$2 billion.[xcvi]

At the federal level, policymakers have recently proposed legislation to support advanced grid solutions. In March 2024, Senate bill S.3918 (The Advancing GETs Act) was proposed, which would require FERC to establish a shared saving mechanism for GETs and require transmission owners to report congestion data if passed.[xcvii] In December 2023, House bill H.R.6747 (The Clean Electricity and Transmission Acceleration Act of 2023) was proposed with requirements for "grid-enhancing asset" studies and deployment on the transmission system, including allowing interconnection customers to request deployment of those assets.[xcviii]

FERC has also taken significant actions on grid modernization in recent years. Additional rulemaking on transmission planning and cost allocation is expected in 2024. The lack of broad adoption to date of advanced transmission solutions has increased federal regulatory interest, with FERC Commissioner Allison Clements noted in November 2023, "these [GETs] are modest investments, they're going to save customers money… and if we don't tell the transmission owners to do it, they're not going to do it."[xcix]

Five FERC orders impacting grid modernization, which are in various stages of implementation, include:

- **FERC Order No. 881** requires transmission owners, both inside and outside of organized markets, to use ambient-adjusted ratings (AAR) to improve the accuracy of transmission line thermal ratings. This will lower consumer costs by increasing the utilization of the existing grid. The rule did not mandate the more advanced dynamic line ratings, but it did require organized market operators to enable transmission owners to use dynamic line ratings (if they choose to) by establishing and maintaining supporting systems.[c]

- **FERC Order No. 896 and 897** directs NERC to develop a reliability standard to require extreme temperature analysis be included in transmission planning and required transmission providers to submit one-time extreme weather vulnerability assessments. This effort is intended to improve system reliability during extreme events that "may cause unacceptable risk."[ci]

- **FERC Order No. 2222** requires regional organized wholesale markets to enable DER aggregators to participate in wholesale markets by establishing DERs as a market participant category. This opens wholesale markets up to a new source of resources which can drive lower consumer costs, improve grid flexibility and resilience, and promote innovation.

- **FERC Order No. 2023** aims to address interconnection queue backlogs with a wide array of revisions

47 These states include CA, CT, HI, IL, MD, NC, NV, RI, WA.

48 Performance-based regulations are a regulatory tool that realigns utility incentives around goals such as energy efficiency and DER penetration, which the traditional cost of service model does not fully motivate.

49 Non wires alternative is a term for any grid investment that defers or removes the need for construction or improvement of traditional "wires" transmission and distribution infrastructure.

to current interconnection processes partially focused on preventing undue discrimination against new technologies.

External pressures driving grid modernization

External pressures including wildfires, major weather events, and increasing DER penetration are driving utility modernization investments. Across fifty major IOUs, nearly a third of investment was concentrated in Florida, Louisiana, and Georgia where severe weather is most costly and almost another third was concentrated in California where wildfire threats and DER penetration are growing.[cii] Increasing DER penetration in the northeast is driving utility investment in advanced AMI and DER integration solutions.[ciii] Transmission constraints and load growth are motivating utilities and RTO/ISOs to pursue fast and affordable capacity enhancing solutions like DLR.

Federal support is helping industry deploy advanced grid solutions to address these pressures. For example, DOE's Grid Deployment Office's GRIP program selected Dominion Energy Virginia for a $33.7M grant to alleviate transmission system congestion using DLR technology. Thirteen wildfire resilience projects across the U.S. were selected for $662.5M in grant funding. GRIP funding will also be directed towards FLISR and topology management upgrades to protect from hurricane threats at Surry Yadkin EMC (a cooperative in rural North Carolina) as well as a DERMS platform to manage increased electrification at CPS Energy (a municipal utility in San Antonio, Texas), among others. The DOE's Loan Programs Office is actively engaged with developers and utilities regarding transmission reconductoring and HVDC projects along with VPPs and other advanced grid solutions. For example, LPO has conditionally committed to a $3B loan guarantee for VPP deployments in Puerto Rico to support local grid modernization and resilience priorities.

Advanced grid technology deployments are already driving positive impacts to improve system reliability and capacity in the face of these challenges. For example, Arizona Public Service (APS) implemented ADMS in response to wildfire risks and increased DER penetration. Since implementation, ADMS has enabled APS to effectively integrate more rooftop solar and better manage the grid to prevent and endure wildfires.[civ] In March 2024, Heimdall Power completed the largest DLR deployment to date with 52 sensors installed for Great River Energy (a cooperative in Minnesota and Wisconsin). The initial deployments resulted in an average 42.8% transmission capacity increase, relieving transmission constraints.[cv]

See Appendix E for additional advanced grid solutions case studies.

Chapter 3: Pathway to Liftoff

Key takeaways

- Advanced grid solutions can be an important bridge to manage rising load while new transmission infrastructure is built out.
- While deploying advanced grid solutions individually overnight could increase grid capacity by 20-100 GW, realistic deployment will take time; achieving liftoff within three to five years is possible with an estimated 6–12 large scale deployments across a diverse set of utility contexts for each advanced grid technology.
- These solutions could be deployed without directly increasing costs to household ratepayers.
- Liftoff can be realized through advancing four priorities simultaneously:
  1. **Build the bank of evidence to validate the technology value proposition**
  2. **Develop implementation and operational know-how**
  3. **Refine planning and investment case approaches**
  4. **Align economic models and incentives**
- Liftoff will be achieved when utilities and regulators comprehensively value and integrate advanced grid solutions as part of core grid planning, investment, and operations.

Section 3.a. Priorities to achieve Liftoff

Liftoff will be achieved when utilities, regulators, and other stakeholders comprehensively value and integrate advanced grid solutions as part of core grid planning, investment, and operations. When these technologies are fairly and effectively considered on par with alternatives, utilities and regulators can choose the best solution to drive system-optimal outcomes for the long-term, whether it is an advanced technology, new infrastructure expansion, or conventional like-for-like asset replacement.

Achieving liftoff within three to five years is possible by deploying 6-12 large operational, no regrets deployments across a diverse set of utility contexts for each advanced grid technology—deployed individually or in combination. Four priorities should be simultaneously addressed during these deployments to achieve liftoff.

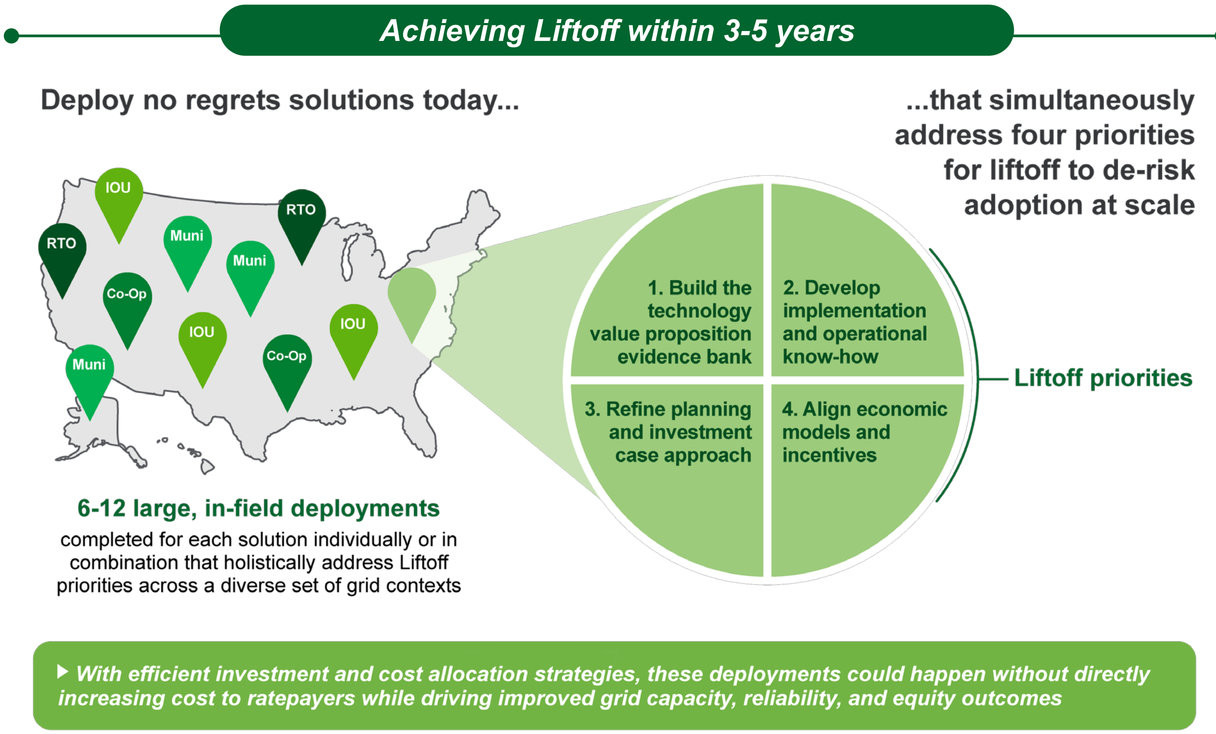


Figure 17. Achieving liftoff for advanced grid solutions

1. **Build and share the bank of evidence for the technology value proposition:** Building widespread understanding and confidence in these advanced technologies as viable alternatives to conventional solutions is critical to broader acceptance by utilities and regulators. Outcomes from these deployments should be transparently shared across industry players and regulators—including lessons learned from successes *and* failures—to build industry familiarity in these technologies' capabilities, operational impacts, and value propositions. Both utilities and regulators must gain a detailed understanding of the specific system conditions that enable these technologies to provide value, or that prevent them from doing so. Advanced grid solution deployments can vary widely in types of technologies invested, sequence of implementation, and applicability to targeted sections of the grid, which necessitates this increase in a diverse bank of evidence to better understand technology use cases and various interacting effects.

2. **Develop implementation and operational know-how:** Grid operators need to know how to procure, install, and operate these innovative solutions. Key processes underpinning greater scale deployment include standardized and interoperable technical specifications, installation and inspection checklists, workforce partnerships and training, proactive peer-sharing approaches, and operational guidance and best practices. The necessary know-how will vary by technology type—e.g., data-oriented software solutions like ADMS require guidance on integrating into existing operational systems, often requiring new workflows and training for employees to avoid piecemeal procurement; hardware solutions like advanced conductors require engineering guidance on new installation practices. The know-how and resources developed in early deployments can inform workforce training programs and deployment playbooks at scale.

3. **Refine planning and investment case approaches:** Grid planners and operators need to know how to include these technologies in system planning and assess and prioritize these solutions for investment. Regulators and governance boards likewise need to understand the cost effectiveness of these technologies and how they should be incorporated into affordable grid modernization plans to prudently oversee utility proposals. This requires a comprehensive understanding of, and methods

for, evaluating the benefits and costs of these technologies—including benefits that are hard to measure and value today—along with guidance on best practices for deployment strategies without prescribing a "one-size-fits-all" approach.

4. **Align economic models and incentives:** Grid operators are looking for certainty on how these solutions will be paid for and, for profit-motivated operators, if they can generate sufficient financial returns to warrant investment. For regulated utilities, this will require regulators to lead in aligning utility compensation models with the value generated from, and costs of, advanced grid solutions to deliver ratepayer benefits—e.g., implementing performance-based regulation, allowing some operational expenditures to be capitalized. New mechanisms are needed that allocate costs in ways that better align with beneficiaries and equitably share benefits.

All four priorities are essential pillars of success. Priorities 1 and 2 necessitate action from grid operators and industry to drive technology deployment capabilities. Priorities 3 and 4 will require action from regulators, governance boards, and grid planners; these priorities are particularly important linchpins to address to build sustained market demand for advanced grid solutions. Collaboration across industry stakeholders will be necessary to simultaneously advance these priorities.

These priorities are interrelated; the learnings and data from the 6-12 deployments should inform and reinforce these priorities and broader adoption at scale. The outcomes from these deployments can provide the necessary information to enable other utilities and grid operators to quickly move from operational pilots to broad deployment across their system—avoiding the "pilot purgatory" that has historically plagued new grid technologies. These priorities can serve as a high-level checklist for the key steps necessary to support deployment at scale across these technologies. Action on all four of these priorities has already begun and can continue to evolve to enable liftoff and deployment at scale. Future efforts should focus on closing gaps rather than continuing to validate already known features.[50] Chapter 4 further discusses potential solutions to address key challenges.

If liftoff and broad deployment is pursued quickly, advanced grid solutions can be an important bridge while new transmission infrastructure is built out. These solutions can then also be integrated into that new construction from day one to maximize system value. Investing in the operational and planning models needed to support these advanced grid solutions can help pave the way for future adoption of grid innovations that are in pre-commercial stages today.

Through more efficient and equitable investment approaches, these deployments could increase near-term grid performance without directly increasing costs to residential ratepayers. Given the significant investment that will need to happen to replace, expand, and modernize the grid, strategic investment in advanced grid solutions today can help manage overall system costs in the long run.

For example, using just one-fifth of the current investment in conventional transmission and distribution asset replacement to instead upgrade assets with advanced grid solutions could nearly double industry investment in advanced grid solutions, driving greater grid impacts without increasing costs to ratepayers.[51, cvi] As an illustrative example in Figure 18, shifting 20% of the existing $10B investment in conventional transmission asset replacement towards an advanced transmission technology upgrade like advanced power flow control (APFC) would enable five times more APFC deployments, which could be spread across a larger portion of the grid to unlock more grid capacity while alleviating strain on

50 For example, for advanced conductors, there have been many deployments across the United States and globally, which a sufficient bank of evidence of the technology's value proposition is likely available but needs to be gathered and disseminated. Digital substations, however, have had more limited adoption so may require additional operational deployments to clarify the value proposition and build the necessary operational know how.

51 Approximately $26B capital investment was spent on transmission and distribution replacement and $5.8B on advanced transmission and distribution technologies in 2023. Reallocating 20% of this $26B (or ~$5B) would nearly double investment into advanced transmission and distribution technologies. This illustration puts the opportunity in context; grid operators and regulators will still need to close evaluate the opportunity to reallocate replacement investment to maintain system reliability.

existing assets and help defer upgrades.[52] In this example, the net impact could be a 1.8x impact on transmission capacity without additional cost to ratepayers.

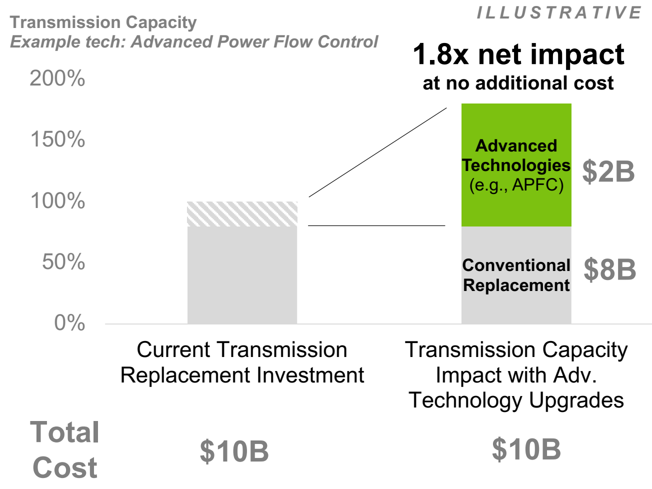


Figure 18. Example impact of using current transmission replacement investment for an advanced grid solution

Additional sources of capital can also support liftoff and deployments at scale, such as revising cost allocation mechanisms, building new revenue streams, and leveraging federal funding programs. For example, the costs of grid capacity upgrades associated with new data centers and manufacturing customers or interconnection of bulk power generators could be paid by those beneficiaries. Since many advanced grid solutions are low cost, the incremental cost is marginal relative to the benefit to these customers of being able to connect to the grid. As another example, deployment of advanced grid solutions in collaboration could reduce costs or open new revenue sources to help cover or offset investment costs, such as electric cooperatives sharing the costs of DERMS platforms or generating new revenue by providing broadband services as part of its communication infrastructure to support advanced grid solutions.[53, cvii]

Additionally, federal funding is available to support deployment of advanced technologies and reduce pressure on customer rates. For example, at the DOE, the Grid Deployment Office's GRIP program is awarding $10.5B for advanced grid deployments and resilience solutions. In its first round of selections in October 2023, $2.1B in GRIP funds will be directed towards projects that deploy the advanced technologies covered in this report.

Section 3.b. Utility examples: What liftoff could look like

A simplified set of hypothetical utility examples were developed in this report to illustrate what liftoff might look like for these advanced grid solutions. This includes the implications for grid operators and regulators on new investment approaches and economic models (liftoff priorities 3 and 4) that can be applied to these technologies.[54] A subset of this analysis is summarized here. Additional detail and examples are in Appendix B.

52 APFCs are typically less than 15-25% of the cost of a conventional upgrade to achieve the same capacity impact (see Chapter 1, Section C for additional discussion), so a midpoint of 20% was used in this illustrative example.

53 A National Rural Electric Cooperative Association (NRECA) survey found, of the coops that have deployed fiber-based consumer broadband solutions, >90% leveraged fiber to modernize substations and >75% leveraged fiber to deploy advanced sensors and smart reclosers.

54 These utility cases are simplified, illustrative examples that leverage real benefit and cost assessment models but are not intended to be guidance for any specific utility or on any specific benefit/cost assessment method. Utilities and regulators will need to identify the appropriate advanced grid solutions for their individual needs and objectives, agree on a relevant benefit/cost framework, and determine the appropriate planning and economic models to support these investments.

Example in practice 1: Medium IOU (Midwest)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Med IOU ***Midwest***	• Shift from fossil gen to renewables • Aging assets (vulnerable to weather, IBRs) • Extreme weather (winter storms, wind, tornadoes)	• Increase system capacity and flexibility to accommodate range of generation resources • Improve reliability & resilience	✓ **Point-to-point HVDC** (converting aging HVAC to HVDC) *Capacity and efficiency solution to connect renewables over long distance, improve system reliability* ✓ **8h energy storage** *Complement renewables, improve system resilience, provide grid-balancing services*	✓ **Digital substations** *Enhance network flexibility and resilience, support renewable integration, amplify storage and APFC* ✓ **Advanced Power Flow Control (APFC)** *Improve transmission utilization and unlock needed capacity as generation mix shifts*

In this hypothetical example, the state regulator, in collaboration with the regional ISO, identified a long-term need to improve regional grid reliability and resilience amidst increasing extreme weather and to integrate additional low-cost generation resources to replace retiring fossil assets. The local medium-sized IOU developed an integrated system plan to identify investments that would effectively and efficiently achieve these objectives based on its local context, existing assets and capabilities, and customer needs.

In this scenario, the Midwest IOU identified a set of advanced grid solutions that met these long-term objectives while driving near-term value. For example, instead of replacing several aging long-distance transmission lines with like-for-like HVAC lines, the IOU identified that these lines could be converted to point-to-point HVDC system to increase transmission capacity, efficiency, and improve system reliability and resilience with greater renewable penetration and extreme weather. The utility proposed 8h energy storage as an attractive resilience measure along with digital substations, which can better integrate storage as a distributed energy resource. This package could improve reliability by providing short duration contingency power during peak load times and during interruption events. In the future, storage coupled with new renewable generation could be used to address demand growth. These reliability improvements and potential increases in distributed generation could defer the IOU's transmission and distribution capacity needs to varying degrees. Additionally, advanced power flow controls and digital substations could enhance and optimize the existing grid's utilization and reduce line overloading, thereby effectively increasing transmission capacity in certain situations.

Example success factors (not exhaustive):

- Regulator and IOU proactively identified opportunities to leverage advanced technologies to address current and expected future grid needs.
- IOU tailored the investment bundle and deployment roadmap to local conditions, utility service objectives, and existing capabilities.
- IOU reallocated regular asset replacement investment to support advanced grid solutions (e.g., HVDC, power flow control), and preposition grid for greater renewable energy generation.
- IOU and regulator agreed on best practices for grid modernization planning, including taking an objective-based approach and longer time horizon to identify needs and inform investment strategies.

Example in practice 2: Rural Co-Op (Northwest)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Rural Co-Op *Northwest*	• Intense & variable weather (wildfire, wind, high temp) • High disruption risks across rural areas • DER penetration expected for reliability	• Improve reliability & resilience • Prepare system for DERs	✓ **8h Energy Storage** *Improve system resilience, complements expected DER, manage power costs* ✓ **Smart Reclosers** *Identify faults quickly and accurately, reduce outage times, improve grid reliability*	✓ **Digital Substations** *Key amplifier of storage and smart reclosers; improves network flexibility and resilience, including with expected DERs*

In this hypothetical example, in collaboration with its Board of Trustees, the rural cooperative identified strategies to improve distribution system reliability and resilience to better support customers during extreme climate events. Smart reclosers and 8h energy storage were identified as key technologies that could improve reliability and resilience today and in the long term. These technologies build off the co-op's existing communications broadband infrastructure with some minor upgrades.

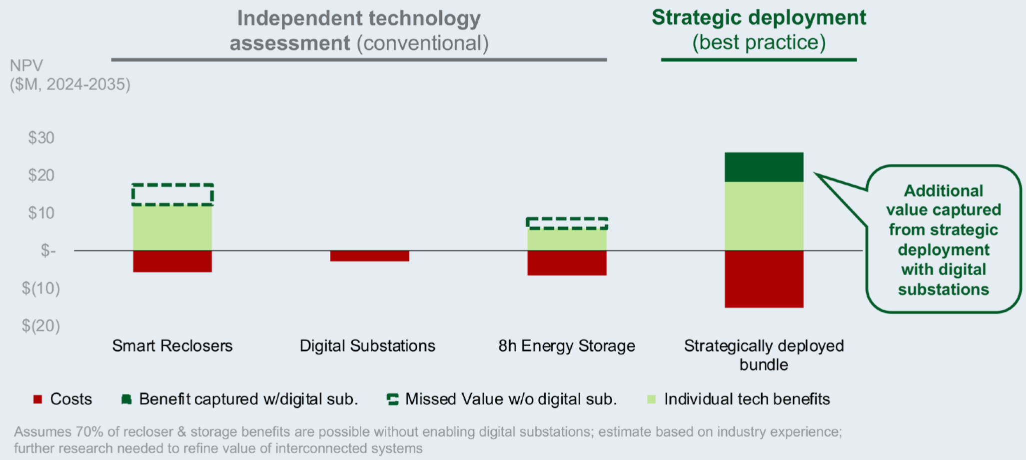


Figure 19. Benefit-Cost Assessment Outcomes of Rural Co-Op solutions bundle

In the near term, the co-op identified an opportunity to digitize several substations to unlock additional value today from smart reclosers (through better situational awareness of faults) and energy storage (through better monitoring and control).[55] As an enabling technology, digital substations have lower standalone value and can be harder to justify for investment, but this solution can meaningfully amplify the impact of other technologies when deployed in combination. As shown in Figure 19, the cooperative identified a positive benefit-cost (B-C) ratio for the combined value of these technologies. The additional value of smart reclosers and energy storage can be captured at relatively low cost, justifying the bundle investment.

Example success factors (not exhaustive):

- Co-op developed an investment plan that created customer value today through improved reliability while laying a foundation for additional resilience and DER solutions down the road.
- Co-op identified complementary technology bundles to maximize system value—including digital substations, which have limited standalone value but are a key amplifier of other solutions.
- Upgrades to foundational systems and technology deployments are right-sized today to unlock access to new technologies and compounding benefits down the road (e.g., smart reclosers that can work with FLISR, upgrades to communications today can support near-term and long-term technology deployments).

55 Digital substations can enhance smart recloser benefits by enabling coordinated protection schemes to further improve reliability impacts and energy storage by improving automatic optimization of charging and discharging.

Example in practice 3: Large IOU (Southeast)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Large IOU *Southeast*	• Manufacturing-driven load growth • Transmission constrained • High energy burdens	• Expand system to support local economic growth • Equitably alleviate cost pressures	✓ **ADMS VVO** *Dx efficiency improvement reduces ratepayer costs & alleviates Tx capacity needs* ✓ **Dynamic line rating (DLR)** *Low cost, near-term Tx capacity solution; increased system visibility improves reliability*	✓ **Advanced Conductors** *Increases Tx capacity to meet C&I demand; enhances system efficiency to reduce costs* ✓ **Digital Substations** *Key amplifier of VVO & DLR to maximize value; improves network flexibility and resilience*

In this hypothetical example, the large IOU was starting to see increased curtailment of low-cost energy generation due to a lack of sufficient transmission capacity. This was causing increasing congestion costs for ratepayers as gas-fired peaker plants were being deployed instead of the lower-cost renewables.

In this setting, a conventional cost-of-service compensation model can skew the financial incentive of the utility to choose higher capital expenditure (CAPEX) projects over more cost-effective solutions, as utilities receive a rate of return on approved capital expenditures. Although a low-cost solution like DLR could reduce congestion by unlocking effective capacity headroom on existing transmission lines, the cost to deploy DLR on several lines at roughly $10 million would only generate $1 million in ROI, which is often less than potential earnings from more expensive CAPEX alternatives (e.g., new transmission, asset replacement). Thus, the IOU may not prioritize DLR if congestion is not an imminent reliability threat and the investment brings limited financial value under current regulatory frameworks. The IOU can continue normal operations with gas-fired peaker plants serving demand. The resulting higher energy costs would be passed to consumers while the IOU pursues other investments (e.g., new transmission).

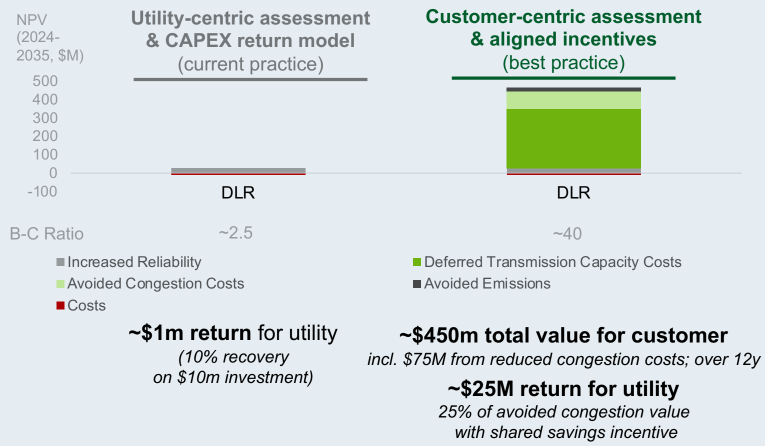


Figure 20. Benefit-Cost Assessment of DLR at Large IOU

When using a proactive, comprehensive, and customer-centric investment approach, the IOU identifies DLR as a viable low-cost option to reduce congestion costs. This comprehensive assessment identified additional benefits, including deferred transmission capacity cost, avoided congestion cost, and reduced greenhouse gas emissions. In total, this deployment could drive $450M in total value for customers over the 12-year investment period assessed—including $100M in total avoided congestion costs.

The PUC recognized the need to align the IOU's incentives with customer outcomes. The PUC established a shared savings mechanism where the utility could receive 25% of the value of the $100M reduced congestion costs. This translated into $25M in financial incentive for the utility, with $75M in benefits still going to customers through lower energy costs. This $25M incentive (significantly higher than the $1M return the IOU would have seen under conventional cost-of-service regulation) motivates the utility to prioritize DLR.

Example success factors (not exhaustive):

- Comprehensive, customer-centric benefit-cost assessment used to identify system and societal benefits of investment over longer time horizon.
- Regulator adopted a new incentive mechanism to financially reward the utility based on the benefits for customers in terms of reduced congestion costs (lower energy costs).

Section 3.c. Additional considerations on the pathway to liftoff

Successfully achieving liftoff and deploying these grid solutions at scale will have broader implications for industry and society.

Energy Justice and Equity

As discussed in Chapter 1, properly and intentionally implemented advanced technology deployments on the existing system have the potential to enhance energy justice and equity for communities today. These benefits must be intentionally prioritized to ensure realized outcomes equitably benefit disadvantaged communities and do not exacerbate existing inequalities. Given the scope of the Liftoff report focused on the existing grid, there is a risk of exacerbating compounding burdens for communities that have faced historical injustices and energy burdens from inadequate grid infrastructure. For example, if aging infrastructure in a disadvantaged community cannot support advanced ADMS-VVO applications, these deployments may then be prioritized in higher income areas with higher quality grid infrastructure. Instead, grid operators can look at the opportunity to focus on investments in not only upgrading aging infrastructure in these disadvantaged communities but enhancing it with more advanced technologies to drive positive outcomes above and beyond conventional replacements to benefit these communities. Additionally, expanding access through new system expansion is an essential solution to advance energy justice that is not covered in this report.

Careful consideration should be given to the distribution of benefits and costs of advanced technology deployments to advance equity outcomes. Several advanced technologies can help reduce energy costs, such as DLR that reduces congestion costs or ADMS-VVO that reduces energy consumption through improved efficiency. These benefits could be intentionally distributed to help reduce the energy burdens for disadvantaged communities. Further, technology costs can be allocated to reduce energy burdens (e.g., allocated to generators or large commercial and industrial customers instead of socializing costs across ratepayers).

Beyond the benefits of these technology deployments, the significant investment opportunity to advance these efforts can create high-paying, stable jobs in disadvantaged communities. Special attention should be given to recruit and retain talent from underrepresented groups when developing workforce recruiting and training programs.

Communities must be engaged early in the development of grid modernization planning and investment to ensure they have a voice in the design and deployment of these solutions.[56] This is core to ensuring procedural justice. Creating accessible engagement opportunities is essential to ensure disadvantaged communities can effectively participate, such as including flexible participation options (e.g., virtual meetings, online commenting options), providing financial compensation and other support (e.g., childcare), providing non-technical educational resources on grid topics, and engaging with local and trusted community groups through existing community forums. Regulators, grid operators, and policymakers must ensure that communities are engaged consistently throughout all grid planning and modernization processes to ensure their voices are heard and reflected in decisions.

Workforce

Actively engaging labor in key planning and policy processes and expanding and training the grid workforce—from planners and control room operators to line workers and IT/OT developers—is critical for deployment at scale of advanced grid solutions.

56 The Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts offers additional information and guidance on cross-cutting issues related to EEJ, community and labor engagement, workforce development and quality jobs, and diversity, equity, inclusion, and accessibility. Lawrence Berkeley National Laboratory's Integrated Distribution System Planning resources include guidance on developing stakeholder engagement processes and integrating equity objectives during planning. Community Benefits Agreements (CBA) frameworks can serve as a useful tool for regulators and grid operators to engage with the community and consider how the benefits of local projects can benefit the affected community.

Deploying advanced grid solutions—and grid modernization and expansion more broadly—has the potential to accelerate industry employment and create good-paying, high-quality jobs across the grid landscape. In 2022, the transmission, distribution, and storage industry employed an estimated ~1.4 million employees (up ~2.2% from 2021), with an estimated 3% of workers engaged in grid modernization or smart grid efforts with the majority still employed in traditional grid careers.[57,cviii] This moderate growth comes after decades of declining industry employment, driven by both attrition from retiring workers and a shift toward contracted labor instead of in-house employees.[58,cix] Building on recent momentum and the industry's existing union strength to expand high-paying jobs can reverse this trend.[59,cx] Special attention should be given to recruit and retain workers from underrepresented groups, including implementing support structures that help address common barriers to completing training or apprenticeship programs (e.g., child care support, transportation assistance, emergency cash assistance, career navigation and mentorship).[60,cxi]

Advanced technology deployments will require both upskilling parts of the existing workforce and training a new workforce on how to plan, install, operate, and maintain these systems.[cxii] The grid workforce is already highly skilled given the complex and technical nature of the work and extensive training required, but work experience is varied with an estimated 56% of workforce having less than ten years of experience.[cxiii] This basis and the availability of several established industry recruitment and training programs (including those run by International Brotherhood of Electrical Workers, Electric Power Research Institute, and Center for Energy Workforce Development) provide a strong platform to build from to educate workers on advanced grid solutions. Further investment in expanding training and Registered Apprenticeship[61] programs that integrate advanced grid solutions can ensure the future grid workforce is sufficiently equipped across the full technology lifecycle (from planning through end of life). Additionally, leveraging these training programs to proactively manage shifts in types of jobs (potentially away from centralized grid roles to more distributed and more IT-oriented jobs) will be important to ensure workers are not left behind, and the quality of jobs is maintained or improved in the transition to a more modernized grid.

Grid operators, labor organizations, regulators, policymakers, government agencies, and other stakeholders have key roles to play in driving strong workforce and operational outcomes during advanced grid technology deployments. Given the time associated with advanced grid technology training, industry employers (e.g., utilities, contractors, solutions providers) and labor groups can pursue proactive hiring and training strategies today to build needed workforce capabilities that enable future deployment. Regulators can play an important role in advancing workforce outcomes by reviewing utility staffing processes and roles, implementing performance standards that include workforce metrics (e.g., wages, benefits), and establishing transparency requirements on the use of contracted workers. Policymakers can advance supportive policies such as expanding PUC authority to include just workforce transition objectives or implementing measures to prioritize local hiring, creation of good paying jobs with essential benefits and career mobility potential, and implementation of training models that include essential support structures. Wage standards, such as prevailing wage, essential benefits to retain a skilled workforce, and project labor agreements, community workforce agreements are also good tools for securing and investing in a skilled workforce.

57 Transmission, distribution, and storage, as tracked by the DOE's Office of Energy Jobs, includes electric bulk power transmission and control, electric power distribution, natural gas distribution, EV charging, and battery storage jobs. See the U.S. Energy and Employment Report for additional information.

58 Between 1990 and 2020, electric power generation, transmission, and distribution employment declined by an estimated ~30%.

59 The transmission and distribution industry has some of the highest rates of unionization with 18% of employees represented by a union or under a project labor or collective bargaining agreement. Previous analysis has suggested 4.3 to 8.9 jobs can be created for every $1M spent on smart grid.

60 Women comprised only 2% of electrician and 9.4% of electrical and electronics engineering workforce as of 2021. Across the transmission, distribution, and storage sector (including natural gas), Black and African American workers represented only 10% of the workforce in 2022.

61 Registered Apprenticeships provide on-the job training, a wage from day one that grows over time, a national-recognized and industry-valued credential at the completion of the program, classroom instruction and mentorship.

Supply Chains

As advanced grid solutions reach liftoff, increased demand will challenge already stretched supply chains. Securing supply resources and scaling up domestic manufacturing capacity will be needed to support adoption at scale.

For example, the electric grid is currently facing supply chain constraints, particularly for distribution transformers, large power transformers, and HVDC systems. Utilities are reporting lead times of 1-2+ years for distribution transformers and more than two years for large power transformers.[cxiv] HVDC cables are in high demand globally, and HVDC substation procurement is being secured up to 7+ years in advance (e.g., HVDC substations for offshore wind are fully booked through 2032 globally). Limited domestic manufacturing for HVDC cable and substation components exacerbates these challenges.[cxv] These global bottlenecks will likely require global supply chain expansion, with opportunities for U.S. expansion as well. Recent DOE supply chain analysis found other moderate constraints impacting grid hardware and component parts—including advanced conductors, switchgear, and power electronics for smart grid solutions—which could become more critical bottlenecks as demand grows.[cxvi] While domestic manufacturers are already adding capacity for critical components, some with federal support (e.g., via the 48C Advanced Energy Project tax credit), additional buildout will be required to support deployment at scale for these advanced grid solutions.

How the 48C Advanced Energy Project tax credit can support grid component manufacturing.

The 48C Advanced Energy Project credit provides an investment tax credit of up to 30% for qualifying projects placed in service within 4 years. The Inflation Reduction Act provided $10B to be competitively allocated to selected applicants; manufacturing for "electric grid modernization equipment or components" qualifies under IRS guidance for 48C. The Department of Treasury has announced that they will issue a notice for the second round of allocations for the 48C Qualifying Advanced Energy Project Credit in the coming months.

Grid Security (cyber, physical)

Incorporating security-centric best practices during the assessment and deployment of new and advanced grid technology is crucial to ensuring the reliability and resiliency of the system. A growing and evolving set of cyber and physical threats in recent years along with the rapid evolution of the grid topology and resource mix necessitate a robust security posture.

Grid stakeholders should consider and integrate cyber and physical security when deploying advanced grid solutions, including a cyber/physical risk assessment, addressing supply chain risks (including trusted sourcing), and establishing maintenance and system update requirements.[62] Existing cybersecurity standards and best practices, such as multifactor authentication, endpoint detection and response, encryption, and a skilled and empowered security team, may need to be refined to integrate the unique properties of varying advanced grid solutions. When implementing both cyber and physical security measures, vendors, planners, and system operators should optimize systems for resilience—with the goal of surviving an attack while maintaining critical functionality.

Artificial Intelligence and Advanced Analytics

Advanced grid solutions could enable greater deployment of artificial intelligence (AI) and advanced analytics applications across the grid by enhancing the availability, quality, and granularity of system data. This data—if gathered and managed well—can support high impact use cases of advanced analytics and AI to enhance grid forecasting, planning, security, orchestration, and more.

62 Additional resources on cybersecurity include: DOE's Cybersecurity Capability Maturity Model (C2M2) program, which provides free tools and guidance to help organizations evaluate their cybersecurity capabilities and optimize security investments. The Cyber-Informed Engineering (CIE) framework aims to proactively build cybersecurity into U.S. energy systems. Cybersecurity Considerations for Distributed Energy Resources and Cybersecurity Baselines for Electric Distribution Systems and DER can help regulators, utilities, and DER operators and aggregators mitigate cybersecurity risk.

Basic AI solutions are already being used across the grid landscape to enhance grid outcomes, including improving grid forecasting and operational efficiencies. Industry first-movers are beginning to shift business models to solve data management challenges and increase the sophistication of their AI and data capabilities.[63] The opportunity—and potential need—for greater deployment of AI is growing as managing the complexity of a more dynamic modern grid grows. Industry and public sector interest and investment in understanding and identifying opportunities to leverage AI has likewise increased.[64]

Strong data management is a prerequisite to fully capturing the opportunity of AI and advanced analytics within the grid landscape. Today, a lack of high-quality and accessible grid data (including the historical data needed to train AI models) is a key bottleneck to the ability of grid operators and technology providers to fully leverage AI capabilities.[65,cxvii] The deployment of advanced grid solutions will create an influx of data, but resolving industry challenges and building enhanced data capabilities across the grid ecosystem will be needed to effectively leverage AI. See Chapter 4 for additional discussion on data quality and management.

63 Over the last 4 years, Avangrid has built a robust AI analysis team that "informs upper management decision making" and "has enabled significant success in rate cases". To build this data science capability, Avangrid first created a division that bridged IT and OT verticals and then constructed a relational data base that unified their data sources (including from advanced grid solutions like ADMS). This enabled significant AI projects that improve their asset management and grid reliability.

64 For example, at a major grid technology conference in 2024 (DISRTRIBUTECH International), each of the four keynote speakers discussed the sizeable potential of AI in the grid.

65 Today, it is hard to aggregate the necessary data for AI applications because data sharing and ownership rules are challenged between solutions providers and utilities, between utilities, and within utilities. Additionally, historical data is often not collected for non-core utility functions, which could enable valuable AI use cases.

Chapter 4: Challenges and Solutions for Liftoff

Key takeaways

- Many of the required solutions to deployment challenges have been or are being developed but are not yet widely adopted.
- Reducing execution variability with widely shared best practices, implementation guides, and operational playbooks could accelerate greater standardization across key technology dimensions, including establishing procurement standards, interoperability requirements, and data protocols.
- Establishing venues to encourage controlled risk taking can help spur a much-needed appetite for innovation across the industry.
- Economic models for advanced grid technology deployments do not have to depend on the traditional utility model that socializes all costs to ratepayers; alternative cost allocation strategies could be considered to reduce ratepayer costs.

Section 4.a. Challenges and potential solutions

Many of the required solutions to deployment challenges have been or are being developed but are not yet widely adopted. Liftoff will require a combination of dissemination of existing and development of new solutions in several areas.

Delivering these solutions—existing and new—will require collaboration across a diverse set of stakeholders, including utilities, regulators, technology providers, policymakers, consumer advocates, community groups, labor groups and unions, and industry associations, among others. These stakeholders can start adopting current best practices today—several of which are highlighted below—to quickly move industry forward even as additional progress is made.

The following summary of challenges and potential solutions is meant to initiate a dialogue; it is not a comprehensive inventory.

Table 7. Summary of key challenges and potential solutions for liftoff (not exhaustive)

Challenge		Potential solutions
Tech.	**1.** Awareness and common understanding are low for advanced grid solutions and their benefits and impacts are not well understood.	Publicly available and easily accessible technology information and data
Planning & Incentives	**2.** Current planning approaches and investment decision-making tools do not integrate advanced grid solutions in the analysis.	Integrated planning requirements Modeling platforms, tools, and services that better capture advanced grid solutions capabilities.
	3. Advanced grid solutions are not comprehensively and consistently evaluated.	Comprehensive evaluation criteria developed and broadly adopted
	4. Traditional regulated utility compensation models often create a financial disincentive to deploy advanced grid solutions.	Utility incentives and cost recovery models adjusted Alternative cost allocation models implemented
Implementation	**5.** Operational models and protocols to support advanced grid solutions are underdeveloped.	Implementation and operational best practices Industry change management resources and technical assistance Workforce development programs
Cross-Cutting	**6.** Structural and cultural barriers to innovation impede adoption of advanced grid solutions.	Regulatory and economic incentives and models that explicitly encourage innovation

Challenge 1: Awareness and common understanding are low for advanced grid solutions, and their benefits and impacts are not well understood.

This lack of common understanding hinders the ability of grid operators, regulators, and governance boards (including cooperative member-owners and municipal city councils) ability to make informed investment decisions.

For many advanced grid solutions, there is not a widely adopted industry definition or taxonomy. This perpetuates technology misperceptions and can drive unintended investment outcomes. For example, solutions providers may use advanced technology phrases as selling points but the actual product does not have the full set of capabilities (e.g., ADMS). Additionally, as a result of inappropriate technology characterizations, regulators have reported believing that advanced technologies had been implemented in their jurisdictions when they had not yet actually been deployed.[66]

A lack of comprehensive and publicly available historical performance data has led to uncertainty (real and perceived) among grid operators in technology capabilities. Utilities are hesitant to be 'early adopters'—even of technologies with high technology readiness levels—without broad confidence in the delivered benefits and other potential operational impacts (e.g., impact on other grid components, product reliability). This exacerbates technology misunderstandings.[67]

This lack of widely shared technology data is reflective of broader industry challenges associated with effectively collecting, managing, sharing, and using data within and between stakeholders. To protect their business models and due to potential security and customer privacy concerns, both regulated utilities

66 As an example, one regulator reported believing DLR had already been widely deployed across the state, but the system was still largely using static line ratings or ambient adjusted ratings.

67 For example, there is a common misperception that DLR shifts real time operational processes instantaneously in ways that threaten reliability. Ratings are actually set in fixed periods of time and can be overridden if needed.

and technology solution providers are incentivized to keep a close hold of grid data. Even within utilities, data sharing may often be limited due to the siloed nature of planning and operations today.[cxviii] These challenges are exacerbated by uncertainty on grid data ownership rules. These structural challenges often leave data sources incomplete, fragmented, and underutilized, which reduces the potential benefits that advanced grid solutions can provide.

Potential solution: Publicly available and easily accessible technology and deployment information.

A widely adopted common source of truth on technology definitions, benefits, and operational impacts could help address persistent industry misperceptions while clarifying technologies' real limitations. Additionally, outcomes from technology deployments should be transparently shared and accessible to a diverse set of stakeholders—including grid operators, solutions providers, regulators, and community advocates. Tracking and sharing technology performance, benefit, and cost data is not only critical for grid operators and solutions providers to inform technology design and deployments but also to enhance regulators and governance boards' ability to review investment proposals (further discussed in the challenges below).[68]

Example actions could include:

- **Public and private sector stakeholders could collaborate to establish a broadly accessible resource library national center of excellence or clearinghouse for advanced grid solutions.** This platform could, for example, house case studies, outcomes from deployments, standard taxonomies, and other best practices to improve information sharing.[69] Any efforts to increase availability and accessibility of technology deployment data can build on existing industry efforts.[70]

- **Solutions providers and grid operators could collaboratively develop and broadly adopt common taxonomies and definitions for advanced grid solutions.** Industry associations, DOE, or other industry stakeholders could help coordinate this alignment.

- **Public associations (e.g., NARUC, NASEO), DOE, industry think tanks, industry consortiums, and other expert stakeholders could collaboratively develop advanced grid solution trainings and resources tailored to regulators** (e.g., technology briefs, guides on what advanced technologies to look for in utility planning proposals).

- **Grid operators and solutions providers can track and publicly share outcomes from deployments.** This can establish a track record of technology performance and system impacts—including realized benefits, downside impacts, and other technology deployment considerations.

- **Recipients of federal funding could be required or incentivized to publicly share data and lessons learned to support public knowledge sharing.**[71] User-friendly summaries, standard data reporting formats, accessible databases, and peer-to-peer experience sharing could help facilitate broader ecosystem learning. This can complement ongoing DOE efforts to publish information on the impact of and best practices and lessons learned from DOE projects funded through the Bipartisan Infrastructure Law and Inflation Reduction Act.

68 Industry organizations have provided frameworks and standards to help address segments of the data sharing challenge, such as NARUC's Grid Data Sharing Playbook and IEEE's Standard 1547-2018. While broad adoption is still needed, some localities have started acting. For example, the New York state regulator established the Integrated Energy Data Resource Program to increase energy data sharing.

69 For example, the European Network of Transmission System Operators for Electricity (ENTSO-E) launched a Technopedia tool in 2020 to house technology fact sheets to support grid operators and regulators with understanding the latest on new grid technology solutions.

70 Example existing efforts that could be leveraged (not exhaustive): DOE's Grid Modernization Initiative platform could share advanced technology deployment information and resources; DOE's Voices of Experience series could build on existing smart grid experience sharing to focus on advanced grid technologies; Idaho National Laboratory's Transmission Optimization with Grid-Enhancing Technologies research, modelling and simulation methodology developments, and field test results, the Energy Systems Integration Group (ESIG) GETs Working Group, and EPRI's Energy Delivery and Customer Solutions portfolio could support technology information sharing.

71 For example, a criteria of the DOE's Grid Resilience and Innovation Partnerships (GRIP) Program is that the project is a catalyst for broader industry implementation, encouraging applicants to include initiatives to share best practices. See Appendix A for a longer list of other federal funding programs that can support advanced grid technology deployments.

- **DOE, national laboratories, or other industry experts could develop and share more detailed assessments of advanced grid solutions' applicability across the United States.** This could help address persistent uncertainty about a technology's use case and inform regulators, utilities, consumer advocates, and other stakeholders of the relevance of advanced grid solutions in specific locations.

- **Advocacy groups and grid operators could conduct community-focused educational campaigns to communicate the value of advanced grid solutions.** Gaining community buy-in can significantly derisk investment in new grid technologies and approaches.

Challenge 2: Current planning approaches and investment decision-making tools do not integrate advanced grid solutions in the analysis.

Current planning approaches are short-term and prioritize least-cost options to meet grid needs. The short-term planning horizons of <3–5 years—particularly for asset replacement and distribution systems—result in prioritization of solutions that address near term needs but that may be suboptimal for long-term grid performance. This premise is fundamentally based on the presumption that the existing grid is sufficient to meet customer needs, which drives utilities towards investments that incrementally build on existing assets and drives regulators to view "prudency" in terms of reducing costs to ratepayers today rather than considering future needs.

Additionally, as discussed in Chapter 2, grid planning is siloed between the bulk power and distribution systems and between capital expansion, asset replacement decision-making, and reliability and resilience enhancements. This results in missing or undervaluing opportunities to use advanced technologies that have system-wide value across transmission and distribution and that could be an upgrade solution that meets multiple grid modernization objectives.

The grid forecasting, modeling, and planning tools and approaches widely used throughout industry today have limited capabilities to model the impact of advanced grid solutions. Grid planners currently model how power flows through the system using various methodologies to simplify the calculation due to challenges of computational complexity (e.g., modeling direct current instead of alternating current for optimal power flow, assuming one-directional power flow). Additionally, grid planners often use different modeling approaches depending on the context. For example, planners will often use summer and winter peak loads only for considering capacity expansion, whereas hourly or sub-hourly data is used for reliability. Due to these limitations, planning tools often do not have the ability to assess the full benefits of advanced grid solutions and therefore determine their optimal deployment and use (e.g., DLR's impact on increasing effective capacity; VPP as solution to serve demand).

Potential solution: Integrated grid planning requirements to enable system-optimal decisions.

Integrated planning and grid modernization processes are evolving, but regulators and utilities can adopt current best practices as a first step to improve planning today (e.g., longer time horizons, scenario-based and integrated system modeling, stakeholder engagement requirement). Developments in planning can build from current best practices, such as DOE's *Integrated Distribution System Planning* resources or SEPA's *Incorporating Non-Wires Alternatives into Your Grid Modernization Program*.[cxix]

Additional investment in standardizing and templatizing these planning approaches is needed along with education and capacity-building to enable widespread adoption. Communities, labor groups, and policymakers are important stakeholders to proactively engage in shaping these grid modernization planning processes.[72]

72 Several states have taken steps to require or encourage utilities to engage with disadvantaged communities in planning processes. For example, Washington State's Clean Energy Transformation Act, passed in 2019, requires that the state's utilities ensure customers and communities benefit equitably from the clean energy transition, which resulted in the formation of equity advisory groups for the utilities. California provides intervenor compensation for under-resourced groups to formally engage with the California Public Utilities Commission during various proceedings.

Example actions could include:

- **Regulators could require utilities to consider advanced grid solutions in current planning processes as solutions to grid needs.**[73] Utilities could be required to provide justification for any exclusion of advanced grid solutions.
- **Grid operators could proactively improve planning processes and integrate advanced grid solutions—**both into current and new planning approaches. This involves considering multiple grid objectives simultaneously, considering a range of demand, supply and reliability scenarios, and thinking about system integration. The resources highlighted above can be leveraged to improve planning.
- **Regulators could require grid operators to adopt improved planning practices, such as integrated distribution system planning (IDSP) or total system planning across generation, transmission, and distribution.** This could include integrating asset replacement and capacity expansion processes. Regulators could leverage existing federal technical assistance and resources to enhance expertise and capacity to oversee these new planning processes.[74]
- **DOE could require applicants to consider advanced grid solutions in applications for federal grants or loans.**
- **DOE and industry groups could provide technical assistance and capacity-building resources to support state and Tribal regulators and policymakers.** This could support implementing planning process changes to ensure advanced technologies are appropriately integrated.
- **Policymakers and regulators could require utilities to engage with key stakeholders—including community and labor groups—and conduct an equity and energy justice analysis when developing advanced grid solutions investment plans.**

Potential solution: Capabilities of modeling platforms, tools, and services are improved to capture advanced grid solution benefits.

Industry stakeholders involved in grid planning (e.g., consultants, modeling platform providers, academia) can update their approaches and service offerings to better model the complexities of grid operations such as by using longitudinal data with shorter time intervals, increasing computational power and algorithm efficiency to improve model performance, and considering multiple scenarios through stochastic modeling approaches and the impacts on integrated systems. Advances in modeling capabilities can ensure that advanced grid solution benefits can be quantitatively captured and tradeoffs better considered when doing analysis of investment alternatives. For advanced grid solutions, modeling tools and service offerings can leverage best available data from historical deployments and the 6–12 deployments for liftoff to update planning processes and then refine these solutions over time as more industry data becomes available.

Challenge 3: Advanced grid solutions are not comprehensively and consistently evaluated.

Benefit-cost assessment (BCA) methodologies and cost-effectiveness frameworks used to assess conventional grid assets are not well suited for advanced grid solutions, as previously highlighted in Chapter 3. The societal and system benefits that result from many of these advanced grid solutions are often not fully considered and may be difficult to quantify and/or monetize (e.g., system resilience, greenhouse gas emission reduction, improved customer service). Additionally, advanced grid solutions are typically considered individually, missing out on the meaningful value of deploying these technologies in

73 Several states already require consideration of non-wires alternatives into grid distribution system planning processes. This could be expanded to include additional advanced grid technologies.

74 Existing programs include the DOE and National Laboratories resources and training programs on Integrated Distribution System Planning and DOE's State Technical Assistance Program, Technical Assistance Resilience program, and Clean Energy Innovator Fellowship.

combination, including combined benefit capabilities and cost synergies.[cxx] Further, the costs associated with these advanced technologies are often not well accounted for. For example, the costs of initial foundational infrastructure investments are often fully allocated to one new technology deployment—increasing the upfront costs significantly—rather than appropriately sharing the costs of the foundational investments across future technologies that are now unlocked.

When newer BCA methods for grid modernization are used, the application of these methods is often inconsistent. A Lawrence Berkeley National Laboratory review of twenty-one IOU grid modernization plans identified significant variations in which benefits are identified[75] and how they were defined for a range of innovative technologies. This challenge leads to lack of consistent and logical justifications for investments, inconsistencies across filings, and a suboptimal presentation of information.[cxxi]

These challenges adversely impact regulators' abilities to effectively review advanced grid technology proposals and investment cases.[cxxii]

Potential solution: Comprehensive evaluation criteria are established and broadly adopted for advanced grid solutions.

Clearly defining and developing measurement methods for the benefits expected from grid technologies and applications (including if/how it might vary based on deployment context) is an important first step to improve consistency in evaluation methods. Considerable progress has been made recently to improve benefit-cost methodologies for grid modernization investments. These efforts can continue to be refined with greater advanced grid technology performance data and deployment experiences, particularly to inform valuing impacts that are currently not well accounted for, such as reliability, resilience, greenhouse gas emission reductions, and socioeconomic and equity benefits. Additionally, new approaches may be needed to best account for the interdependencies and interactions between advanced grid solutions. Evaluation criteria for deployments should comprehensively track and report on the benefits, costs, and operational impacts to inform investment and operational decisions more fully. This can help mitigate a utility's uncertainty about the technology and speed up the time between an initial operational pilot to broad deployment—helping avoid perpetual piloting.[76]

Improved performance metrics and guidance on how to apply these metrics to evaluate costs and benefits over time is needed, particularly leading indicators for technologies that have long-term and/or especially diffuse benefits (e.g., DERMS, foundational infrastructure).[cxxiii]

Approaches for effectively assessing advanced grid solutions will continue to evolve, but utilities and regulators could start using emerging best practices for benefit-cost assessments today.

Example actions could include:

- **Grid operators, solutions providers, national laboratories, and other technology experts could develop and align on more comprehensive assessment criteria and frameworks for advanced grid solutions**. These frameworks can build on current best practices[77] that can be further refined through the 6-12 operational advanced technology deployments completed for liftoff.
- **DOE and the national laboratories—in collaboration with NARUC/NASEO and other industry stakeholders—could develop a cost-benefit guide or tools for regulators.** This could improve

75 In LBNL's review of twenty-one IOU modernization plans, there were thirteen benefit categories cited with various frequency. Reliability, DER integration, distribution O&M, and energy savings were listed in most reports, however less than 25% of reports claim power quality, resilience, and economic development as benefits.

76 Example benefits could include reliability improvement, cost savings, congestion relief, infrastructural deferral, climate benefits, technology synergies, climate impact, and energy justice impacts; example costs could include costs of security upgrades, increased aging of hardware from higher asset utilization, and operational costs associated with data management. (not exhaustive)

77 For example, the National Standard Practice Manual for Benefit-Cost Analysis of Distributed Energy Resources provides a comprehensive framework for cost-effectiveness assessment of DERs.

regulatory capacity in reviewing utility proposals to ensure investment plans are following best practices and fairly and consistently evaluating advanced grid solutions.[78]

- **Regulators or policymakers could continue to update and revise guidance on BCA frameworks to increase consistency in utility rate cases and investment proposals.** This could build off existing BCA framework and best practice.[79]
- **Solutions providers, grid operators, associations, and other stakeholders could clarify technology key performance indicators (including leading and lagging indicators) to support tracking of technology deployment success.** This could help equip utilities and regulators in understanding the success of early deployments to support investment and scaling—particularly for technologies whose benefits accrue over time and/or are more diffuse today.

Challenge 4: Traditional regulated utility compensation models often create a financial disincentive to deploy advanced grid solutions.

Broadly speaking, under traditional cost-of-service regulation, IOUs earn profits based on capital expenditures (CAPEX) investments and volumetric energy sales rather than customer outcomes. Operational expenditures (OPEX) are passed on to customers at cost, without generating a return for utilities.[80] This business model can disincentivize investments in innovative technologies that have relatively lower CAPEX costs, have higher OPEX, improve system efficiency, or facilitate integration of third-party owned generation and storage (e.g., distributed energy resources, VPPs).[81]

Additionally, the value of advanced grid solutions sometimes flows to customers, other grid stakeholders, or society at large, while the utility bears the cost without realizing significant financial benefit.[82] In the absence of a financial incentive or regulatory mandate, utilities are likely to prioritize investments in other projects that generate higher financial returns, rather than prioritizing solutions that may drive better overall system or societal impact.

Traditional accounting rules on what can be counted as CAPEX (for an approved return on equity) or OPEX (which does not generate returns) can deter investments in advanced grid solutions, drive suboptimal investment outcomes, and disincentivize effective data management and utilization. For example, in many jurisdictions, only on-premise software is allowed to be accounted for as CAPEX. Cloud-based software-as-a-service solutions are often treated as OPEX. This drives utilities to pursue bespoke in-house or on-premise solutions rather than adopting more advanced cloud-based services.

Potential solution: Regulated utility incentives and cost recovery models adjusted to align with the value created by advanced grid solutions.

For regulated utilities, regulators can pursue reforms that incentivize utilities to pursue advanced grid solutions that improve overall system outcomes. This could include incentives and cost recovery options for early pilot deployments as well as supporting foundational systems and capabilities (e.g., advanced analytics and data management development).

78 For example, DOE and Berkeley National Laboratory are developing a benefit-cost assessment tool for advanced conductors that can support industry and regulators in evaluating technology viability (see the Reconductoring Economic and Financial Analysis (REFA) Tool for more information).

79 See the New York Benefit-Cost Assessment Framework as an example state-issued guide. See Lawrence Berkeley Lab's Benefit-Cost Analysis for Utility-Facing Grid Modernization Investments: Trends, Challenges, and Considerations (2021) for additional considerations for regulators.

80 A simplified example of the revenue requirement is calculated as follows: *Revenue Requirement = Rate Base * (Rate of Return) + Operating Expenses*. The rate base is largely comprised of CAPEX costs, which receive a rate of return, while OPEX costs typically do not.

81 For example, in its annual capital planning process, a utility may prioritize high-CAPEX asset replacements and defer non-critical, low-CAPEX projects like topology optimization. As another example, while advanced conductors are more efficient than traditional conductors at the same operating temperature, utilities do not benefit from this efficiency improvement enough to warrant prioritizing these conductors despite the high long-term value for customers from reduced energy costs.

82 For example, a transmission operator will incur all the investment costs and technology risks of deploying DLR on its system, while the value of reduced congestion costs and avoided curtailment are often largely realized by customers and generators.

Example actions could include:

- **Federal and state regulators could consider shifting from a cost-of-service regulation paradigm to models such as performance-based regulation (PBR).** PBR intends to reward utilities based on performance and outcomes rather than just on capital spend. Regulators can leverage various PBR components individually and/or in combination (e.g., performance incentive mechanisms, shared savings). These models give utilities financial incentive to prioritize solutions that maximize customer value and advance local policy objectives in addition to their core focus on delivering electricity. PBR frameworks can be incrementally implemented and expanded over time to manage the transition and enable iterative improvements.
- **Regulators could consider broader cost-recovery options in the near-term, such as allowing returns on some operational expenditures.** This could support more deployments today (particularly for cloud-based solutions and software-as-a-service applications, e.g., ADMS) while utility business model reform is pursued.[83] Other near-term cost-recovery mechanisms that states have pursued include allowing expedited cost recovery options for grid modernization investments and establishing return-on-equity adders for advanced grid solutions.
- **DOE could expand its technical assistance programs to support state and federal agencies in evolving regulatory and cost recovery practices to support advanced grid solutions.**[84]

Potential solution: Alternative cost allocation models implemented that better align costs with beneficiaries and advance equity outcomes.

Economic models for advanced grid solutions do not have to depend on the traditional utility model that socializes all costs to ratepayers. Alternative cost allocation strategies could be considered to reduce ratepayer costs, which could support reducing energy burdens if appropriately designed. There is an opportunity for further innovation in benefit and cost allocation models across the grid industry.

Example actions could include:

- **Regulators could allow alternative cost allocation models for bulk power and distribution system upgrades.** For example, generators (bulk and distributed resource owners) could pay all or part of the costs associated with innovative investments or accompanying system upgrades as an incremental fee associated with interconnecting.
- **Regulators and grid operators could develop new customer rate classes to better distribute costs.** For example, large commercial and industrial customers that have high and inflexible peak demand (e.g., data centers) could be separated into a rate class that more fairly accounts for the costs associated with managing this inflexible demand.
- **National laboratories and industry analysts could evaluate various cost allocation innovations for advanced grid solutions to inform decision-making, accompanied with technical assistance for regulators and policymakers.**[85]

83 The UK has implemented Totex ratemaking to allow both OPEX and CAPEX to be combined for an approved rate of return. See RMI's *Making the Clean Energy Transition Affordable* for additional Totex considerations.

84 These efforts can build on existing federal programs, such as DOE's State Technical Assistance Program, Technical Assistance Resilience program, and Clean Energy Innovator Fellowship. As an example, in line with DOE's Electricity Advisory Committee recommendations on big data, DOE could support valuation methods for big data analytics to inform cost recovery decisions. For additional information and other recommendations, see the DOE's Electricity Advisory Committee report: *Big Data Analytics: Recommendations for the U.S. Department of Energy* (2021).

85 This could build on existing research into these spaces, such as Lawrence Berkeley National Laboratory's Energy Markets and Policy analysis.

Challenge 5: Operational models and protocols to support advanced grid solutions are underdeveloped.

Many advanced grid solutions may require grid operators to change or build new organizational capabilities and operational practices. For example, this could include new data management capabilities and decision-making tools to manage and generate value from data-rich advanced technologies,[86] coordination across currently siloed transmission and distribution operational teams, or new standard operating practices to manage a dynamic grid in real-time (from the static assumptions used today).[87] Grid operators' uncertainty on which organizational capabilities are needed, the level of sophistication needed, and how to integrate capabilities into existing organizational structures can slow adoption of advanced grid solutions. The costs associated with updating legacy systems and infrastructure and investing in necessary workforce development programs are particularly acute for smaller grid operators with limited access to capital (e.g., small municipalities and cooperatives).

Additionally, many advanced grid solutions lack standard policies and specifications to inform procurement, installation, maintenance, and deployment procedures along with standard data protocols. Because of the lack of common deployment practices, a diverse set of bespoke legacy utility platforms, and the inherently localized nature of grid operations, solution providers often construct bespoke and/or highly tailored solutions for grid operators. This increases implementation timelines and integration cost, inhibiting scalability and driving industry concerns over execution certainty and potential cost overruns.

Lastly, the lack of standardization and best practices for installation and operation also increase the perceived risks of and operator discomfort with advanced grid solution deployments.[88] For example, grid operators who are used to manual control systems have cited discomfort with utilizing the automated features of advanced grid solutions without clear operational protocols and risk mitigation measures.

Potential solution: Implementation and operational playbooks, checklists, best practice guidance, and standard practices created for advanced grid solutions.

Reducing execution variability with these tools could accelerate greater standardization across key technology dimensions, including establishing procurement standards, interoperability requirements, and data protocols. For example, establishing expectations for common interfaces and data models, creating standard approaches for collecting, storing, using, and sharing grid data, and clarifying data ownership rules and interoperability requirements could help reduce the complexity and uncertainty associated with integrating new technology solutions. Additionally, these efforts could help equip utilities in proactively identifying and investing in necessary upgrades to legacy systems to better integrate with external providers and advanced grid solutions.

Increased technical assistance and resources to develop these materials are needed. Resources should help streamline advanced grid technology execution practices without prescribing a "one-size-fits-all." Technologies and operational practices will need to be adaptable to a utility's local assets and needs. Yet, even across this diverse landscape of utility operators, increased technology standardization and commonly adopted deployment resources can help accelerate adoption of advanced grid solutions.

86 Key data capabilities include improving collection, storage, management, and use of existing and new data streams, including data integration across siloed utility verticals. This can unlock a larger set of use cases for advanced grid solutions (e.g., customer chat bots within VPPs with access to system data can increase customer buy-in and VPP effectiveness) and enable the deployment of AI and advanced analytics.

87 Example operational changes include: Digital substations exponentially increase the amount of data coming into control rooms and require systems and operational processes that can manage and process this data into actionable insights. VPPs and energy storage can serve both transmission and distribution, which are operationally siloed today. In restructured markets, topology optimization requires that utilities and RTO/ISOs have a process to communicate and implement identified grid reconfigurations, rather than the static default processes used today.

88 New platform solutions (e.g., ADMS, DERMS) must often integrate with legacy systems, including bespoke systems developed in house by utilities. IT/OT coordination is required within utility teams to integrate innovative solutions with existing platforms. The implementation effort required for these advanced solutions can create uncertainty about a utility's ability to execute deployments on time and on budget.

Example actions could include:

- **Industry associations—in collaboration with grid operators, solutions providers, and labor groups—could collaboratively establish a common set of industry guides and playbooks.** These could be developed with learnings from past deployments and the 6–12 deployments for liftoff.
- **Solution providers could focus on maturing and streamlining technology offerings to improve interoperability, modularity, and scalability.** This can help standardize integration processes and mitigate adoption hurdles to enable widescale uptake across the diverse utility landscape.
- **DOE and national laboratories could facilitate best practice and experience sharing for implementing advanced grid solutions.** This can help accelerate needed innovation and enhance industry coordination on complex grid operational and orchestration challenges (e.g., coordinating GETs across the transmission system, managing and integrating DERs for VPP deployments).[89]
- **Grid operators, solutions providers, and regulators could broadly adopt standardized data protocols and best practices across a variety of grid entities** (e.g., Common Information Model (CIM), Green Button standards).[cxxiv]
- **Dedicated federal funding and technical assistance for advanced grid solutions could be expanded for resource-constrained utilities (e.g., small cooperatives, municipalities)**.[90]
- **Industry standard setting organizations and industry associations (e.g., IEEE, EPRI) can help simplify industry standards and best practices for advanced grid solutions**.

Potential solution: Change management resources and technical assistance.

Establishing frameworks, guides, and support resources for grid operators to efficiently implement needed organizational changes and build new capabilities could support advanced grid technology adoption. In a survey by consulting firm West Monroe, over half of utility executives reported needing to restructure their organizations because of grid modernization efforts.[91,cxxv] Industry participants (including regulators) reported needing greater clarity on how to identify and build the necessary organizational and technological capabilities to support advanced grid solutions and grid modernization broadly.[cxxvi]

Proactive engagement between employers and organized labor (who bring extensive experience in negotiating technology adoption and change in the workplace) can help ensure critical workforce and jobs issues are addressed in grid modernization policy and planning.

Example actions could include:

- **Industry associations, grid operators, service providers, and/or DOE could coordinate working groups for industry experience sharing.** This could include, for example, case studies on utility change management experiences, working groups on organizational model reforms, and capability mapping and assessment tools to equip operators to identify potential changes needed to support advanced grid solutions.[92]
- **DOE, industry associations, labor groups, and other private sector stakeholders could provide**

89 As an example, DOE's Connected Communities program supports innovations in integrating and managing grid-interactive building controls. This supports development of practices and approaches for managing grid edge assets that could support advanced grid technologies like VPPs.

90 This could build on existing resources such as DOE's Grid Resilience Innovation Partnerships, USDA's Empowering Rural America New ERA Program for rural electric cooperatives, and EPA's Greenhouse Gas Reduction Fund,

91 A key driver of this restructuring has been integrating information technology (IT) and operational technology (OT) processes and systems (often referred to as IT/OT convergence), which is increasingly needed to be able to manage a dynamic and smart grid.

92 For example, DOE could build on its existing Voices of Experience program focused on emerging technology experience sharing to support organizational efforts.

technical assistance and frameworks to guide change management processes to align with grid modernization objectives and technology capabilities.

- **Grid operators can proactively identify and begin addressing organizational changes needed to build capabilities and enable advanced grid solutions.** This can include investment in workforce hiring and training and foundational systems in anticipation of future objectives. These efforts can both be informed by and help inform changes to grid planning and investment approaches, as discussed in Challenge 2 above.

- **Municipally and cooperatively owned utilities could pursue new collaboration models to support implementing and operating advanced technologies.** There is an opportunity to innovate on current approaches for small utilities, such as new buying coalitions to improve the economies of scale for new technologies, shared investments in foundational infrastructure where possible, or consortium building for existing federal grant and technical assistance programs.[93] State or regional organizational bodies, industry associations (e.g., American Public Power Association, National Rural Electric Cooperative Association), and solutions providers and industry consultants can play an important role in facilitating innovative collaboration models.

Potential solution: Expansion of workforce development programs for advanced technology installation, operations, and maintenance.

Workforce development programs need to include the full range of skillsets across advanced grid solutions rather than narrow job tasks. This means investing in comprehensive training and continuing education so line workers are able to safely install and handle the new materials of advanced conductors, and control room operators are able to manage advanced DERMS applications.

Example actions could include:

- **Solutions providers, utilities, unions and labor organizations (e.g., IBEW, AFL-CIO), and trade associations could further collaborate and expand partnerships to develop new training programs tailored to advanced grid solutions.** [94] These efforts can focus on both training new employees and empowering the existing workforce to adopt these solutions.

- **DOE could fund and support the expansion of existing and new workforce and apprenticeship programs specifically for advanced grid solutions alongside other important grid modernization skillsets**.[95] This could be completed in collaboration with industry partners, labor organizations, and workforce development institutions, and in coordination with the Department of Labor.

Challenge 6: Structural and cultural barriers to innovation impede adoption of advanced grid solutions.

Grid operators and regulators are often culturally hesitant to embrace innovations that could increase system risk (real or perceived risks). Unlike other industries where fast failure and innovation is often encouraged, utilities and regulators face higher stakes when embracing innovations that could impact grid reliability and customer well-being. While rooted in a desire and statutory obligations to ensure reliability for customers, this widespread aversion to innovation and taking managed risks can drive suboptimal

93 For example, 42 distribution cooperatives across Nebraska, Wyoming, Colorado and New Mexico are working in consortium through Tri-State Generation and Transmission to take advantage of economies of scale. Funded by a $27.8M DOE GRIP grant, Tri-State will implement an Energy Services Platform and a DERMS as shared services platforms for the coops, facilitating renewable energy integration and aggregation of grid-edge devices.

94 For example, advanced grid technology implementation and operational trainings could be included in EPRI's Center for Grid Engineering Education power systems engineering courses or IBEW-NECA's electrical training ALLIANCE programs.

95 This could build from programs like the Good Jobs and Workforce Development. DOE's Industrial Assessment Center program focused on clean energy manufacturing could serve as a model for potential modern grid workforce initiatives.

performance outcomes. With transmission and distribution infrastructure largely operated as regulated monopolies, the lack of competition can limit broad adoption of innovation unless explicitly prioritized.

Additionally, the costs of not embracing new technologies and the costs of underinvesting in certain infrastructure are not well understood, particularly at the regulatory level. This can further impede regulatory approval for investments in advanced technologies that may be seen as "gold plating" the system.

Grid operators typically bear all financial and operational risks of new technology deployments. Utilities may perceive limited upside in adopting new technologies where performance or execution uncertainty could impact deployment success in terms of performance and financial return.

Even when innovation is attempted, most advanced grid solutions pilots become stuck in "pilot purgatory" within utilities, which can be driven by a lack of sufficient incentives and by utility organizational models that silo innovation teams from core operating practices (discussed further in Challenge 4 and Challenge 5 above).[cxxvii]

Potential solution: Regulatory and economic incentives and models that explicitly encourage innovation.

Establishing venues to encourage controlled risk taking to reap the benefits of innovation (including normalizing and learning from fast failures, iterative and agile design processes) can help spur a much-needed appetite for innovation across the industry. This can help drive investments in advanced grid technology deployments, which, despite being technically mature, are often still new solutions for a utility and regulator to integrate and learn about.

Labor groups and community advocates should be included and engaged in these processes to ensure new models of innovation that drive advanced grid solutions can continue to serve workforce and consumers.[96]

Example actions could include:

- **Regulators could establish "regulatory sandboxes"[97] to pilot new incentive mechanisms and support advanced grid solutions in managed settings that mitigate risks before wide adoption.**[98]
- **Regulators could increase cost recovery options for early advanced grid solution deployments—even if deployments are not ultimately "successful".** When appropriately managed, failed or underperforming advanced technology deployments can still be highly valuable learning opportunities to inform future efforts and could still be allowed for cost recovery.
- **Technology providers could share in performance risk for early deployments,** such as structuring investment agreements so that utilities only pay when certain milestones are achieved. This could further strengthen the needed partnerships between utilities and solutions providers and help close any technology gaps (e.g., technology features, systems integration processes, interoperability, scalability).
- **Grid operators could proactively embed innovation teams into core processes and operations**. Collaborative internal working groups could be established that include both innovation and core division decision-makers.

96 Additional considerations for innovation in utility business models, including with workforce and community advocates, are highlighted in *The Role of Innovation in the Electric Utility Sector*, a research effort coordinated through the DOE's Grid Modernization Lab Consortium.

97 Generally, regulatory sandboxes are a formal classification that provide structured frameworks to support experimentation and innovation of new technologies or approaches, usually with specific regulatory oversight and time-bound testing programs.

98 Connecticut's PUC, for example, established the Innovative Energy Solutions Program in 2023 to encourage grid innovation, including defining features such as a four phase process from ideation to scale up, cost recovery guidance, and screening and performance metrics.

- **Regulators and/or grid operator executives could require operational pilot programs to include scaling plans and resources in initial program designs.**[cxxviii]

Section 4.b. Summary of key actions by stakeholder

Grid stakeholders can start acting today—taking advantage of unprecedented federal funding support and technical assistance programs—to accelerate deployment of the advanced grid solutions needed to maintain a reliable, safe, and affordable grid.

Potential priority steps that industry stakeholders could begin pursuing are summarized below. This list is not exhaustive and is intended to be a starting point for further conversation.

Grid operators *(e.g., IOUs, cooperatives, public power, RTO/ISOs)*

- **Deploy "no regrets" solutions—leveraging federal funding resources—in collaboration with industry stakeholders** (e.g., solutions providers, DOE/national labs, trade associations, labor organizations, community groups, regulators, other utilities) to address needs today while building scalable deployment models.
- **Transparently share outcomes from technology deployments**—including successes and failures—to support broader adoption and accelerate performance improvements.
- **Revamp current transmission and distribution planning processes** to fully consider advanced grid solutions.
- **Start developing a grid modernization strategy** following emerging best practices to identify applicability of innovative technologies and develop roadmaps for deployment.
- **Proactively engage with labor and community groups** in planning and deployment processes.

Regulators and governance boards *(e.g., PUCs/PSCs, FERC, city councils, co-op boards, Tribal authorities)*

- **Require use of and revamp transmission, distribution, and grid modernization strategies and planning processes** by adopting emerging best practices.
- **Require advanced grid solutions to be considered** in current planning processes.
- **Realign regulated utility incentive structures** to support advanced grid solutions.
- **Develop appropriate cost recovery mechanisms** that equitably share costs and benefits.
- **Advance understanding of advanced grid solutions** (e.g., engage with stakeholder working groups, solicit utility and advocacy input, engage in planning process improvements).
- **Convene key stakeholders—including utilities, policymakers, labor groups, community groups, and solutions providers—**to collaborate on advanced grid solution planning and deployments.

Policymakers *(e.g., federal and state legislators, governors, state energy offices)*

- **At the state level, establish a clear vision on energy policy objectives** and the grid's role in supporting these objectives to clarify priorities for industry and regulators, potentially leveraging legislative mandates.
- **Pass enabling legislation** for advanced grid solution deployments (e.g., efficiency requirements, planning requirements, performance-based incentive models).
- **Increase budget and staff capacity** for regulators (e.g., public utilities commissions) and other key entities (e.g., state energy offices) to implement advanced grid solution priorities.

- **Collaborate with local regulators to ensure advanced grid solutions are considered** in existing utility plans and proposals based on local needs and priorities.
- **Coordinate multi-stakeholder collaborations** to accelerate equitable grid modernization planning and investment.
- **Use platform to recognize and amplify industry leaders** that are driving grid innovation (including learnings from failures and successes).

Solutions Providers *(e.g., technology providers, engineering firms, consultants, system planning and modeling providers)*

- **Integrate advanced grid solutions into service offering** (e.g., system planners incorporate in planning platforms, EPCs integrate in ongoing expansion and replacement projects).
- **Build and leverage a common taxonomy** for technologies and applications to improve common awareness and understanding.
- **Proactively articulate, quantify, and value the benefits** of solution offerings to support utility investments and contribute to industry education and standard-setting.
- **Share in performance risk** for proven, but sub-scale technologies to accelerate deployment.
- **Close technology gaps to meet utility-grade standards** and enable scalability (e.g., cybersecurity, interoperability).
- **Proactively engage with labor organizations and grid operators** to improve technology deployment capabilities and scalability in real-world conditions.

DOE *(headquarters, National Labs)*

- **Support field deployments** of advanced grid solutions to accelerate liftoff—leveraging existing funds (e.g., GRIP, Transmission Financing Program, LPO, technical assistance) and expanding dedicated resources where needed.
- **Create and/or collaborate in a 'resource library' for advanced grid solutions deployments** to share outcomes and learnings from failures and successes (building from existing resources like the Grid Modernization Initiative and national laboratory research).
- **Require and/or encourage applicants for DOE grid deployment funding to consider advanced grid solutions** and provide justification if not included.
- **Expand technical assistance and capacity-building resources** to industry and regulators, policymakers, and boards to support planning, investment, and economic model reforms for advanced grid solutions (e.g., benefit/cost assessment tool, technology applicability analysis, business model innovation, DOE Clean Energy Innovator Fellowship for advanced solutions).
- **Expand and integrate advanced grid solutions into new and existing grid programs supporting labor organizations, community groups, and tribes** to improve equitable access to and engagement on grid modernization topics.
- **Establish system efficiency standards** to accelerate adoption for proven innovative technologies (e.g., advanced conductors, ADMS-VVO).
- **Increase dedicated funding for capital constrained operators** (cooperatives, municipalities) to support foundational infrastructure and advanced grid solution deployments.

Trade Associations and Labor Organizations *(e.g., industry, regulatory, utility, labor)*

- **Participate in deployments** to validate technology performance, develop deployment guidance, establish technology standards where needed, translate outcomes into tools and insights for members (e.g., regulatory tools, briefs), and set and circulate best practices.
- **Drive collaborations between solutions providers and utilities** to standardize deployment and operations processes and close technology gaps to smooth technology adoption.
- **Establish playbooks for members** to inform planning, investment, and deployment approaches for advanced grid technologies.
- **Support industry collaborations and coalition-building** (e.g., buying groups for cooperatives).
- **Expand partnerships to proactively build workforce and develop training programs.**

Community Groups and Intervenors *(e.g., communities and community groups, consumer advocates, NGOs)*

- **Engage in regulatory dockets and rate cases** to highlight opportunities to use advanced technologies and ask for these to be considered.
- **Engage with policymakers and regulators** to highlight opportunities for policy action to drive equitable modernization vision and technology deployments.

Chapter 5: Metrics

Three core metrics can be tracked to evaluate progress towards advanced grid technology liftoff:

1. **Number of operational deployments completed by technology with outcomes shared (#)**
   The target number of deployments should be 6–12 across diverse set of utility contexts by 2027-2029.

2. **Total investment in advanced grid solutions ($, by technology)**
   Total industry investments should increase over time—with some improvement expected during liftoff and significant increase thereafter as advanced technologies are deployed at scale. Additional analysis is needed to determine the investment needed for liftoff by 2027-2029.

3. **Number of states and utilities with proactive, robust grid investment plans (#, % of total)**
   By technology liftoff by 2027-2029, ideally 100% of states and utilities will have established and/or are establishing proactive grid investment plans. This is a key indicator of whether there is a shift toward the future-oriented grid investment and management approach that is needed to support advanced grid solutions and modern grid needs more broadly.

Additional metrics that could be tracked to support industry progress are summarized below. This is a non-exhaustive list.[99] To measure progress towards liftoff, three categories of metrics could be tracked:

- **Outcomes** track the value created by advanced grid solutions as related to broader social and environmental goals.
- **Leading indicators** signal market readiness for technology adoption and growth.
- **Lagging indicators** track observed progress toward advanced grid solution liftoff.

Given the influence of jurisdiction-specific utility regulation and energy policy over advanced grid technology deployment, metrics should be tracked at the regional, state, and/or utility level and by individual technology (or technology category) to the extent possible. Community and/or demographic detail should be captured to track benefits distribution and alignment to the Justice40 Initiative.

99 Several organizations already track relevant industry data (e.g., S&P Global, BNEF, Wood Mackenzie, EEI, SEPA, GridWise Alliance). These existing data sources could be expanded to focus on specific technology deployments and include detail at the technology, regional, state, utility, and/or community level where not already tracked.

Table 8. Summary of grid metrics to track to support liftoff

Category	Outcome	

Key grid outcomes	• **Electricity affordability** measures, such as:
	  ‣ Customer energy cost ($/kWh)
	  ‣ Households with a high or severe energy burden (total number, % of overall U.S. household)
	  ‣ Congestion costs ($)
	• **Enhanced grid reliability and resilience** measures, such as:
	  ‣ Frequency and duration of outages and outage recovery time (SAIDI, SAIFI metrics)
	• **Clean energy generation** measures such as:
	  ‣ Interconnection time (average time in queue)
	  ‣ Utilization of demand-side resources such as VPPs and DERs (total MW, % of total peak load served)
	• **Improved utilization of existing grid infrastructure**, such as:
	  ‣ transmission and distribution capacity utilization (%)	

Path to Liftoff	**Leading indicators**	**Lagging indicators**

Achieving liftoff for advanced grid solutions	• **Proactive investments**, such as:
	  ‣ Number of DOE funding applications that include advanced grid solutions
	• **Favorable regulatory frameworks to drive planning improvements,** e.g., number of states, FERC orders, and/or RTO/ISOs with:
	  ‣ Integrated distribution system planning and/or grid modernization plan requirements (using current best practice)
	  ‣ Requirements to consider advanced technologies in planning
	  ‣ Benefit-cost frameworks established for advanced grid solutions
	• **Favorable regulatory frameworks to align economic and incentive models,** e.g., number of states, FERC orders, and/or RTO/ISOs with:
	  ‣ Performance-based incentive frameworks
	  ‣ New cost allocation models established for advanced grid solutions
	• **Favorable legislative and policy actions** on grid modernization, such as number of:
	  ‣ Legislative actions that support advanced grid solutions
	  ‣ States with grid modernization strategy
		• **Outcomes transparently shared from 6-12 deployments for each technology** across a diverse set of industry contexts (# of deployments, % with outcomes publicly available)
		• **Total investment in advanced grid solutions** ($ invested, % of spend versus conventional investment, % of spend versus conventional replacement)

Deploying at scale	• **Proactive investments** to support advanced grid solutions, such as:
	  ‣ Advanced technologies included in utility rate cases and/or modernization plans (# of technologies proposed, total $ proposed, $ as a % of total investment)
	  ‣ Foundational technology penetration (e.g., communications, data mgmt. systems) (number, % of total utilities with tech.)
	  ‣ Utility spending on IT/OT (total $, average $ per customer)
	• **Workforce development programs** with advanced grid solutions (# programs; # and completion and successful placement rate of participants)
	• **Domestic manufacturing** capacity (total capacity, % utilization)
	• **Public and private sector collaborations and resourcing** for industry and regulatory capacity building (number of initiatives, $ available in technical assistance and similar programs)
		• **Ease of technology implementation** measures (avg. implementation cost, # of deployments completed on time and budget)
		• **Grid modernization workforce** (total number, % of total industry workforce)
		• **Cost break down of utility expenditures (e.g., CAPEX, OPEX, energy efficiency programs)** (total $, % of total)

Appendices

Appendix A: Deployment-focused DOE funding and technical assistance programs

The funding programs and technical assistance resources below include opportunities focused on supporting the deployment of advanced transmission and distribution technologies covered in this report. These programs are largely funded by the Bipartisan Infrastructure Law.

This is not an exhaustive list of all DOE funding programs. Additional resources on grid funding and technical assistance programs include:

- Grid and Transmission Program Conductor: Summary of GDO's transmission and grid resilience financing programs, as well as other existing DOE transmission and grid programs.
- Public Sector Funding & Technical Assistance Programs: Additional information on a variety of technical assistance opportunities for states and local governments.

Table 9. DOE grid-related funding and technical assistance resources (not exhaustive)

Category	Program	Description
Direct Support	Grid Resilience and Innovation Partnerships (GRIP) Program	$10.5B in grant funding for grid investments, including for advanced grid solutions and applications.
	Grid Resilience State and Tribal Formula Grants	$2.3B in formula grants for grid resilience against extreme weather. There is funding available for all states, territories, and federally recognized Indian tribes, including Alaska Native Regional Corporations and Alaska Native Village Corporations. This funding can be claimed to then subaward to entities that will invest in projects that reduce the likelihood and consequence of disruptive events caused by extreme weather, wildfires, and other natural disasters.
	Energy Improvements in Rural and Remote Areas	$1B in funding to improve the resilience, reliability, and affordability of rural energy systems.
	Distributed Energy Systems Demonstrations Program	$50M to demonstrate aggregated approaches to managing distributed energy systems that show solutions to long term operations.
Loans and Financing Programs	Transmission Facilitation Program	$2.5B in commercial support for qualified transmission projects through tools such as capacity contracts, public-private partnerships, and loans.
	Transmission Facility Financing Program	$2B in direct loan authority for facility financing.
	Innovative Energy Loan Program (1703)	Offers loan guarantees to support clean energy deployment of innovative or significantly improved technologies, including advanced grid solutions.
	Energy Infrastructure Reinvestment Loan Program (1706)	Offers loan guarantees available to projects that retool, repower, repurpose, or replace Energy Infrastructure that has ceased operations, including for advanced grid solutions.
	Tribal Energy Finance Program (TEFP)	Offers loan guarantees exclusively to support federally recognized tribes, including Alaska Native village or village corporations, or a Tribal Energy Development Organization that is wholly or substantially owned by a federally recognized Indian tribe or Alaska Native Corporation. Financing is available for a broad range of energy technologies, including advanced grid solutions.
	Empowering Rural America Program **USDA program*	$9.7B in loans available for rural electric co-ops through USDA Rural Utilities Service.

Technical Assistance	Grid Resilience Assistance	Technical and other assistance that supports state, Indian tribe, territory, and industry needs to support grid resilience, including—if requested—support for advanced technologies.
	State Technical Assistance Program	Provides high-impact technical assistance and resources for state regulators and policymakers through a variety of support options, including—if requested—support for advanced grid solutions.
	Indian Energy Technical Assistance	Provides technical assistance and resources specifically for federally recognized Indian Tribes, including Alaska Native regional corporations and village corporations, and Tribal entities.
Tax Credits	48C Advanced Energy Project Credit	Provides an investment tax credit of up to 30% for qualifying projects placed in service within four years. The Inflation Reduction Act provided $10B to be competitively allocated to selected applicants; manufacturing for "electric grid modernization equipment or components" qualifies under IRS guidance for 48C.
Other Deployment Related Programs	National Interest Electric Transmission Corridors (NIETC)	Special designation that enables DOE and the Federal Energy Regulatory Commission (FERC) to use financing and permitting tools to spur construction of transmission projects within a NIETC.
	Puerto Rico Grid Modernization and Recovery Project	Technical assistance program provided to Puerto Rico energy system stakeholders with tools, training, and modeling support to enable planning and operation of the electric system with greater resilience against further disruptions.
	Clean Energy Innovator Fellowship	Funds recent graduates and energy professionals to support public utility commissions, co-ops, Puerto Rican energy associations, tribal utilities, and other grid operators.

Appendix B: Overview of several DOE grid programs

Recognizing the imperative to expand and modernize the grid, DOE has dozens of initiatives and funding programs to support the electric industry across grid research, development, demonstration, and deployment, including technology, regulatory and policy, and supply chain support**.**

Table 10 summarizes several of these efforts across the DOE focused on advancing grid outcomes—this is not an exhaustive list.

Note: R&D = research and development; D&D = demonstration and deployment; Reg. & Policy = regulatory and policy. Column marks (X) indicate the primary focus areas for the program. Many programs are cross-cutting and may touch on multiple areas.

Table 10. Example DOE grid-related programs across RDD&D phases

Program	R&D	D&D	Reg. & Policy	Supply Chain
Grid Modernization Initiative (GMI) Crosscutting, multiyear program focused on research, development, demonstration, and deployment (RDD&D) to ensure an affordable, resilient, flexible, secure, sustainable, equitable, and reliable grid. The GMI is organized into six strategic pillars: Devices and Integrated Systems; Operations; Planning; Markets, Policies, and Regulations; Resilient and Secure Systems; Flexible Generation and Load. GMI includes the Grid Modernization Lab Consortium (GMLC), a partnership between DOE and the national laboratories. See the GMI Strategy 2020 for additional information (updated strategy document forthcoming in 2024).	X	X	X	X

Applied Grid Transformation Solutions (AGTS) Supports the validation and demonstration of new grid technology to support adoption and deployment, including scoping new and enhancing existing test beds in collaboration with national labs, academia, and industry.		X	X	X
Coordinated Interagency Transmission Authorizations and Permits Program (CITAP) Focuses on accelerating Federal environmental review and permitting processes for qualifying onshore electric transmission facilities. Consistent with the Fiscal Responsibility Act of 2023, the Program aims toward a better coordinated, more streamlined process that will set deadlines for Federal authorizations and permits for electric transmission on a two-year timeline while ensuring meaningful engagement with Tribes, local communities, and other stakeholders.			X	
Distribution Grid Transformation Includes guidance on Integrated Distribution System Planning, Operational Coordination, and Distribution System Design to support distribution grid modernization.	X	X	X	
Electricity Advisory Committee (EAC) Public-private group that advises DOE on grid modernization topics.			X	
Energy Storage Grand Challenge (ESGC) Focuses on development, commercialization, and utilization of next-generation energy storage technologies, including related manufacturing, valuation, and workforce challenges.	X	X	X	X
Interconnection Innovation e-Xchange (i2X) Enables a simpler, faster, and fairer interconnection of clean energy resources by conducting four key activities: stakeholder engagement, data collection and analysis, strategic roadmap development, and technical assistance.			X	
North American Energy Resilience Model (NAERM) Enables advanced modeling and analysis of the nation's energy infrastructure and interdependent systems. NAERM offers energy system planners, operators, and federal agency partners premier modeling and situational awareness capabilities to predict the consequences and evaluate mitigations and responses to natural hazards and malicious attacks.			X	
Resilient Distribution Systems (RDS) Develops transformative technologies, tools, and techniques to enable industry to modernize the distribution system, such as microgrids, dynamic controls and communications, electricity delivery systems, and sensors.	X	X	X	
Transmission Optimization with Grid-Enhancing Technologies (TOGETs) Based out of Idaho National Laboratory, this program guides research to fill knowledge gaps of GETs, develops new modeling and simulation methodologies, and conducts a full-scale, multifaceted field exercise on INL's Power Grid Testbed.	X			
Transmission Reliability Program (TRR) Supports collaboration between the national labs, the electricity industry, and DOE to develop technologies that keep the nation's electric grid resilient and secure. Focus areas include: Advanced Applications R&D; Data Development for Transmission Systems; Human Factors, Visualization and Tool Modernization for Grid Ops; Transmission Measurement & Standards; and Grid-Enhancing Technologies.	X			
Transformer Resilience and Advanced Components (TRAC) Focuses on addressing challenges with large power transformers, Solid State Power Substations, high-voltage transmission, and other critical grid hardware components.	X			X

Appendix C: Example utility investment cases (additional detail)

A simplified set of hypothetical utility examples[100] were developed in this report to illustrate what liftoff might look like for these advanced grid solutions. This is not exhaustive and intended to merely illustrate some hypothetical examples based on real-world contexts. A subset is summarized in Chapter 3, with additional detail included here. Five hypothetical utility contexts are included across varying example regions: Rural Electric Cooperative (Northwest), Urban Municipality (Southwest), Small IOU (Northeast), Medium IOU (Midwest), and a Large IOU (Southeast). See Appendix F for input information.

100 These are simplified, illustrative examples that leverage real benefit and cost assessment models but are not intended to be guidance for any specific utility or on any specific benefit/cost assessment method. Utilities and regulators will need to identify the appropriate advanced grid solutions for their individual needs and objectives, agree on a relevant benefit/cost framework, and determine the appropriate planning and economic models.

Example 1. Rural Co-Op (Northwest)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Rural Co-Op *Northwest*	• Intense & variable weather (wildfire, wind, high temp) • High disruption risks across rural areas • DER penetration expected for reliability	• Improve reliability & resilience • Prepare system for DERs	✓ **8h Energy Storage** *Improve system resilience, complements expected DER, manage power costs* ✓ **Smart Reclosers** *Identify faults quickly and accurately, reduce outage times, improve grid reliability*	✓ **Digital Substations** *Key amplifier of storage and smart reclosers; improves network flexibility and resilience, including with expected DERs*

As discussed in Chapter 3, in this hypothetical case, the rural cooperative collaborated with its Board to identify long-term system reliability and resilience objectives to better support its customers, particularly during extreme climate events. The co-op developed a long-term distribution system plan to achieve these objectives.

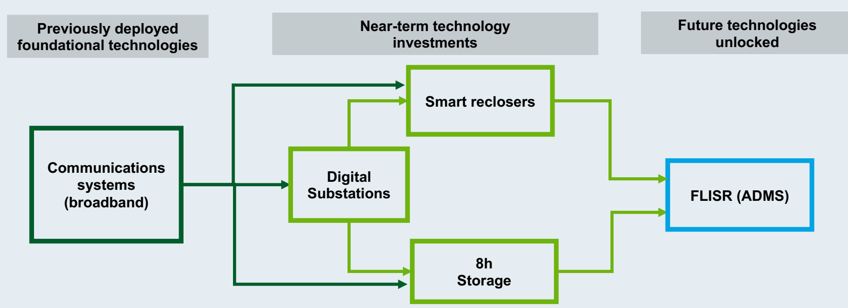


Figure 21. Deployment of complementary technologies for rural co-op

Building off its existing broadband infrastructure, it identified smart reclosers and 8h energy storage as key technologies to improve short- and long-term system reliability and resilience.

The co-op identified a near-term opportunity to digitize several substations to unlock additional value from smart reclosers and energy storage. As shown in Figure 21, the co-op evaluated a bundle of complementary technologies with shared dependencies. Longer term, the co-op identified an opportunity to deploy FLISR to manage smart reclosers and coordinate with energy storage to improve system reliability. To achieve this goal, the co-op prioritized smart reclosers and communications upgrades to unlock access to future FLISR deployments.

Example best practices used (not exhaustive):

- Co-operative identified shared communications infrastructure requirements to inform communication upgrades today that support current and future technology deployments.
- Co-operative mapped out longer-term technology roadmap to build up capabilities over time and inform technology priorities that align with its reliability and resilience objectives.

Example 2. Urban Muni (Southwest)

HYPOTHETICAL EXAMPLE

Example utility and region

Urban Muni
Southwest

Local context

- Urban load growth
- Rapid DER adoption
- Extreme weather events

Grid objectives

- Flexibility to adapt to high demand
- Leverage DERs to serve demand
- Decarbonize by 2035
- Improve resilience

Advanced grid solutions identified

✓ **DERMS**
Control and optimize DER power flows to improve integration, visibility, and monitoring

✓ **VPPs**
Aggregate DERs to manage and serve peak loads; increase DER value; accelerate decarbonization

✓ **Power Factor Correction**
Preserve system reliability with high DER penetration

✓ **Smart Reclosers**
Identify faults quickly and accurately, reduce outage times, improve grid reliability

The hypothetical urban municipal utility identified a need to enhance system reliability amidst growing demand, DER adoption, and extreme heat and weather events. The municipality also needed to identify a pathway to achieve its carbon-free electricity by 2035 goal.

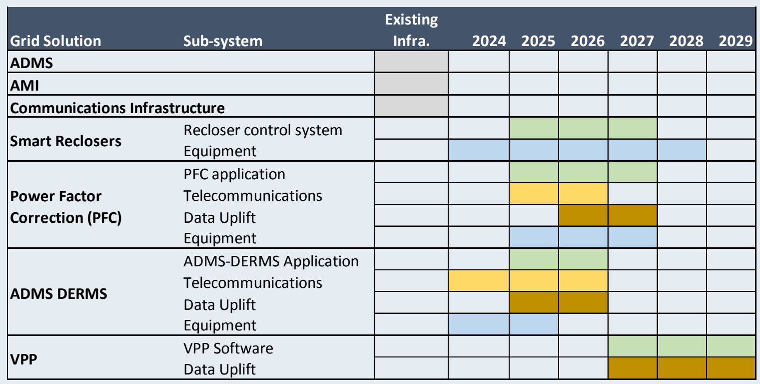


Figure 22. Urban muni's advanced technology roadmap

Leveraging DOE technical assistance resources, the municipality worked with a national lab to model a range of scenarios to improve near-term reliability while supporting long-term needs. The utility opted to install DERMS, VPPs, power factor corrections, and smart reclosers. Power factor corrections were used to manage system reliability with large DER capacity coming online. A DERMS system—building off the utility's existing ADMS platform, AMI deployment, and communications infrastructure—could aggregate DERs to serve growing load through VPPs. Although the utility considered FLISR to address extreme weather events, due to limited budget and bandwidth, the utility opted for smart reclosers as a simpler near-term reliability measure. As summarized in Figure 22, the utility developed a roadmap to logically phase in solutions towards more advanced technologies from situational awareness and system visibility solutions (ADMS-base, AMI) to passive DER management (DERMS) to more advanced system control (VPPs). This roadmap informed the foundational investments necessary to support future investments.

The utility proposed this plan to the City Council, which reviewed and verified it could cost-effectively address load growth and improve system flexibility and resilience. The City Council allocated budget funding to provide additional incentives for low-income residents to adopt DERs and necessary upgrades to participate in VPP programs.

Example success factors (not exhaustive):

- Municipality proactively deployed advanced technologies (DERMS, VPPs) to prepare for expected trends before urgent peak load and DER management crisis arose.
- Municipality developed technology roadmap following best practices to inform identification and deployment of strategic bundles to support near- and long-term objectives.
- City Council asked for and municipality provided clear investment strategy to justify right-sizing upgrades to existing systems (e.g., communications, AMI) to support expected VPP deployment.

Example 3. Small IOU (Northeast)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified
Small IOU *Northeast*	• Legislated state climate goals • Electrification-driven demand growth straining T&D capacity (no new ROW) • Extreme weather (heat, storms, flooding)	• Improve resilience • Expand system to support load growth • Enhance grid to manage amounts of DER capacity	✓ **Network Topology Optimization** *Relieve transmission congestion and improve T&D utilization to serve higher demand* ✓ **Advanced Flexible Transformers** *Upgrade aging assets to improve flexibility to respond to changing grid conditions* ✓ **ADMS FLISR** *Improve system reliability to reconfigure and quickly re-energize the grid during outages*

In this hypothetical example, the small IOU engaged with regulators and community stakeholders to identify top grid modernization needs: improved resilience and reliability amidst more extreme weather and greater flexibility to support local demand growth and DER penetration. The regulator provided a BCA framework, asked the utility to integrate its IRP and asset replacement planning processes, and developed a performance incentive mechanism (PIM) to reward the IOU for improved reliability.

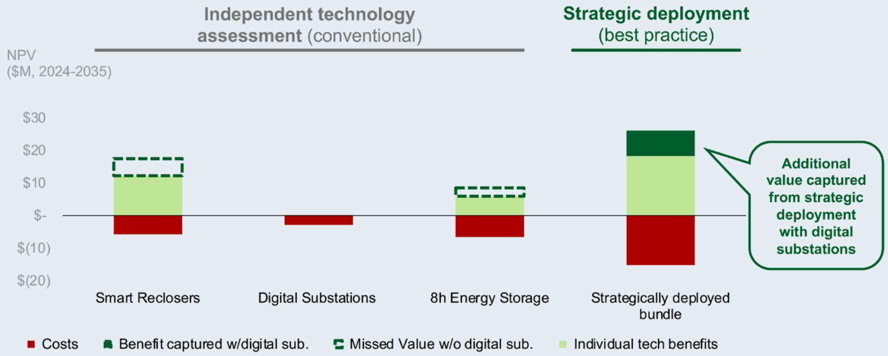


Figure 23. Benefit-Cost Analysis of Small IOU's advanced grid solution package

The IOU identified advanced technologies that could enhance the system in the near term and pave the way for future expected needs and objectives. The IOU chose a bundle of advanced transformers, network topology optimization (NTO), and FLISR, building on its existing ADMS system. By integrating its expansion and replacement planning, the IOU identified opportunities to proactively replace aging transformers with advanced flexible transformers at marginal incremental cost to improve system flexibility and amplify NTO impacts. The IOU coordinated with the RTO to implement topology optimization reconfigurations to manage congestion and optimize transmission utilization to support rising demand. The bundle addresses several issues: ADMS-FLISR identifies disruptions and reconfigures the system to respond quickly to grid disruptions and NTO provides mapping information on new paths for power to be routed. These systems also enable increased DER adoption, as transformers improve flexibility, while ADMS-FLISR can support future roll out of DERMS. The IOU conducted a BCA for this package (summarized in Figure 23) to inform its investment proposals to regulators.

Example success factors (not exhaustive):

- Regulator adopted best practices for planning, including an objective-based BCA framework and robust stakeholder engagement process.
- Regulator adopted incentive to reward utility for reliability improvements.
- IOU made proactive upgrades to invest in asset replacement to improve the system.

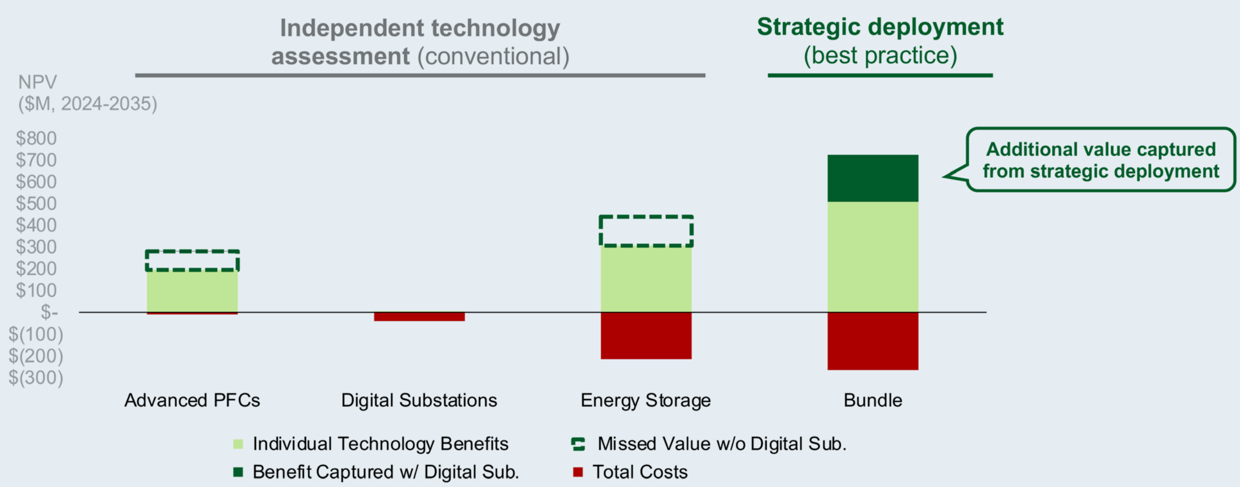
Example 4. Medium IOU (Midwest)

HYPOTHETICAL EXAMPLE

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Med IOU ***Midwest***	• Shift from fossil gen to renewables • Aging assets (vulnerable to weather, IBRs) • Extreme weather (winter storms, wind, tornadoes)	• Increase system capacity and flexibility to accommodate range of generation resources • Improve reliability & resilience	✓ **Point-to-point HVDC** (converting aging HVAC to HVDC) *Capacity and efficiency solution to connect renewables over long distance, improve system reliability* ✓ **8h energy storage** *Complement renewables, improve system resilience, provide grid-balancing services*	✓ **Digital substations** *Enhance network flexibility and resilience, support renewable integration, amplify storage and APFC* ✓ **Advanced Power Flow Control (APFC)** *Improve transmission utilization and unlock needed capacity as generation mix shifts*

In this hypothetical example, the state regulator and the regional ISO identified long-term grid reliability and resilience needs amidst increasing extreme weather events and the need for system capacity and flexibility to integrate renewable energy. The Midwest IOU developed an integrated system plan to achieve these objectives.

As discussed in Chapter 3, the IOU identified HVDC lines, 8h energy storage, digital substations, and advanced power flow controls as high priority technology investments. Using best practices for benefit-cost assessments of advanced grid solutions, the IOU identified potential benefit synergies between advanced power flow control, energy storage, and digital substations, so it evaluated these together in its benefit-cost assessment to surface potential benefit and cost synergies from strategic deployments together. As shown in Figure 24, while digital substations had lower standalone value, the IOU found it could amplify the value of advanced power flow controls and storage meaningfully (in addition to other qualitative benefits from improved system visibility) to justify investment.



Assumes 70% of advanced PFCs & storage benefits are possible without enabling digital substations; estimate based on industry experience; further research needed to refine value of interconnected systems

Figure 24. Benefit cost analysis of Medium IOU's advanced grid solution package

Example success factors (not exhaustive):

- IOU leveraged best practices for planning, including taking a longer time horizon (12 years) and holistically tailoring investments to key grid objectives.
- IOU evaluated advanced technologies as complementary investment to realize synergies.

Example 5. Large IOU (Southeast)

Example utility and region	Local context	Grid objectives	Advanced grid solutions identified	
Large IOU *Southeast*	• Manufacturing-driven load growth • Transmission constrained • High energy burdens	• Expand system to support local economic growth • Equitably alleviate cost pressures	✓ **ADMS VVO** *Dx efficiency improvement reduces ratepayer costs & alleviates Tx capacity needs* ✓ **Dynamic line rating (DLR)** *Low cost, near-term Tx capacity solution; increased system visibility improves reliability*	✓ **Advanced Conductors** *Increases Tx capacity to meet C&I demand; enhances system efficiency to reduce costs* ✓ **Digital Substations** *Key amplifier of VVO & DLR to maximize value; improves network flexibility and resilience*

As discussed in Chapter 3, in this example, beyond the increased curtailment of low-cost energy generation due to transmission capacity constraints, this large Southeast IOU is also seeing unexpected near-term growth in demand from local data centers and industrial manufacturing activity in addition to longer-term population growth and transportation electrification trends. Additionally, more frequent and intense hurricanes and natural disasters are creating a need for improved reliability and resilience.

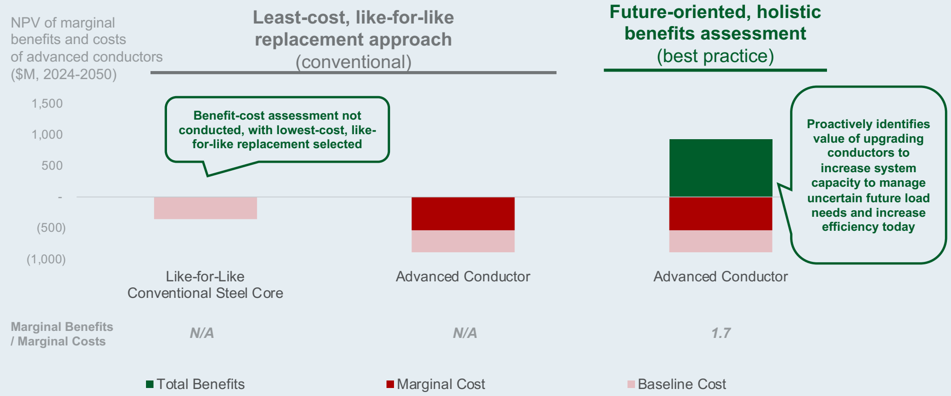


Figure 25. Marginal BCA outcomes for advanced conductor deployment

The IOU coordinated its integrated resource plan (IRP) and asset replacement plan to surface opportunities to leverage ongoing replacement expenditures to efficiently address these growing pressures. This integration involved setting up new organizational models to improve collaboration between previously siloed planning teams, data systems, and processes.

This process revealed an opportunity to replace aging steel core conductors with higher capacity, more efficient advanced conductors to help increase transmission capacity to support the surging demand today as well as enhance the system for potential load growth in the future. Conventional approaches to asset replacement would typically use a least-cost, best-fit assessment to restore the asset to its current operating potential, which would have resulted in a conventional steel core conductor replacement. Instead, the IOU conducted a benefit-cost assessment and holistically evaluated the advanced conductor option (including efficiency benefits, transmission deferral value, and emissions benefit from improved efficiency). As shown in Figure 25, the resulting marginal-benefit to marginal-cost ratio of 1.7 cleared the IOU and state regulator's threshold, supporting the investment case for advanced conductors. In addition to the added capacity and efficiency improvements, this approach also provides the IOU with greater operational flexibility to ensure reliable power delivery.

Example success factors (not exhaustive):

- IOU integrated capacity expansion and asset replacement processes to identify opportunities to proactively upgrade transmission lines with advanced conductors.
- Holistic benefit-cost assessment completed to inform investment decision, instead of default least-cost, best-fit method.

Appendix D: Foundational systems

The following charts summarize the four foundational systems that enable many advanced grid solutions (alternate timing and synchronization, communications technologies, data management systems, and system digitization and visualization). In each chart, two ratings are provided:

- **Importance**: Defined as the importance of the foundational infrastructure to the function of the specific grid technology/application. Importance answers questions like: how essential is this foundational system for implementation and function of the advanced grid solution? The scale ranges from 1 = trivial/minor use of foundational technology to 4 = essential use; 0 = irrelevant.
- **Quality of service**: Defined as the required foundational infrastructure quality needed to achieve the assessed potential of the advanced grid solution. Quality of service answers questions like: does state-of-the-art implementation unlock more benefits for a technology compared to basic implementation? The scale ranges from 1 = minimum viable implementation to 4 = world class implementation; 0 = unnecessary.

Alternate timing and synchronization (ATS) solutions are not essential to the implementation of any technology but provide alternate time sources that can compensate for and maintain system function if a primary signal—such as GPS—is lost. In some high-quality ATS implementations, clock stability can be improved beyond traditional sources, which can unlock significant benefits for technology applications where time-sensitive coordination and control across many devices is an important element of system function. Examples include ADMS FLISR, advanced sensors, and digital substation if implemented. Many technologies, especially those dealing with general power flow control, require some amount of time awareness but do not require accuracies that would benefit from world class alternative timing. Overall, there may be additional benefits from alternate timing and synchronization not realized among this set of technologies and it is worthwhile to explore additional benefits in future studies.

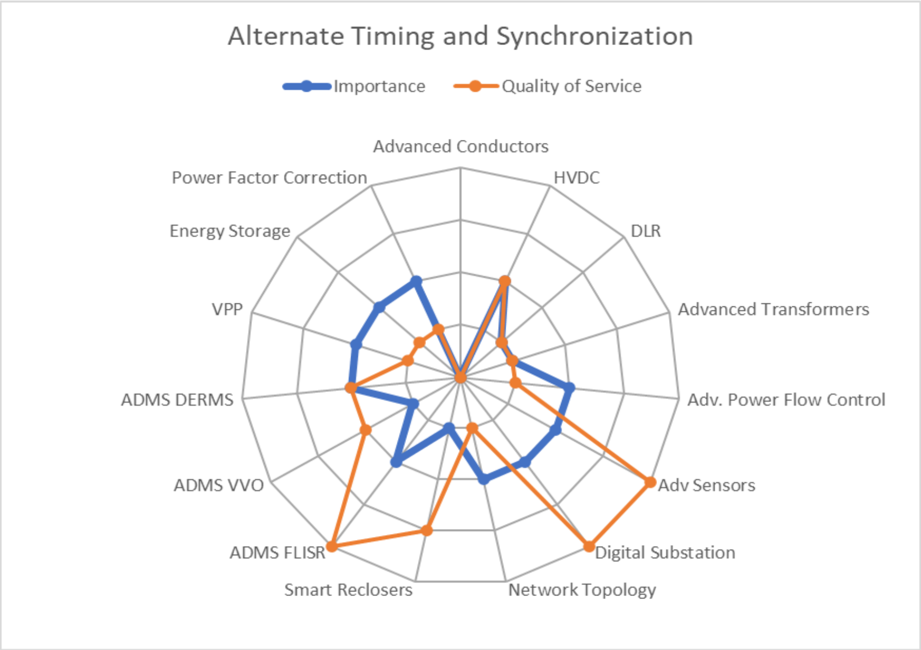


Figure 26. Foundational technology spider diagram: alternative timing and synchronization

Communications technologies are foundational to any technology that relies on an awareness of present grid state to act. Most advanced grid solutions that act only on a single grid facility or localized grouping of devices require basic communications infrastructure to realize full benefit (e.g., DLR, VVO, and Power Factor Correction). On the other hand, solutions that provide grid services through optimization of numerous resources and systems can only maximize grid benefits with low-latency, reliable, and high-quality communications infrastructure. Applications such as the protection schemes from digital substation technologies or fault location in distribution systems from ADMS FLISR can only offer those benefits with appropriate quality of communication technology.

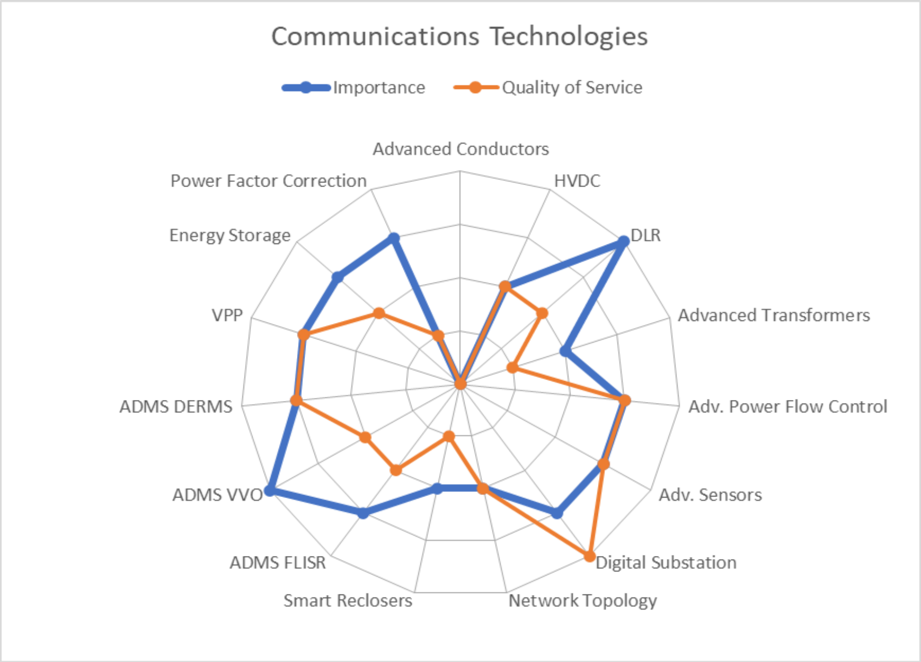


Figure 27. Foundational technology spider diagram: communications technologies

High quality **data management systems** are crucial to the functioning of many innovative technologies, especially those that contribute to the observation and assessment of grid conditions. Advanced sensors can provide utilities, grid operators, and customers with granular information on grid status that can augment traditional control strategies to enable pursuit of diverse benefits, but the data management system must be able to receive and manage large volumes of information. Technologies like VPPs, ADMS, and topology optimization rely on awareness of the whole-system state and forecast to act. Any useful data analytics beyond the basics will only improve the benefits seen from technologies that improve system observation and state awareness or are controlled in response to these capabilities.

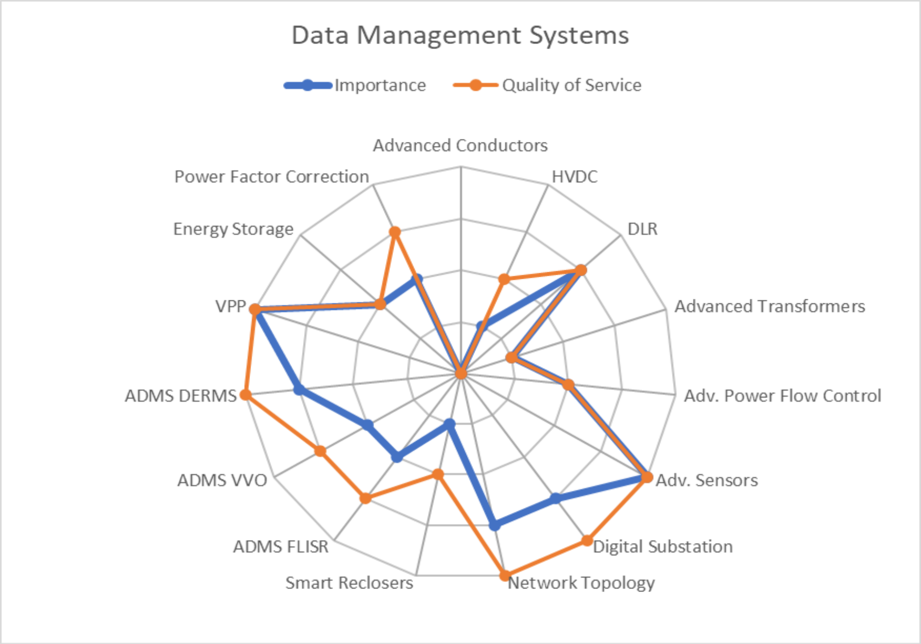


Figure 28. Foundational technology spider diagram: data management systems

System digitization and visualization has the greatest importance to VPPs, digital substations, and network topology. These technologies all rely on a utility's ability to perceive the grid and make control room decisions, ideally aided by automation. Additionally, many technologies like HVDC, APFC, and DLR only require basic levels of system digitization to function but provide additional benefit when the quality of service is high. These technologies all contribute to the transmission system beyond standard operating procedure. Better understanding of their unique qualities and capabilities, and integration of those capabilities into automation schema can increase the realized benefits from those technologies.

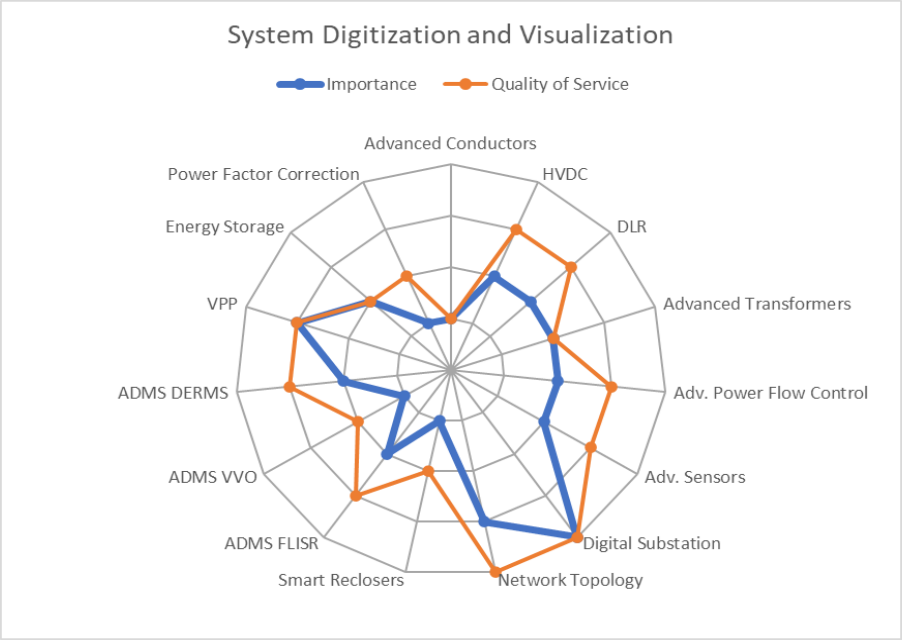


Figure 29. Foundational technology spider diagram: system digitization and visualization

Appendix E: Case studies of Advanced Grid Solutions

Note: Foundational systems are not included as standalone case studies. Example technology deployments highlighted below are not exhaustive.

Advanced Conductors

- AEP uses advanced conductors for capacity expansion and energy efficiency improvements. In 2016, American Electric Power (AEP) replaced two 120-mile long 345 kV circuits of ACSR conductor with composite core (ACCC) conductors, with the goal to nearly double line capacity without having to rebuild or replace existing structures. The project was completed eight months ahead of schedule and nearly doubled line capacity while reducing line losses by 30%.

- SCE uses advanced conductors to mitigate sag and increase capacity. In 2016, Southern California Edison (SCE) used composite core (ACCC) conductors to mitigate sag clearance issues and increase line capacity from 936 amps to 1520 amps on two 230 kV lines. The ACCC conductors enabled SCE to minimize the need to modify or replace existing structures on the 137-circuit mile project, while also eliminating load shedding during low-hydro conditions.

- Tennessee Valley Authority (TVA) completes advanced conductor testing. To evaluate the use of advanced conductors on the TVA system, TVA contracted with TS Conductors Inc. to install a test span on the Goose Pond transmission lines. The pilot project enabled the development of new solutions to maintain transmission efficiency while increasing capacity without building new infrastructure. TVA and TS Conductor were awarded the Edison Pioneers Innovation of the Year Award in 2023 for adoption of advanced conductors to support grid modernization.

- *For additional advanced conductor case studies, see the Advanced Conductor Scan Report (Idaho National Laboratory, 2024).*

Advanced Distribution Management System (ADMS)

- ADMS implementation at Arizona Public Service. In their implementation of ADMS, Arizona Public Service (APS) merged geospatial data with operational technologies to obtain flexible grid management. APS focused on improving data integrity to support its ADMS implementation. By customizing an ADMS through incorporation of geospatial data along with their geographic information system (GIS), APS developed a real-world network model capable of enhancing wildfire response capabilities, increasing DER visibility, and improving system efficiency.

- Sacramento Municipal Utility District implements ADMS. In 2022, Sacramento Municipal Utility District (SMUD) launched an ADMS, as well as the initial phase of their distributed energy resource management (DERMS) platform, to support the expansion of load flexibility resources and their role in SMUD's Zero Carbon Plan. Using software services from Open Systems International (OSI) to implement ADMS and DERMS, the two systems will allow SMUD to shift from a one-way centralized distribution system to a two-way decentralized distribution system that allows SMUD to manage and optimize DERs.

- *For additional ADMS case studies, see the ADMS Voices of Experience Report (DOE).*

Advanced Power Flow Controllers (APFC)

- Georgia Power deployment of APFC. In 2013, Georgia Power installed 33 APFC units to test performance over a 16-month period. The benefits provided motivated Georgia Power to expand the system, doubling the amount of installed devices and integrating them into the existing Energy Management system (EMS).

- UK Power deployment of APFC. In 2019, SmartWires collaborated with UK Power on the LoadShare project, which aimed to relieve a congested zone on UK Power's network. Use of Distributed Series Reactor (DSR) APFCs allowed for 95 MW of additional network capacity, saving customers £8 million in one year (compared to traditional upgrades). The initial program is reported to have cost only £2.4 million "plans to deploy this newly-developed innovative technology in other areas of the network to accommodate even more renewable energy generation at a reduced cost to consumers."

- National Grid deployment of APFC. SmartWires, in partnership with National Grid Electricity Transmission (NGET), deployed five DSR devices in 2021 in the UK. These APFCs were installed to reduce congestion for renewable generation and increased transmission capability by 1.5 GW. The APFCs were connected to National Grid's SCADA system to enable control room operators to manage the devices across the system.

- *For additional APFC case studies, see the Grid-Enhancing Technologies: A Case Study on Ratepayer Impact (DOE) and A Guide to Case Studies for Grid-Enhancing Technologies (INL)*

Advanced Transformers

- Flexible Transformers deployed at Cooperative Energy. General Electric, funded in part by the DOE TRAC Program, installed the "world's first flexible large power transformer" at a local utility in Mississippi (Cooperative Energy). This was a 6-month field demonstration to evaluate benefits of this flexible transformer such as adapting to a range of voltage ratios and impedance levels, withstanding severe weather, and providing stability in the face of a surge or drop in renewable generation.

- Siemens Energy Rapid Response Transformers. In 2021, Siemens Energy delivered and installed three single-phase generator step up (GSU) transformers, in response to a failed conventional transformer at a combined cycle power plant. These multi-voltage, modular transformers are capable of being transported and installed within weeks rather than the typical 9 to 12 months for conventional transformers. These transformers offer smart technology that transmits real-time data to cloud-based storage, analytics, and visualization platform for performance optimization.

Advanced Sensors

- National Grid roles out AMI 2.0 deployment. In New England, National Grid is upgrading its metering technology with Sense's AMI 2.0 which is slated to become a distributed sensing, control, and computation platform at the edge of the grid. These meters can connect real-time load conditions behind the meter to available capacity on the distribution network and help aggregators and utilities balance loads through automation. Nearby, Eversource and Rhode Island Energy have also been approved for AMI 2.0 deployments by their state commissions due to the strong affordability and flexibility benefits to consumers.

- Norway utility deployment of advanced sensors. Elvia, a large electricity network company in Norway, is implementing advanced sensors for monitoring of grid assets. With support from CINELDI, one of Europe's largest research centers for intelligent electricity distribution, Elvia integrated location data from advanced sensors into an ArcGIS mapping and analytics platform to continuously monitor asset heat signatures in real time. The advanced sensors, in combination with the platform, enable Elvia to visualize and analyze all conditions of grid assets, allowing staff to quickly identify any unexpected changes in baseline asset performance indicators prior to asset damage.

Distributed Energy Resource Management System (DERMS)

- PG&E scales up DERMS platform to provide peak summer capacity and integrate DERs. Over 2016-2018, Pacific Gas and Electric (PG&E) demonstrated a DERMS solution developed by GE to manage ~5MW of solar and storage across residential, commercial, and utility owned DERs. The DERMS performed well in use cases from adding situational awareness to managing two-way power flows to creating operational flexibility. Building on this success, PG&E announced in 2023 that it was scaling up its DERMS platform through partnerships with Microsoft and Schneider Electric. Key use cases cited for this deployment at scale included peak capacity during summer, DER integration and visibility, reliability and resilience with energy storage, and supporting transport electrification.

- DERMS facilitates solar interconnection at Avangrid. In New York, Avangrid is using DERMS to help interconnect solar farms that would historically be rejected due to local grid capacity. Before deploying Strata Grid's solution, only 2.6 MW of local solar projects were approved for connection instead of the full 15 MW. The DERMS solution enabled all 15 MW to be interconnected by optimizing grid capacity and helping avoid the upgrades and associated costs that would otherwise be required for a firm interconnection.

Dynamic Line Rating (DLR)

- National Grid and LineVision deploy DLR. National Grid launched a DLR project in 2022 for two 30-mile 115kV transmission lines in western New York, in partnership with the company LineVision, which provides DLR sensors and software solutions. The project, which is located near two large wind farms, is expected to reduce wind curtailment in the region by 350 MW and increase the transmission corridor's overall capacity by an average of 190 MW. Notably, National Grid has plans to overhaul the transmission corridor with higher-capacity lines later in the decade but moved forward with the DLR project because of the immediate benefits and relative ease of implementation.
- PPL deploys DLR across three lines. Pennsylvania Power & Light deployed DLR in 2023 and saw significant congestion cost savings. The project has created $23M in annual congestion cost savings and increased capacity by ~20% on normal lines and ~9-17% on emergency lines.
- Idaho Power deploys DLR. Idaho Power implemented weather-based DLR which provides increased situational awareness for more than 450 miles of transmission lines in highly complex terrain. Contingency relief has been realized multiple times as DLR forecasts are researched and validated. Resulting studies found that DLR improved ratings 95% of the time versus static line ratings for short transmission lines.
- *For additional case studies, see A Guide to Case Studies for Grid-Enhancing Technologies (INL), DLR Report to Congress (DOE, 2019) and DLR: Innovation Landscape Brief (IRENA, 2020).*

Energy Storage

- Rappahannock Electric Cooperative deploys Utility-Scale Battery Storage. Rappahannock Electric Cooperative deployed a grid-scale 8-hour energy storage solution in early 2021. This project reduced electricity costs by dispatching stored energy during peak hours and deferring substation upgrades. It also increased resiliency to customers by providing electricity through storage in the event of transmission system failure.
- Gridstor starts energy storage facility operations in California. Gridstor has begun operations to provide Southern California Edison with 40 MW of 4-hour energy storage. This solution will support decarbonization while ensuring grid reliability during the hours of greatest demand. The project was built with larger 60 MW inverters to allow the facility to meet greater demand at times of need.
- *For additional case studies of energy storage as a transmission and distribution asset, see Storage as Transmission Asset Market Study (Quanta Technology, 2023).*

Fault, Location, Isolation, and Service Restoration (FLISR)

- CenterPoint Energy deploys FLISR. CenterPoint replaced their legacy DMS, OMS, and D-SCADA systems with ADMS and FLISR. This deployment included intelligent grid switching devices. FLISR has increasingly digitized and automated CenterPoint's operations and enabled near real time distribution load flow data.

- Duke Energy deploys FLISR. Duke installed "Self-Healing Teams" of field devices for FLISR operations. These teams of devices include centrally located control software, and field installed electronic reclosers and switches that use digital-cell or radio communications. These devices measure and digitally communicate information of distribution line loadings, voltage levels, and fault data to a central application that remotely locates and isolates faulted distribution line sections automatically restores service to non-faulted line sections.
- Southern Company deploys FLISR. Southern Company deployed automated feeder switches, automated capacitors and voltage regulators, and equipment condition monitors. Southern Company's integrated distribution management system (IDMS) monitors data streams for a variety of systems including meter data management, outage management, and the distribution automation (DA) communications infrastructure, which connects to devices used for accomplishing FLISR operations.
- *For additional case studies, see the Smart Grid Investment Grant FLISR report (DOE)*

High Voltage Direct Current (HVDC)

- SOO Green HVDC transmission line being deployed on existing rights-of-way. SOO Green is a company owned by investment funds managed by Copenhagen Infrastructure Partners, Siemens Energy, and Jingoli Power. The SOO Green HVDC Link will connect the company's converter station in northern Iowa to its Illinois converter station just west of Chicago, roughly 350 miles away. It will use paired 525-kV cross-linked polyethylene-class cables installed underground primarily along existing railroad rights-of-way to make the connection. Minneapolis, Minnesota-based Direct Connect Development Company is heading the project.

Power Factor Corrections

- Power factor correction deployed to save on energy rates in Pennsylvania. The owner of a large Pittsburgh commercial office building partnered with Eaton to improve their electrical system efficiency to eliminate power factor penalties and generate savings on electric utility bills. Eaton installed power factor correction capacitor banks sized to their system to correct the system's power factor, improving from 0.86 to over 0.95. Installation of these units, purchased and installed for $12,000, removed the power factor penalty of $1,932 the facility was paying per month, resulting in a payback of just over 6 months.
- PFC Engineering deployed power factor corrections to reduce energy costs. PFC Engineering, a UK based company, was contracted to improve a client site's poor power factor, causing excessive amounts of reactive power, leading to high reactive charges on electric bills. By installing a power factor correction scheme, PFC Engineering was able to improve the system's power factor from 0.77 to over 0.95. Installation of these units, purchased and installed for £20,612 (approximately $26,000), removed the power factor penalty of £0.93/KVA/month (approximately $1.18 KVA/month), resulting in a payback of approximately 10 months.

Smart Reclosers

- Potomac Edison expands deployment of smart reclosers. In West Virginia, Potomac Edison is expanding their deployment of smart reclosers, which have reduced extended outage times to ~60 seconds on unfaulted feeder segments. An influx of new residents and businesses is driving Potomac Edison to improve its system reliability.
- Oncor deploys smart reclosers. Oncor Texas deployed automated smart reclosers to enhance service restorations. After an initial deployment, Oncor reported that the solution can reduce average outage

times from 45 minutes to as little as two minutes on the unfaulted feeder segments leading to a large improvement on its System Average Interruption Duration Index (SAIDI) metric. Oncor plans to deploy the solution across its entire system by 2026 so it can "benefit as many customers as possible."

Substation Automation and Digitization

- National Grid (U.S.) digitize substations across its system. In 2018, National Grid was the first utility to digitize its transmission substations fully in part of a strategy to develop a highly intelligent transmission network to meet customers' long-term needs and adapt to the rapidly changing energy landscape. National Grid decided to digitize the entire substation (including all equipment such as transformers, circuit breakers), which went beyond traditional IEC 61850 programs. National Grid plans to place 40 fully digital substations in service by 2028.

Topology Optimization

- Alliant Energy uses topology optimization to reduce congestion. Alliant and NewGrid use topology optimization software and expertise to find regionally beneficial reconfiguration solutions to congestion events affecting Alliant Energy customers. The analysis avoids overly complex reconfigurations and identifies solutions that relieve congestion while respecting system security limits (such as N-1 contingency criteria and voltage limits). Over the two year period since October 2021, the effort delivered $14 million in savings to Alliant customers (18% reduction), in addition to further regional savings. Congestion costs could have been further reduced by another 36% ($27 million) if other reconfigurations that had been identified were fully implemented, for a total cost reduction estimate of 54%. Further, reconfigurations identified could reduce constraint overload risks by 90%, providing significant reliability benefits.

- Topology optimization mitigated overloading of a major constraint in the SPP market. The Cimarron transformer constraint is a key power supply connection for the Oklahoma City metropolitan area. This was the most significant constraint in the SPP market in 2022. SPP implemented a reconfiguration identified by NewGrid to fully mitigate this congestion when the constraint was overloading and uncontrollable with redispatch on several occasions during summer of 2022. The reconfiguration provided about 20% reduction in congestion.

Virtual Power Plant (VPP)

- U.S. virtual power plants expected to proliferate as reliability needs rise. In the United States, there are more than 500 VPPs that are operational. Most deployed VPPs are concentrated in California, New York, and Texas, which have favorable regulatory mechanisms.

- Rocky Mountain Power deploys storage based VPP. Rocky Mountain Power collaborated with battery company Sonnen to establish the "Wattsmart Battery" program that provides significant grid services and customer benefits. Customers receive upfront incentives upon enrollment of $400/kW for residential batteries and $600/kW for commercial batteries in addition to ongoing monthly bill credits. In 2019, Rocky Mountain Power deployed 5 MW of solar PV and 12.6 MWh of battery storage across 600 homes in Utah.

- National Grid launches ConnectedSolutions program to reduce summer peak demand. The ConnectedSolutions program provides up to a $200/kW incentive for customers to reduce energy use during the summer to reduce system peaks. This bring-your-own-device program consists of over 1,000 customer accounts accounting for 350 MW of peak curtailment (largely commercial and industrial customers) and over 100,000 customer devices yielding 50 MW of peak curtailment (largely from residential customers and small to medium sized businesses).

Volt-Var Optimization (VVO)

- AEP Ohio scales up VVO deployment. AEP Ohio piloted VVO on seventeen distribution circuits in 2009 and found significant benefits in energy efficiency and load reduction for more efficient use of the existing distribution grid. AEP found that VVO reduced energy (kWh consumed) and demand (power, in KW) by 2-4%. They also determined that peak load was reduced 3 percent. In 2013, AEP expanded its pilot into a deployment at scale by adding VVO to almost 80 distribution circuits.
- KCP&L implements VVO pilot. In the early 2010s, Kansas City Power & Light (KCP&L) deployed VVO technologies in a pilot to serve 5 square miles of Kansas City. After deployment, they found that VVO reduced total energy usage by 1.63% and peak energy usage by 1.13%. After merging with KCP&L in 2018, Evergy expanded the VVO pilot and invested in a solution that can create energy savings of ~3-5% and aid in DER integration and grid visibility.

Artificial Intelligence (AI) examples

AI is not a standalone technology considered in the report but has emerging applications that leverage data from and accelerate deployment of advanced grid solutions. Some examples are highlighted here.

- Avangrid deploys Artificial Intelligence to increase reliability. Avangrid has built a robust historical AI analysis team as an operations function that informs every upper management decision. Avangrid is creating three unique AI systems: Predictive Health Analytics, GeoMesh, and HealthAI. Each technology pulls from existing data from Avangrid's electric grids and analyzes the information to forecast future performance of the grid, analyze conditions of grid equipment, or target at-risk locations for inspections and investment.
- SoCal Edison deploys AI to enhance regulatory processes. Southern California Edison (SCE) uploaded 22,000 regulatory documents into Microsoft's Azure platform to create EdisonGPT, an internal generative AI that gathers and summarizes regulatory documents and information. This tool accelerates SCE's pace of work and improves management of regulatory processes. The AI is also available externally, enabling customers to receive regulatory information more quickly.

Appendix F: Key Assumptions and Inputs

Methodology 1: National full potential capacity, capacity deferral, and reliability and resilience impact analysis

Objectives of analysis: The purpose of this analysis was to understand the full potential benefits that advanced grid solutions could provide to the grid if they were deployed at scale wherever technically applicable and economically viable. The outcomes represent an estimated order of magnitude understanding of the national impact of these technologies on the current grid footprint (as of 2023). As the grid grows, the potential benefits are likely to increase for each technology.

Approach: Generally, the analysis started with a national statistic (e.g., peak power, interruption events), estimated what portion could be impacted by the advanced technology (based on the technology's estimated technical and economic applicability, line losses, adoption of competing technologies, and other potential derates), and then applied a potential improvement range of the technology based on case studies and/or industry expertise. There is a low, medium, and high case considered based on the technology's capacity impact range. Transmission and distribution capacity impacts were evaluated based on impact to U.S. peak load (GW). Transmission and distribution deferral values were based on average value of deferring this infrastructure on a $/GW basis—and applied to the amount of capacity that is avoided. Reliability and resilience impacts were evaluated based on total annual customer interruption events (number of events). Congestion cost reduction impacts were based on total annual energy consumption (GWh) and an average congestion cost value per GWh.

Simplifying assumptions and limitations: This analysis was simplified and standardized across the twenty technologies in scope to be able to get an order of magnitude national estimate—additional analysis is needed to refine these impacts based on local contexts. Additionally, these impacts are evaluated as if the technologies were deployed to their full potential overnight (without looking at actual deployment timelines given the wide variability). For capacity, the approach assumes that bulk energy generation is distributed uniformly over the transmission and distribution system. National averages are generally used throughout analysis (not regional and/or hourly data).

Example capacity calculation for dynamic line rating (simplified):

Step 1: Evaluate technical applicability: Peak Load Capacity (742 GW) x DLR technical feasibility (97%) x Remove transmission losses (99.5%) = Power that could be technically impacted by DLR (716 GW)

Step 2: Evaluate economic applicability: Power that could be technically impacted by DLR (716 GW) x lines that are operating at or near rated capacities and could be economically viable for DLR (50%) x system where DLR is not used today (99%) x System without competing technology (95%) x lines that are thermally limited where DLR is most relevant (99%) x portion of time that DLR generates a capacity increase over static line ratings (95%) = Power that could have DLR applied (317 GW)

Step 3: Capacity impact: Power that could have DLR applied (317 GW) x DLR capacity increase (25% in mid-case) = Effective capacity increase (~80 GW increase in mid-case)

Key assumptions and inputs:

Advanced Conductors: Assumes ~15% of US lines are reconductored (based on 20% of lines that could be reconductored (INL) and applying an estimate that 80% of structures have sufficient life left to be viable for reconductoring (industry interviews)). Capacity increase range of 1.7x, 2x, and 3x (low, med, and high range) (INL).

Dynamic Line Rating: Assumes 50% of US lines are economically viable for DLR where they are operating above 75% of rated capacity (WECC; industry interviews). The minimum capacity increase was 6%, average was 25%, maximum was 44% (DOE, IRENA). Assumed an average of 50% congestion could be avoided in a mid-case.

Advanced Power Flow Controller: Assumes 50% of US lines are economically viable based on where lines are estimated to be overloaded and be connected to available lines (Guidehouse). Assumes a minimum capacity increase of 10%, average of 17%, and maximum of 25% (DOE, Watt Coalition, industry interviews). Assumed an average of 40% of congestion could be avoided (Grid Strategies).

Topology Optimization: Assumes 90% of transmission system is economically viable for topology optimization given the low cost and broad viability (industry interviews). Assumes a minimum capacity increase of 3%, average of 8%, and maximum of 12% (Brattle, National Grid, industry interviews). Assumed an average of 50% of congestion could be avoided (case studies).

Energy storage: Assumes energy storage can be applied to ~50% of grid system (NREL). Assumes minimum capacity impact of 10%, average of 50%, and maximum of 100% (Guidehouse).

VPP and DERMS: Assumes VPPs and DERMS are viable in ~30% of the grid today where DER penetration is sufficiently high. Assumes minimum peak capacity reduction of 10%, average of 18%, and maximum of 26.5% (DOE, NREL).

VVO: Assumes VVO is economically viable in 70% of use cases (Guidehouse). Assumes energy savings (relief to transmission and distribution capacity) at a minimum of 1%, average of 3.7%, and maximum of 6.4% energy savings based (NREL).

Power Factor Correction: Assumes power factor corrections are viable across 30% of the grid today (NERC, Guidehouse). Assumes energy savings of minimum of 2%, average of 2.3%, maximum of 2.5% (ORNL, Eaton).

Smart Reclosers: Assumes that 60% of circuits are viable for smart reclosers deployment (Guidehouse). Assumes a minimum outage reduction of 25%, average of 38% and maximum of 50% (Guidehouse).

FLISR: Assumes approximately 45% of circuits are viable for FLISR deployment (Guidehouse). Assumes a reduction in customer minutes of interruption reduction of a minimum of 30, average of 40%, and maximum of 50% (DOE)

Key general assumptions:

2024-2033 Peak Demand Growth: based on peak demand growth from NERC Long-Term Reliability Assessment (NERC, December 2023).

2023 current demand: 742 GW, 4.23M GWh (EIA)

Transmission and Distribution Deferral Calculation Inputs:

Discount rate: 8%

NPV time-period: 5 years (based on average industry practices for capacity deferral benefit)

Assumptions: Avoided Transmission Capacity Costs of $74,150/MW-year; Avoided Distribution Capacity Costs is $17,940/MW-year (CPUC Avoided Cost Calculator)

Methodology 2: Example Utility Investment Case Analysis

Objectives of analysis: The purpose of this analysis was to identify realistic bundles of technologies that could solve grid needs based on hypothetical utility case examples and evaluate their cost-effectiveness through a benefit-cost assessment (BCA). This BCA analysis leveraged emerging best practices, including taking a longer timeline horizon (typically 12 years, from 2024-2035), considering the comprehensive benefits of these solutions, and evaluating these technologies in bundles to capture potential synergies. These assessments are illustrative of the benefit/costs of real utility contexts but are not specific guidance.

General approach: The benefits from the national impact assessments (e.g., capacity, reliability, etc.) were used and scaled down to the utility based on key assumptions. These benefits included additional assessments including value of avoided emissions from avoided energy generation, avoided generation capacity costs, and others. Costs were evaluated based on estimated industry CAPEX and OPEX estimates, based on Guidehouse assessments, and scaled based on relevant utility assumptions.

Key utility assumptions:

Table 11. Key assumptions across representative utility investment case archetypes

Metric	Rural Co-Op (Northwest)	Urban Muni (Southwest)	Small IOU (Northeast)	Med IOU (Midwest)	Large IOU (Southeast)	Unit
Discount Rate	8%	8%	8%	8%	8%	%
Customers	20,000	500,000	100,000	1,700,000	2,500,000	#
Energy Demand	250,000	13,000,000	4,000,000	50,000,000	100,000,000	*MWh*
Peak Power	300	3,000	700	8,000	18,000	*MW*
FTE Employee Cost	$120,000	$120,000	$120,000	$120,000	$120,000	*$/employee*
Number Feeders	30	650	125	2,125	3,125	#
Feeder Line Miles	1,050	3,250	1,250	21,250	31,250	*Miles*
Number Substations	5	90	15	270	1,040	#
Num. Transmission Lines	0	10	80	50	100	#
Transmission Line Miles	0	600	8,000	5,000	10,000	Miles

Benefit streams quantified in analysis for advanced grid solutions:
Note: these are not necessarily exhaustive of all benefits of advanced grid solutions. These were identified as some of the primary values, which were prioritized for this illustrative analysis.

- **ADMS FLISR**: Reduced O&M, Avoided Emissions, Increased Reliability
- **ADMS VVO**: Avoided Generation Capacity Costs, Avoided Energy Generation, Avoided Transmission Capacity Costs, Avoided Distribution Capacity Costs, Avoided Emissions, Decreased Utility Revenue/ Customer Savings
- **Advanced Conductors**: Avoided Generation Capacity Costs, Avoided Energy Generation Costs, Avoided Transmission Capacity Costs, Avoided Transmission Congestion Costs, Avoided Emissions, Increased Reliability
- **Advanced Flexible Transformers**: Increased Reliability
- **Advanced Power Flow Controls (APFCs)**: Avoided Generation Capacity Costs, Avoided Energy Generation Costs, Avoided Transmission Capacity Costs, Avoided Transmission Congestion Costs, Avoided Emissions
- **DERMS**: Avoided Generation Capacity Costs, Avoided Transmission Capacity Costs, Avoided Distribution Capacity Costs, Avoided Emissions
- **Digital Substations:** Increased Revenue from Reduced CMI, Reduced O&M, Cost Savings from Reduced Customer Interruptions
- **Dynamic Line Rating (DLR):** Avoided Transmission Capacity Costs, Avoided Transmission Congestion Costs, Avoided Emissions, Increased Reliability
- **Energy Storage**: Avoided Generation Capacity Costs, Avoided Transmission Capacity Costs, Avoided Transmission Congestion Costs, Increased Revenue from Reduced CMI, Reduced O&M, Cost Savings from Reduced Customer Interruptions, Avoided Emissions, Increased Resilience
- **Network Topology Optimization**: Avoided Transmission Capacity Costs, Avoided Transmission Congestion Costs, Increased Reliability
- **Power Factor Correction**: Avoided Generation Capacity Costs, Avoided Transmission Capacity Costs, Avoided Distribution Capacity Costs, Avoided Transmission Congestion Costs, Increased Resilience
- **Smart Reclosers**: Increased Revenue from Reduced CMI, Reduced O&M, Avoided Emissions, Cost Savings from Reduced Customer Interruptions
- **VPPs**: Avoided Generation Capacity Costs, Avoided Transmission Capacity Costs, Avoided Distribution Capacity Costs, Avoided Transmission Congestion Costs, Increased Reliability

Benefit synergies assumption: Advanced grid solutions that were identified as being key amplifiers of other solutions (e.g., digital substations), it was assumed that these amplifiers unlocked 30% of the full potential benefits. Additional analysis is needed to better quantify the interacting effects between advanced grid solutions to refine this understanding in real world applications.

Deployment timeline assumptions: Benefits and costs are generally assumed to ramp linearly with deployment timeframes. The tables below summarize the start and end year roll out assumptions.

Table 12. Deployment timeline assumptions for example utility technology bundles

Urban Muni (Southwest)		
Technology	**Assumption**	**Value (Inputs)**
Smart Reclosers	Baseline Utilization	0%
	% Deployment	100%
	Deployment Start Year	2024
	Deployment End Year	2028
Power Factor Correction	Baseline Utilization	0%
	% Deployment	10%
	Deployment Start Year	2025
	Deployment End Year	2027
ADMS DERMS	Baseline Utilization	0%
	% Deployment	60%
	Deployment Start Year	2027
	Deployment End Year	2029
VPP	Baseline Utilization	0%
	% Deployment	100%
	Deployment Start Year	2030
	Deployment End Year	2031

Medium IOU (Midwest)		
Technology	**Assumption**	**Value (Inputs)**
Advanced PFCs	Baseline Utilization	0%
	% Deployment	25%
	Deployment Start Year	2026
	Deployment End Year	2029
Digital Substations	Baseline Utilization	25%
	% Deployment	75%
	Deployment Start Year	2028
	Deployment End Year	2031
HVDC Lines	Baseline Utilization	0%
	% Deployment	0%
	Deployment Start Year	2031
	Deployment End Year	2031
Energy Storage	Baseline Utilization	15%
	% Deployment	50%
	Deployment Start Year	2026
	Deployment End Year	2028

Large IOU (Southeast)		
Technology	**Assumption**	**Value (Inputs)**
ADMS-VVO	Baseline Utilization	0%
	% Deployment	60%
	Deployment Start Year	2026
	Deployment End Year	2030
DLR	Baseline Utilization	0%
	% Deployment	20%
	Deployment Start Year	2025
	Deployment End Year	2028
Advanced Conductors	Baseline Utilization	0%
	% Deployment	10%
	Deployment Start Year	2029
	Deployment End Year	2029
Digital Substation	Baseline Utilization	20%
	% Deployment	80%
	Deployment Start Year	2028
	Deployment End Year	2032

Rural Coop (Northwest)		
Technology	**Assumption**	**Value (Inputs)**
Smart Reclosers	Baseline Utilization	0%
	% Deployment	100%
	Deployment Start Year	2024
	Deployment End Year	2028
Digital Substations	Baseline Utilization	0%
	% Deployment	100%
	Deployment Start Year	2026
	Deployment End Year	2029
Energy Storage	Baseline Utilization	0%
	% Deployment	60%
	Deployment Start Year	2026
	Deployment End Year	2028

Small IOU (Northeast)		
Technology	**Assumption**	**Value (Inputs)**
ADMS-FLISR	Baseline Utilization	0%
	% Deployment	60%
	Deployment Start Year	2025
	Deployment End Year	2027
Advanced Transformers	Baseline Utilization	0%
	% Deployment	20%
	Deployment Start Year	2026
	Deployment End Year	2028
twork Topology Optimizati	Baseline Utilization	0%
	% Deployment	100%
	Deployment Start Year	2025
	Deployment End Year	2027

Key Cost Inputs:

Technology	System / Sub-System	Type	CapEx Valuation Parameter	CapEx Scale Metric(s)	OpEx Valuation Parameter	OpEx Scale Metric(s)
ADMS - DERMS	DERMS software	Asset	0.5	50% of ADMS Base cost	20%	Maintenance (% of CAPEX)
	DERMS software	Installation, Configuration, Integration	3	3x the license cost	1	# new employees
	DERMS software	Data cleanup and uplift	2	2x the license cost		
	Telecommunications	Asset	$ 10,000	Number of Feeders	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5x the telco cost per feeder		
ADMS - FLISR	FLISR software	Asset	$ 1,500	Number of Feeders	20%	Maintenance (% of CAPEX)
	FLISR software	Installation, Configuration, Integration	3	3x license	1	# new employees
	FLISR software	Data cleanup and uplift	2	2x license		
	Fault sensors	Asset	$ 2,000	Number of Feeders	5%	Maintenance (% of CAPEX)
	Fault sensors	Installation, Configuration, Integration	1.5	1.5x the sensor cost per feeder		
	Circuit ties and switches	Asset	1,500	Number of Feeders	5%	Maintenance (% of CAPEX)
	Circuit ties and switches	Installation, Configuration, Integration	$ 2	1.5x of sensor cost per feeder		
	Telecommunications	Asset	$ 10,000	Number of Feeders	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5x the telco cost per feeder		
ADMS VVO	ADMS base software (DSCADA, DMS, OMS)	Asset	$ 4.5	Number of Customers	$ 3.50	Number of Customers
	ADMS base software (DSCADA, DMS, OMS)	Installation, Configuration, Integration	3	3x the license cost	5	# new employees
	ADMS base software (DSCADA, DMS, OMS)	Data cleanup and uplift	5	1x to 10x license		
	VVO software	Asset	$ 1,500	Number of Feeders	20%	Maintenance (% of CAPEX)
	VVO software	Installation, Configuration, Integration	3	3x license	$ 1	# new employees
	VVO software	Data cleanup and uplift	2	2x license		
	Voltage and line sensors	Asset	$ 7,500	Number of Feeders	5%	Maintenance (% of CAPEX)
	Voltage and line sensors	Installation, Configuration, Integration	3	1.5x the sensor cost per feeder		
	LTC, Cap Banks, Regulators	Asset	$ 20,000	Number of Feeders	8%	Maintenance (% of CAPEX)
	LTC, Cap Banks, Regulators	Installation, Configuration, Integration	1.5	1.5x the sensor cost per feeder		
	Telecommunications	Asset	$ 10,000	Number of Feeders	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5x the telco cost per feeder		
Advanced Conductors	Engineering, planning, procurement, scheduling	Asset	$ 780,000	Line miles	$ 2,436	TransmissionLineMiles
	Construction and commissioning	Installation	$ 520,000	Line miles		
Advanced Power Flow Controllers	Advanced PFC Equipment	Asset	$ 210,000	Number of transmission lines	10%	Maintenance (% of CAPEX)
	Advanced PFC Equipment	Installation, Configuration, Integration	$ 140,000	Number of transmission lines	$ -	
	Advanced PFC Equipment	AFP Systems	$ 5,000,000	Fixed Cost for System	1	# new employees
Advanced Transformers	Software	Install software and integrate	$ 200,000	Number of T lines	$ 1	# new employees
	Equipment	Equipment	$ 1,000,000	Number of T lines	10%	Maintenance (% of CAPEX)
	Equipment	Installation, Configuration, Integration	$ 800,000	Number of T lines		
Digital Substations	Substation automation software	Asset	$ 10,000	Number of Substations	20%	Maintenance (% of CAPEX)
	Substation automation software	Installation, Configuration, Integration	2	2x the license cost	2	# new employees
	Substation automation software	Data cleanup and uplift	3	1x to 5x license		
	Telecommunications	Asset	$ 15,000	Number of Substations	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5 the fiber cost		
	Equipment	Equipment	$ 275,000	Number of Substations	6%	Maintenance (% of CAPEX)
Dynamic Line Rating	DLR Software	Asset	$ 70,000	Number of transmission lines	20%	M&S
	DLR Software	Installation, Configuration, Integration	3	3x the license cost	1	# new employees
	DLR Software	Data cleanup and uplift	4	1x to 10x license		
	Temperature, wind, LIDAR sensors	Asset	$ 5,000	Number of transmission lines	10%	Maintenance (% of CAPEX)
	Temperature, wind, LIDAR sensors	Installation, Configuration, Integration	1.5	1.5x the sensor cost per line		
	Telecommunications	Asset	$ 10,000	Number of transmission lines	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5x the telco cost per line		
Energy Storage	Battery	Asset	$ 4,761,000.00	Number of Substations	$ 180,000	Number of Substations
	Battery	Battery Control Systems	$ 793,500.00	Number of Substations	$ 20,000	Number of Substations
	Battery	Installation, Configuration, Integration	$ 2,380,500.00	Number of Substations	$ -	
HVDC	Engineering, planning, procurement, scheduling	Asset	$ 460,000	Line miles	$1,300.00	Maintenance (% of CAPEX)
	Construction and commissioning	Installation	$ 325,000	Line miles	$ -	
Network Topology Optimization	System	NTO System	$ 1,500,000	License Cost	4	# new employees
	System	Data Uplift	2	2x license cost		
	Equipment	Equipment	5,000	Number of feeders	20%	Maintenance (% of CAPEX)
Power Factor Correction	PFC Application	Asset	$ 4,200	Number of feeders	20%	Maintenance (% of CAPEX)
	PFC Application	Installation, Configuration, Integration	$ 1,800	Number of feeders	1	#new employees
	Telecommunications	Asset	$ 10,000	Number of feeders	10%	Maintenance (% of CAPEX)
	Telecommunications	Installation, Configuration, Integration	1.5	1.5 telcoms cost per feeder		
	PFC Application	Asset Data Uplift	2	2x the license cost		
	Equipment	Asset	$ 36,000	Number of feeders	10%	Maintenance (% of CAPEX)
	Equipment	Installation, Configuration, Integration	$ 24,000	Number of feeders		
Smart Reclosers	Smart Reclosers	Equipment	$ 82,500.0	Number of Feeders	10%	Maintenance (% of CAPEX)
	Smart Reclosers	Recloser Control System	$ 16,500.0	Number of Feeders	10%	Maintenance (% of CAPEX)
	Smart Reclosers	Installation, Configuration, Integration	$ 66,000.0	Number of Feeders		
VPP	VPP Software	Asset	$ 7,000	Peak Load	30%	Annual Software Fee (% of CAPEX)
	VPP Software	Installation, Configuration, Integration	$ 3,000	Peak Load	2	# new employees
	VPP Software	Data cleanup and uplift	2	2x the license cost		

References

i North American Electric Reliability Corporation. December 2023. *2023 Long-Term Reliability Assessment.* https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2023.pdf; ISO New England. 2024. *2050 Transmission Study.* https://www.iso-ne.com/static-assets/documents/100008/2024_02_14_pac_2050_transmission_study_final.pdf; PJM. 2024. *PJM Load Forecast Report.* https://www.pjm.com/-/media/library/reports-notices/load-forecast/2024-load-report.ashx

ii Denholm, P., Patrick, B., Cole, W., et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81644.pdf

iii U.S. Department of Energy. 2023. *National Transmission Needs Study.* https://www.energy.gov/sites/default/files/2023-12/National Transmission Needs Study - Final_2023.12.1.pdf

iv Edison Electric Institute. February 2024. *America's Electric Companies – Delivering the Future of Energy.* https://www.eei.org/-/media/Project/EEI/Documents/Issues-and-Policy/Finance-And-Tax/WSB-Presentation.pdf

v Office of Energy Efficiency and Renewable Energy. N.d. *Energy Accessibility and Affordability.* https://www.energy.gov/eere/energy-accessibility-and-affordability; White House. November 2021. *THE LONG-TERM STRATEGY OF THE UNITED STATES: Pathways to Net-Zero Greenhouse Gas Emissions by 2050.* https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf; Gopstein, A., Nguyen, C., O'Fallon, C., Wollman, D. February 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0.* National Institute of Standards and Technology. https://doi.org/10.6028/NIST.SP.1108r4

vi U.S. Department of Energy. 2023. *National Transmission Needs Study.* https://www.energy.gov/sites/default/files/2023-12/National Transmission Needs Study - Final_2023.12.1.pdf

vii U.S. Department of Energy. January 2024. *Two Years of Building a Better Grid: What it Means for Communities.* https://www.energy.gov/gdo/articles/two-years-building-better-grid-what-it-means-communities

viii Jenkins, J.D., Farbes, J., Jones, R., Patankar, N., Schivley, G. September 2022. *Electricity Transmission is Key to Unlock the Full Potential of the Inflation Reduction Act.* Princeton University. DOI: 10.5281/zenodo.7106176; U.S. Department of Energy. 2023. *National Transmission Needs Study.* https://www.energy.gov/sites/default/files/2023-12/National Transmission Needs Study - Final_2023.12.1.pdf

ix North American Electric Reliability Corporation. December 2023. *2023 Long-Term Reliability Assessment.* https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2023.pdf

x Wilson, J. and Zimmerman, Z. December 2023. *The Era of Flat Power Demand is Over.* Grid Strategies. https://gridstrategiesllc.com/wp-content/uploads/2023/12/National-Load-Growth-Report-2023.pdf

xi Denholm, P., Patrick, B., Cole, W., et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81644.pdf

xii Chojkiewicz, E., Paliwal, U., Abhyankar, N., Baker, C., O'Connell, R., Callaway, D., Phadke, A. Revised February 2024. *Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way.* Energy Institute at Haas. https://haas.berkeley.edu/wp-content/uploads/WP343.pdf

xiii Pfeifenberger, J., Bai, L., Levitt., Plet, C., Sonnathi, C. September 2023. *The Operational and Market Benefits of HVDC to System Operators.* Brattle Group, DNV. https://acore.org/wp-content/uploads/2023/09/The-Operational-and-Market-Benefits-of-HVDC-to-System-Operators.pdf

xiv U.S. Department of Energy. February 2022. *Grid-Enhancing Technologies: A Case Study on Ratepayer Impact.* https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf; Federal Energy Regulatory Commission. June 2022. Congestion and Overload Mitigation using Optimal Transmission Reconfigurations – Experience in MISO and SPP. *https://www.ferc.gov/media/congestion-and-overload-mitigation-using-optimal-transmission-reconfigurations-experience*; Idaho National Laboratory. October 2022. *A Guide to Case Studies of Grid-Enhancing Technologies.* inl.gov/content/uploads/2023/03/A-Guide-to-Case-Studies-for-Grid-Enhancing-Technologies.pdf; Industry interviews

xv Pratt, A., Mendoza, I., Usman, M., Tiwari, S., Padullaparti, H., Baggu, M., and Lightner, E. 2020. *Using an Advanced Distribution Management System Test Bed to Evaluate the Impact of Model Quality on Volt/VAR Optimization: Preprint.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/74723.pdf

xvi U.S. Department of Energy. July 2023. *Households of Color Continue to Experience Energy Insecurity at Disproportionately Higher Rates.* https://www.energy.gov/justice/articles/households-color-continue-experience-energy-insecurity-disproportionately-higher

xvii Ibid; U.S. Department of Energy. August 2023. *Tribal Electricity Access and Reliability.* https://www.energy.gov/sites/default/files/2024-01/EXEC-2023-000952%20-%20Tribal%20Electricity%20Access%20Reliability%20Report%20to%20Congress%20%28Final%20Draft%20-%20Clean%29-signed%20by%20S1.pdf

xviii Mclaughlin, T. May 2022. *Creaky U.S. power grid threatens progress on renewables, EVs.* https://www.reuters.com/investigates/special-report/usa-renewables-electric-grid; McLennan, M. 2020. *Modernising Ageing Transmission.* Public Utilities Fortnightly. https://www.marshmclennan.com/insights/publications/2020/apr/modernising-ageing-transmission.html

xix Doying, R., Goggin, M., Sherman, A. July 2023. *Transmission Congestion Costs Rise Again in U.S. RTOs.* Grid Strategies. https://gridstrategiesllc.com/wp-content/uploads/2023/07/GS_Transmission-Congestion-Costs-in-the-U.S.-RTOs1.pdf

xx Downing, J., Johnson, N., McNicholas, M., Nemtzow, D., Oueid, R., Paladino, J., Wolfe, E.B. September 2023. *Pathways to Commercial Liftoff: Virtual Power Plants.* U.S. Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230911-Pathways-to-Commercial-Liftoff-Virtual-Power-Plants_update.pdf

xxi ISO-New England. November 2023. *ISO-NE's 2050 Transmission Study outlines potential costs, solutions to support reliability.* ISO Newswire. https://isonewswire.com/2023/11/02/iso-nes-2050-transmission-study-identifies-potential-costs-solutions-to-support-reliability-throughout-the-clean-energy-transition/

xxii Lehmann, H., Rosenberger, E., Elko, B. December 2022. *Dynamic Line Ratings Operations Integration.* PPL. https://www.pjm.com/-/media/committees-groups/task-forces/dlrtf/2022/20221212/20221216-item-04---ppl-dlr-presentation.ashx

xxiii Murphy, S. 2018. *Simulating the Economic Impact of a Dynamic Line Rating Project in a Regional Transmission Operator Environment.* PJM. https://cigre-usnc.org/wp-content/uploads/2018/11/04-Simulating-the-Economic-Impact-of-a-Dynamic-Line.pdf

xxiv U.S. Department of Energy. December 2020. *Advanced Transmission Technologies.* https://www.energy.gov/oe/articles/advanced-transmission-technologies-report

xxv Alliant Energy. November 2023. *NewGrid Topology Optimization Pilot.* https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf

xxvi Idaho National Lab. December 2023. *Advanced Conductor Scan Report.* https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf

xxvii Rockefeller Foundation. April 2021. *Frozen Out in Texas: Blackouts and Inequity.* https://www.rockefellerfoundation.org/insights/grantee-impact-story/frozen-out-in-texas-blackouts-and-inequity/; U.S. Department of Energy. August 2023. *Tribal Electricity Access* *and Reliability.* https://www.energy.gov/sites/default/files/2024-01/EXEC-2023-000952%20-%20Tribal%20Electricity%20Access%20Reliability%20Report%20to%20Congress%20%28Final%20Draft%20-%20Clean%29-signed%20by%20S1.pdf

xxviii U.S. Department of Energy. December 2014. *Fault Location, Isolation, and Restoration Technologies Reduce Outage Impact and Duration.* https://www.smartgrid.gov/files/documents/B5_draft_report-12-18-2014.pdf

xxix Denholm, P., Patrick, B., Cole, W., et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/81644.pdf

xxx U.S. Energy Information Agency. March 2023. *Wind, solar, and batteries increasingly account for more new U.S. power capacity additions*. https://www.eia.gov/todayinenergy/detail.php?id=55719

xxxi Downing, J., Johnson, N., McNicholas, M., Nemtzow, D., Oueid, R., Paladino, J., Wolfe, E.B. September 2023. *Pathways to Commercial Liftoff: Virtual Power Plants*. U.S. Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230911-Pathways-to-Commercial-Liftoff-Virtual-Power-Plants_update.pdf

xxxii NERC. June 2023. *An Introduction To Inverter-Based Resources On The Bulk Power System*. https://www.nerc.com/pa/Documents/2023_NERC_Guide_Inverter-Based-Resources.pdf

xxxiii Gopstein, A., Nguyen, C., O'Fallon, C., Wollman, D. February 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0.* National Institute of Standards and Technology. https://doi.org/10.6028/NIST.SP.1108r4

xxxiv U.S. Department of Energy. May 2018. *DOE-417: Electric Disturbance Events*. https://www.oe.netl.doe.gov/oe417.aspx

xxxv Walton, R. April 2023. *Physical attacks on North American power grid rose more than 10% last year: NERC*. Utility Dive. https://www.utilitydive.com/news/physical-attacks-on-north-american-power-grid-rose-more-than-10-last-year/646986/

xxxvi Geocaris, M. August 2022. *Assessing Power System Reliability in a Changing Grid, Environment.* NREL. https://www.nrel.gov/news/program/2022/assessing-power-system-reliability-in-a-changing-grid-environment.html

xxxvii U.S. Department of Energy. December 2020. *Advanced Transmission Technologies*. https://www.energy.gov/sites/prod/files/2021/02/f82/Advanced%20Transmission%20Technologies%20Report%20-%20final%20as%20of%2012.3%20-%20FOR%20PUBLIC.pdf

xxxviii Office of Electricity. October 2021. *Flexible Transformers Transform the Grid of the Future*. https://www.energy.gov/oe/articles/flexible-transformers-transform-grid-future

xxxix Strategen. July 2022. *Peaker problem & CEG*. https://www.strategen.com/strategen-blog/peaker-problem-ceg

xl Siegner, K., Toth, S., Teplin, C., Mulvaney, K. 2024. *GETting Interconnected in PJM: Grid-Enhancing Technologies (GETs) Can Increase the Speed and Scale of New Entry from PJM's Queue*. RMI. https://rmi.org/wp-content/uploads/dlm_uploads/2024/02/GETs_insight_brief_v3.pdf

xli U.S. Department of Energy. February 2022. *Grid-Enhancing Technologies: A Case Study on Ratepayer Impact*. https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf

xlii PPL. 2021. *Juniata - Cumberland 230 kV Line Reconductor.* https://sdc.pjm.com/-/media/planning/rtep-dev/expan-plan-process/ferc-order-1000/rtep-proposal-windows/2020-2021-rtep-proposal-window-1-redacted/proposal-2021-ltw1-218-redacted.ashx; PPL. N.d. *Attachment "2" Susquehanna – Harwood 230 Kv Reconductor Project*. https://www.puc.pa.gov/pcdocs/1164705.pdf

xliii Kazempour, F., Hu, K. November 2023. *Utility investment in grid modernization: H2 2023*. Wood Mackenzie.

xliv Chojkiewicz, E., Paliwal, U., Abhyankar, N., Baker, C., O'Connell, R., Callaway, D., Phadke, A. Revised February 2024. *Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way.* Energy Institute at Haas. https://haas.berkeley.edu/wp-content/uploads/WP343.pdf; MISO. March 2023. *Transmission Cost Estimation Guide.* https://cdn.misoenergy.org/20230315%20PSC%20Item%205e%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP23628223.pdf; Idaho National Laboratory. December 2023. *Advanced Conductor Scan Report.* https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf; Lawrence Berkeley National Laboratory. January 2024. *Reconductoring Economic and Financial Analysis Tool.* https://www.energy.gov/sites/default/files/2024-02/REFA%20tool%20factsheet_rev%20February%202024_optimized.pdf

xlv Lawrence Berkeley National Laboratory. January 2024. *Reconductoring Economic and Financial Analysis Tool.* https://www.energy.gov/sites/default/files/2024-02/REFA%20tool%20factsheet_rev%20February%202024_optimized.pdf

xlvi National Renewable Energy Laboratory. N.d., *Annual Technology Baseline.* https://atb.nrel.gov/electricity/2022/utility-scale_battery_storage

xlvii U.S. Department of Energy. 2023. *National Transmission Needs Study.* https://www.energy.gov/sites/default/files/2023-12/National Transmission Needs Study - Final_2023.12.1.pdf

xlviii Guidehouse analysis

xlix Rand, Joseph. June 2023. *Queued Up: Status and Drivers of Generator Interconnection Backlogs.* Lawrence Berkeley National Laboratory. https://www.energy.gov/sites/default/files/2023-07/Rand_Queued%20Up_2022_Tx%26Ix_Summit_061223.pdf

l Guidehouse analysis

li Idaho National Laboratory. December 2023. Advanced Conductor Scan Report. https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf; Lawrence Berkeley National Laboratory. January 2024. Reconductoring Economic and Financial Analysis Tool. https://www.energy.gov/sites/default/files/2024-02/REFA%20tool%20factsheet_rev%20February%202024_optimized.pdf

lii Industry interviews

liii U.S. Department of Energy. February 2022. Grid-Enhancing Technologies: A Case Study on Ratepayer Impact. https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf

liv Pfeifenberger, J., Sonnathi, C. October 2023. The Operational and Market Benefits of HVDC to System Operators. Brattle Group. https://www.brattle.com/wp-content/uploads/2023/10/The-Operational-and-Market-Benefits-of-HVDC-to-System-Operators-ESIG-Fall-Workshop-Presentation.pdf

lv

lvi Downing, J., Johnson, N., McNicholas, M., Nemtzow, D., Oueid, R., Paladino, J., Wolfe, E.B. September 2023. *Pathways to Commercial Liftoff: Virtual Power Plants*. U.S. Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230911-Pathways-to-Commercial-Liftoff-Virtual-Power-Plants_update.pdf

lvii Chojkiewicz, E., Paliwal, U., Abhyankar, N., Baker, C., O'Connell, R., Callaway, D., Phadke, A. Revised February 2024. Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way. Energy Institute at Haas. https://haas.berkeley.edu/wp-content/uploads/WP343.pdf

lviii Mulvaney, K., Siegner, K., Teplin, C., Toth, S. 2024. *GETting Interconnected in PJM: Grid-Enhancing Technologies (GETs) Can Increase the Speed and Scale of New Entry from PJM's Queue.* RMI. https://rmi.org/wp-content/uploads/dlm_uploads/2024/02/GETs_insight_brief_v3.pdf

lix Tsuchida, T., Ross, S., Bigelow, A. February 2021. *Unlocking the Queue with Grid-Enhancing Technologies*. Brattle Group. https://watt-transmission.org/wp-content/uploads/2021/02/Brattle__Unlocking-the-Queue-with-Grid-Enhancing-Technologies__Final-Report_Public-Version.pdf90.pdf

lx Idaho National Laboratory. December 2023. *Advanced Conductor Scan Report*. https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf

lxi U.S. Department of Energy. February 2022. Grid-Enhancing Technologies: A Case Study on Ratepayer Impact. https://www.energy.gov/sites/default/files/2022-04/Grid%20Enhancing%20Technologies%20-%20A%20Case%20Study%20on%20Ratepayer%20Impact%20-%20February%202022%20CLEAN%20as%20of%20032322.pdf

lxii Pfeifenberger, J., Bai, L., Levitt., Plet, C., Sonnathi, C. September 2023. *The Operational and Market Benefits of HVDC to System Operators*. Brattle Group, DNV. https://acore.org/wp-content/uploads/2023/09/The-Operational-and-Market-Benefits-of-HVDC-to-System-Operators.pdf

lxiii U.S. Department of Energy. February 2022. Achieving American Leadership in the Electric Grid Supply Chain. https://www.energy.gov/sites/default/files/2022-02/Electric%20Grid%20Supply%20Chain%20Fact%20Sheet.pdf

lxiv Andersen, G., Cleveland, M., Shea D. 2021. Modernizing the Electric Grid: State Role and Policy Options. National Conference of State Legislatures. https://www.ncsl.org/energy/modernizing-the-electric-grid; Idaho National Laboratory. December 2023. Advanced Conductor Scan Report. https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf; Marsh McLennan. 2020. Modernising Ageing Transmission. Public Utilities Fortnightly. https://www.marshmclennan.com/insights/publications/2020/apr/modernising-ageing-transmission.html

lxv U.S. Energy Information Administration. August 2019. Investor-owned utilities served 72% of U.S. electricity customers in 2017. https://www.eia.gov/todayinenergy/detail.php?id=40913

lxvi Ibid.

lxvii Ibid.

lxviii National Conference of State Legislatures. October 2019. Engagement Between Public Utility Commissions and State Legislatures. https://www.ncsl.org/energy/engagement-between-public-utility-commissions-and-state-legislatures

lxix Cleary, K. and Palmer, K. Updated March 2022. US Electricity Markets 101. Resources for the Future. https://www.rff.org/publications/explainers/us-electricity-markets-101/

lxx Ibid

lxxi Lawrence Berkeley National Laboratory. Updated 2024. State Requirements for Electric Distribution System Planning. https://emp.lbl.gov/state-distribution-planning-requirements

lxxii Pfeifenberger, J., Gramlich, R., et al. October 2021. Transmission Planning for the 21st Century: Proven Practices that Increase Value and Reduce Costs. Brattle Group, Grid Strategies. https://www.brattle.com/wp-content/uploads/2021/10/2021-10-12-Brattle-GridStrategies-Transmission-Planning-Report_v2.pdf

lxxiii Edison Electric Institute. February 2024. America's Electric Companies – Delivering the Future of Energy. https://www.eei.org/-/media/Project/EEI/Documents/Issues-and-Policy/Finance-And-Tax/WSB-Presentation.pdf

lxxiv Ibid.

lxxv Kazempour, F., Hu, F. November 2023. Utility investment in grid modernization: H2 2023. Wood Mackenzie.

lxxvi Blair, B., Lakin, G. January 2024. End-to-End DERMS: Connecting the Control Room to the Grid Edge. Smart Electric Power Alliance. https://sepapower.org/knowledge/end-to-end-derms/

lxxvii Interviews, U.S. Department of Energy analysis

lxxviii Denholm, P., Cole, W., Blair, N. 2023. Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy23osti/85878.pdf

lxxix U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Long Duration Energy Storage. https://liftoff.energy.gov/wp-content/uploads/2023/10/Pathways-to-Commercial-Liftoff-LDES-May-5_UPDATED-v10.pdf

lxxx Morgan Lewis. March 2024. How Recent FERC Orders are Regulating Electric Storage, QFs, and Inverter-Based Resources. https://www.morganlewis.com/pubs/2024/03/how-recent-ferc-orders-are-regulating-electric-storage-qfs-and-inverter-based-resources

lxxxi Brown, W., Chao, H., Schuff, A., Wang, S. January 2023. Storage as Transmission Asset Market Study. Quanta Technology. https://cdn.ymaws.com/ny-best.org/resource/resmgr/reports/SATA_White_Paper_Final_01092.pdf

lxxxii IRENA. 2020. Innovation landscape brief: Dynamic line rating. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Dynamic_line_rating_2020.pdf

lxxxiii Elia Group. 2024. Dynamic line rating. https://www.elia.be/en/infrastructure-and-projects/our-infrastructure/dynamic-line-rating

lxxxiv Idaho National Laboratory. December 2023. Advanced Conductor Scan Report. https://inl.gov/content/uploads/2024/02/23-50856_R8_-AdvConductorszScan-Report.pdf

lxxxv North Carolina Clean Energy Technology Center. January 2024. The 50 States of Grid Modernization: 2023 Review and Q4 2023 Quarterly Report.

lxxxvi Ibid.

lxxxvii Ibid.

lxxxviii Eversource. N.d. Electric Sector Modernization Plan (ESMP) for Massachusetts. https://www.eversource.com/content/residential/about/sustainability/renewable-generation/electric-sector-modernization-plan

lxxxix Montana Legislative Assembly. 2023. HB0729. https://leg.mt.gov/bills/2023/BillPdf/HB0729.pdf

xc NARUC. June 2020. Multi-Year Rate Plans. https://pubs.naruc.org/pub/3A08E0AB-155D-0A36-31AB-2C7BDE319806

xci U.S. Department of Energy. November 2023. Integrated Distribution System Planning. https://www.energy.gov/sites/default/files/2023-11/IDSP%20Principles%2011%2004%20_optimized.pdf; Puerto Rico Public Service Regulatory Board. July 2021. Updated 10 Year Infrastructure Work Plan. Government of Puerto Rico. https://energia.pr.gov/wp-content/uploads/sites/7/2021/07/20210706-joint-motion-submitting-updated-10-year-infrastructure-work-plan.pdf

xcii Kazempour, F., Hu, K. November 2023. Utility investment in grid modernization: H2 2023. Wood Mackenzie.

xciii North Carolina Clean Energy Technology Center. January 2024. The 50 States of Grid Modernization: Q4 2023 Quarterly Report.

xciv Howland, E. March 2024. Bill aim to spur grid-enhancing technologies with shared-savings incentives from FERC. Utility Dive. https://www.utilitydive.com/news/ferc-shared-savings-incentive-gets-grid-enhancing-bills/710287/

xcv U.S. Congress. December 2023. HR6747. https://www.congress.gov/bill/118th-congress/house-bill/6747?q=%7B%22search%22%3A%22hr+8%22%7D&s=1&r=1

xcvi Howland, E. November 2023. Regulators need to require utilities to use grid-enhancing technologies: FERC's Clements. Utility Dive. https://www.utilitydive.com/news/transmission-grid-enhancing-technologies-gets-utilities-naruc-ferc-clements/699686/

xcvii Federal Energy Regulatory Commission. December 2021. FERC Rule to Improve Transmission Line Ratings Will Help Lower Transmission Costs. https://www.ferc.gov/news-events/news/ferc-rule-improve-transmission-line-ratings-will-help-lower-transmission-costs

xcviii FERC. June 2023. Transmission System Planning Performance Requirements for Extreme Weather. https://www.federalregister.

gov/documents/2023/06/23/2023-13286/transmission-system-planning-performance-requirements-for-extreme-weather; FERC. June 2023. One-Time Informational Reports on Extreme Weather Vulnerability Assessments Climate Change, Extreme Weather, and Electric System Reliability. https://www.federalregister.gov/documents/2023/06/27/2023-13268/one-time-informational-reports-on-extreme-weather-vulnerability-assessments-climate-change-extreme

xcix Kazempour, F., Hu, K. November 2023. Utility investment in grid modernization: H2 2023. Wood Mackenzie.

c Ibid.

ci Hopson, D., Wilke, L. August 2018. Arizona Public Service Leverages Data for Advanced Distribution Management. T&DWorld. https://www.tdworld.com/grid-innovations/distribution/article/20971578/arizona-public-service-leverages-data-for-advanced-distribution-management

cii Heimdall Power Inc. March 2024. Heimdall Power launches largest Dynamic Line Rating project in the U.S. with Great River Energy. https://heimdallpower.com/us/heimdall-power-launches-largest-dynamic-line-rating-project-in-the-u-s-with-great-river-energy/

ciii Ibid

civ National Rural Electric Cooperative Association. October 2022. Rural Electric Cooperative Broadband Benchmarking Report.

cv Ibid

cvi Ibid

cvii National Rural Electric Cooperative Association. October 2022. Rural Electric Cooperative Broadband Benchmarking Report

cviii U.S. Department of Energy. 2023. *U.S. Energy and Employment Report 2023.* https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20REPORT-v2.pdf

cix National Academies of Sciences, Engineering, and Medicine. 2021. The Future of Electric Power in the United States. The National Academies Press. https://doi.org/10.17226/25968.

cx U.S. Department of Energy. 2023. *U.S. Energy and Employment Report 2023.* https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20REPORT-v2.pdf; Saha, D. April 2020. *Grid Modernization: Creating Jobs, Cutting Electric Bills, and Improving Resiliency.* World Resources Institute. https://files.wri.org/d8/s3fs-public/expert-note-grid-modernization.pdf.

cxi U.S. Department of Labor. *Occupations with the smallest share of women workers*. https://www.dol.gov/agencies/wb/data/occupations/occupations-smallest-share-women-workers; U.S. Department of Energy. 2023. *U.S. Energy and Employment Report 2023.* https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20REPORT-v2.pdf

cxii Industry interviews

cxiii Power Grid International. February 2024. *Utility workforce turnover is higher than ever. Here's why.* https://www.power-grid.com/td/utility-workforce-turnover-is-higher-than-ever-heres-why/

cxiv Internal U.S. Department of Energy analysis

cxv Nguyen, R., Severson, M., Zhang, B., Vaagensmith, B., Rahman, M., Toba, A., Price, P., Davis, R., and Williams, S. February 2022. *Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems.* U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-02/Electric%20Grid%20Supply%20Chain%20Report%20-%20Final.pdf

cxvi Internal U.S. Department of Energy analysis

cxvii Industry interviews

cxviii Industry interviews

cxix Office of Electricity. N.d. *Integrated Distribution System Planning*. U.S. Department of Energy. https://www.energy.gov/oe/integrated-distribution-system-planning; Smart Electric Power Alliance. 2019. *Non-Wires Alternatives (NWA) – Incorporating NWAs into Your Grid Modernization Program.* https://sepapower.org/resource/non-wires-alternatives-nwa-incorporating-nwas-into-your-grid-modernization-program/

cxx Woolf, T., Havumaki, B., Bhandari, D., Whited, M., Schwartz, L. February 2021. *Benefit-Cost Analysis for Utility-Facing Grid Modernization Investments: Trends, Challenges, and Considerations.* Lawrence Berkeley National Laboratory. https://emp.lbl.gov/publications/benefit-cost-analysis-utility-facing

cxxi Ibid.

cxxii Ibid.

cxxiii Woolf, T., Havumaki, B. May 2022. *Economic Assessment of Grid Modernization Plans*. Synapse Energy Economics. https://eta-publications.lbl.gov/sites/default/files/synapse_grid_mod_economic_assess_20220519.pdf

cxxiv Paladino, J. February 2024. *2024 Smart Grid System Report.* U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-02/2024%20Smart%20Grid%20System%20Report_untagged.pdf

cxxv West Monroe. January 2018. *Managing Grid Modernization: Integrating IT and Operations at U.S. Utilities.* https://www.westmonroe.com/perspectives/signature-research/managing-grid-modernization-integrating-it-and-operations-at-us-utilities

cxxvi Industry interviews

cxxvii National Academies of Sciences, Engineering, and Medicine. 2021. *The Future of Electric Power in the United States*. The National Academies Press. https://doi.org/10.17226/25968

cxxviii Ibid.