ENHANCING ENERGY SYSTEM RELIABILITY AND RESILIENCY IN A NET-ZERO ECONOMY



EXECUTIVE SUMMARY

ENHANCING ENERGY SYSTEM RELIABILITY AND RESILIENCY IN A NET-ZERO ECONOMY

Ensuring reliability and resilience while rapidly reducing carbon means changing how global stakeholders think about, build, and operate the electric grid. As electricity generation, delivery, and use evolve at an unprecedented scale and pace, nearly every decision has an impact on the energy system. A successful clean energy transition requires extensive, cross-sector collaboration to harness innovation, prioritize investments, and advance new capabilities.

Plan Today to Ensure Grid Reliability at All Timescales

The future power system will comprise a greater mix of inverter-based, variable, decentralized supply and demand resources, which require continual coordination and control. Key actions to advance energy sector abilities to plan, build, and operate a cleaner, more reliable grid over the next decade and on through 2050 include:

- Enhance reliability and resiliency planning through regional and national modeling across transmission and distribution
- Expand operational capabilities to better control dynamic, decentralized resources
- Maintain and incentivize essential grid services
- Streamline regulatory and stakeholder engagement processes to shorten siting, permitting, and construction timelines

Understanding the reliability and resiliency implications of carbon reduction across the energy system is key to accelerating progress toward a low-cost, low-carbon future.

NEXT STEPS

The pace of carbon reduction largely depends on the time required to develop and deploy new technologies and processes. Early collaboration is key to kickstarting feedback loops that transform innovations into viable solutions.

A series of EPRI-led regional studies will identify tailored strategies for resilient, reliable, affordable, low-carbon energy futures, and evaluate their operational feasibility. Starting this fall, these studies will:

- Evaluate the extent to which net-zero pathways meet reliability and resiliency requirements over time
- Identify and estimate the cost of additional supply, delivery, and customer resource investments to support future energy system requirements
- Establish timelines to develop and demonstrate future technologies and procedures

To engage and learn more contact:
Aidan Tuohy - atuohy@epri.com

Link to the full white paper:
Enhancing Energy System Reliability and Resiliency in a Net-Zero Economy

BEYOND TECHNOLOGY PATHWAYS: GRID RELIABILITY AND RESILIENCY CAPABILITIES TO ENABLE A NET-ZERO ECONOMY

INTRODUCTION / MOTIVATION

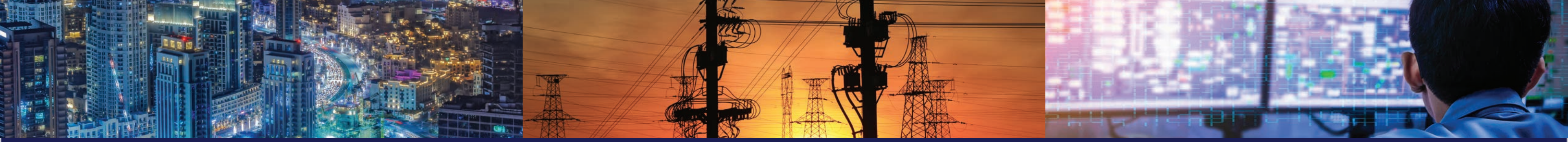
With growing concern about the potential impacts of climate change, nations around the world have made commitments to limit or reduce their greenhouse gas emissions. National emission targets have been substantially strengthened just in the last year with nations currently responsible for over 70 percent of today's global emissions having committed to net-zero emissions by mid-century. Many studies are emerging in the US and elsewhere in the world[1] that identify and evaluate technology pathways to decarbonize the electric sector and the economy, providing a general compass for navigating towards a low-carbon future. A consistent set of recommended actions has emerged, including redoubled efforts on efficiency, rapid decarbonization of electricity including widespread deployment of renewables, electrification of end-uses where possible, and development of advanced technologies -- zero-carbon and carbon dioxide removal technologies along with an array of supporting (e.g., grid) technologies -- that enable very deep reductions.

High reliability and resiliency are essential features of electric systems today, ensuring adequate resources to deliver power to meet customer demands, maintaining power quality (frequency and voltage) within required limits, and being able to deal with extreme events. Equipment and processes for maintaining reliability evolved over the last century, taking advantage of key electrical characteristics of the large rotating machines that dominated and continue to dominate generation. For almost all nations, decarbonization requires a near-complete rethink of system planning. Inverter-based resources – solar, wind, and batteries – will play a leading role in many locations, requiring new or adjusted operational protocols, protection and control schemes, and electricity market designs. At the same time, rapid electrification changes how, when, and where that electricity is used, and importantly, increases our reliance upon it – not just to communicate, cool, and run the economy, but increasingly to transport and to heat. And the grid will have to modernize to integrate hundreds of millions of new resources, controlling both supply (large and small) and demand in real time to balance loads. Thus, a fundamental challenge during this extensive transition is to keep electricity reliable and resilient not just for 2030 or 2050, but for every hour of every day on the journey.

PRIMARY OBJECTIVE:

This paper's objective is to describe the additional investments and capability developments that will be required to implement decarbonization pathways while ensuring the resiliency and operational reliability of the electric power grid.

[1] Many of the studies and policies discussed will be examined through a US lens. However, international experiences will also be used to inform the paper, and the findings and issues raised related to operational reliability are globally applicable.



While the national-level decarbonization studies that have emerged to date have provided direction, only a few have matched future hourly supplies and demands, and none in the US has addressed certain aspects of system reliability or resiliency.[2] Companion studies are needed that identify essential grid reliability and resiliency investment needs and evaluate their operational feasibility over time. Specifically, these studies would:

1. evaluate the extent to which net-zero pathways meet reliability and resiliency requirements over time;
2. identify and estimate the cost of additional supply, delivery, and customer resource investments needed to meet reliability and resiliency requirements; and
3. establish timelines for technologies and procedures that are not commercial/used today and will be required to ensure reliability and resiliency in the future grid.

The supply, delivery, and demand resources of a power system must be able to provide essential reliability services and resiliency characteristics to meet system criteria. Traditionally, this has been done using large synchronous resources. While emerging clean resources have the potential to provide such capabilities, they may not provide as broad a set of reliability services and their provision of grid services often is not as widely understood and tested. As the grid transitions, the resources comprising the grid must provide the required services at every step in the transition. Although slightly dated, EPRI summarized the ability of different supply and demand resource types to provide various essential reliability services in a 2015 paper that includes a qualitative summary of the ability of resources to provide grid reliability services.[3]

ENSURING RELIABILITY & RESILIENCY:

Power system reliability
Refers to the ability of the system to "meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity to meet the electricity needs" (as defined by the North American Electric Reliability Corporation, NERC).[4]

Power system resiliency
While less clearly defined than power system reliability, power system resiliency, is generally understood as the ability to withstand extreme (high impact, low frequency) events, with minimal interruption to the supply of electricity and enabling a quick recovery.[5] Resiliency can encompass the following forms: Damage Prevention, Easier Repair, Isolation and Reconfiguration, Recovery, Community Sustainability.[6]

To ensure reliability and resiliency, one needs to consider:

- ***Adequacy***, a measure of the ability of a system's resources to meet the aggregate power and energy needs of the customer, considering outages of equipment and maintaining flow within equipment limits. Resources include the supply and demand side resources to balance supply and demand as well as the transmission and distribution infrastructure to deliver power to and from customers.

- ***Operational reliability***, or security, refers to the ability of the system to maintain stability in light of changing conditions. This includes both the balancing of the system over seconds, minutes, and hours, and the ability to maintain stability after large disturbances such as loss of generation or transmission.

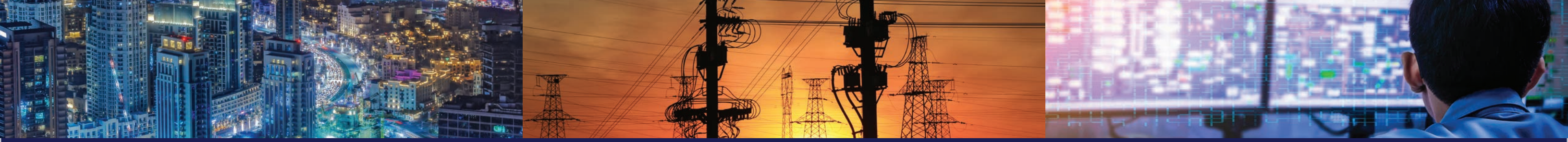
[2] Appendix A provides a brief introduction to recent national and regional decarbonization studies, highlighting the electric system changes those studies propose and describing their consideration of reliability. The appendix also discusses a few regional and non-US studies that do complement basic pathways analyses with reliability assessments.

[3] Electric Power Research Institute, Contributions of Supply and Demand Resources to Required Power System Reliability Services, EPRI, Palo Alto CA, 2015. 3002006400.

[4] NERC, Frequency Asked Questions, August 2013, available https://www.nerc.com/AboutNERC/Documents/NERC%20FAQs%20AUG13.pdf

[5] Raoufi, Habibollah & Vahidinasab, Vahid & Mehran, Kamyar. (2020). Power Systems Resilience Metrics: A Comprehensive Review of Challenges and Outlook. Sustainability. 12. 9698. 10.3390/su12229698.

[6] Distribution Grid Resiliency: Modern Grid Technology. EPRI, Palo Alto, CA: 2015. 3002006783.



Other issues such as the need for and availability of raw materials, the development of supply chains required to ensure deployment of new resources, and environmental justice and equity considerations are also important factors for decarbonization. These are outside the scope of this paper but are being addressed elsewhere at EPRI. The remainder of this paper first describes the reliability and resiliency issues that must be addressed in analyses of decarbonization pathways. It then describes the new technologies and operational capabilities that will be required to operate a decarbonizing grid and discusses the pace and challenges faced in the transition. The last section describes the change management and timelines needed to establish a roadmap to a reliable, resilient, decarbonized electricity system.

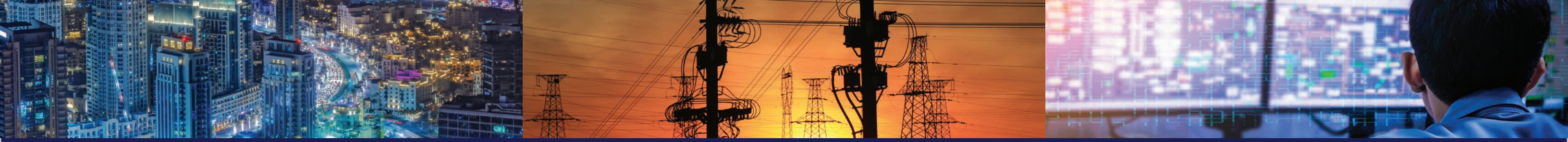
GRID RELIABILITY AND RESILIENCY CONSIDERATIONS

More detailed reliability and resiliency assessments need to be carried out when developing strategies to implement the insights provided from decarbonization pathway studies. While these more detailed studies may not significantly alter the decarbonization plan destination, they may impact the cost and the timing of the pathway to arrive at the destination. We have grouped these grid reliability and resiliency considerations into the following:

1. ***Resource Adequacy***: Sufficiency of resource availability and deliverability to meet energy demand across all hours under extreme conditions and equipment failures.
2. ***Transmission Infrastructure***: Sufficiency of transmission system capacity to enable interregional economic energy flows and intra-regional delivery to load centers.
3. ***Distribution Infrastructure***: Sufficient distribution system infrastructure to enable distributed generation, serve increased demand from electrification, and support flexible load for providing grid services, all while maintaining distribution reliability standards.
4. ***Operational Reliability – Balancing and Flexibility***: Instantaneously balance supply and demand through all operating conditions.
5. ***Operational Reliability – Grid Stability***: Ability of the grid to maintain desired system performance during credible operating conditions and disturbances and to prevent cascading outages and ensure reasonable restoration for disturbances that are beyond planning criteria.

Some of these assessments may identify additional infrastructure investments or operational costs that are required to operate the decarbonizing energy system reliably and resiliently. The additional costs of these investments, while potentially not as significant as the system transition costs captured in the models used to study decarbonization pathways (expected to be in the hundreds of billions to trillions of US dollars), still need to be assessed, planned, and recovered. Potentially more impactful, some of the reliability/resiliency assessments may identify interim solutions required while new technologies are developed or while new infrastructure is built. It can also be noted that simulation tools are not always available to assess these issues, particularly for the two operational reliability categories where tools are still under development. Anticipating these potential challenges will help to prioritize technology development/deployment and infrastructure construction based on the associated timelines and inform any potential regulatory actions and timelines needed to enable them.

EPRI has reviewed recent decarbonization studies from a range of entities using different models. These vary in the extent to which they require resources to meet reliability and resiliency needs as the system decarbonizes. Most do not explicitly consider the more detailed aspects of operational reliability and resiliency to extreme conditions as discussed below. Appendix A provides a summary of how the most relevant recent studies treat reliability and resiliency.



Based upon experience gained from more detailed regional reliability assessments conducted by EPRI and others, Table 1 summarizes qualitatively the potential impacts of adding reliability considerations on pathway investments, direction and timing. The aim of the table is not to quantify the overall impacts; that will require detailed reliability assessments and planning studies. Rather, Table 1 summarizes the potential for the reliability/resiliency considerations identified above to (1) require grid investments not considered in pathway studies (Pathway Investments), and (2) require adjustments to technology timelines due to deployment constraints not considered pathway models (Pathway Direction/Timeline). The associated Low, Medium, and High labels are intended to convey relative impact and not specific quantitative ranges.

The remainder of this section provides more details on the power system issues related to resource, transmission and distribution adequacy, and operational reliability as the power sector and economy decarbonize.

Resource Adequacy

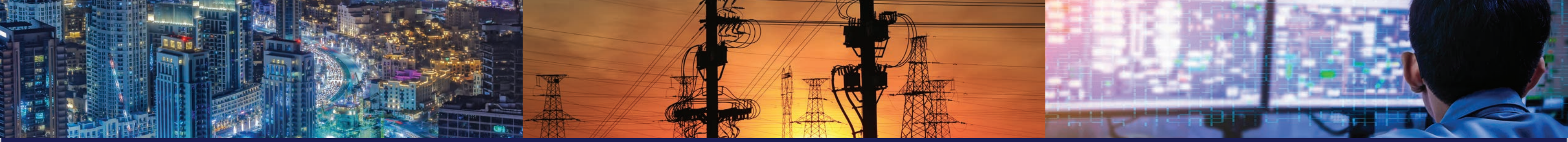
Resource adequacy (RA) is the ability of a system's resources to meet the aggregate demand, taking into account availability of system components.[7] RA is typically measured by assessing the likelihood of being short of capacity to meet customer demand across a variety of expected conditions, using metrics such as Loss of Load Expectation (LOLE) or Expected Unserved Energy (EUE). These metrics are often translated into simpler screening metrics such as a Planning Reserve Margin, which estimate capacity required to

Table 1. *Summary of Modeling Considerations and Potential Impacts on Investments and Timelines*

RELIABILITY/RESILIENCY CONSIDERATION	POTENTIAL IMPACT ON PATHWAY INVESTMENTS	POTENTIAL IMPACT ON PATHWAY DIRECTION/TIMELINE
RESOURCE ADEQUACY	**Low**: Most pathways balance supply and demand with some margin, but additional investment may be needed to manage extreme events.	**Medium:** Existing/new dispatchable resources to bridge until zero-carbon, firm options develop, with additional resources needed to ensure resilience.
TRANSMISSION	**Medium:** Most pathways build inter-region transmission, but intra-regional capacity for renewables, electrification, and reliability/congestion not fully modeled.	**High:** Siting, permitting, cost allocation, and potential supply chain, workforce, and outage coordination challenges may cause delays resulting in inability to connect new resources.
DISTRIBUTION	**High:** Significant network upgrades may be needed and are typically not represented. Grid modernization to enable effective integration of DER and electrification typically not included.	**Medium:** Distribution companies in different stages of grid modernization to enable DER/electrification; planning, investment, and deployment timelines may cause delays in resource availability.
OPERATIONAL RELIABILITY – BALANCING	**Low:** Additional investment small for balancing resources for a 70-80% reduction in electric sector emissions. Needs increase at higher levels.	**Low:** Balancing technologies exist and have short deployment timelines if needed and if allowed within the CO_2 emission goal.
OPERATIONAL RELIABILITY – STABILITY	**Medium:** Grid reliability resource investments not considered but relatively small; RD&D costs for new controls and protection difficult to estimate	**High:** Timelines for RD&D, codes and standards, and deployment for new commercial protection and control products to support highly decentralized and inverter dominated systems.

Impacts are relative to each other, not necessarily high in terms of the overall pathway costs or trajectory

[7] CIGRE ELECTRA, The future of reliability - Definition of reliability in light of new developments in various devices and services which offer customers and system operators new levels of flexibility, 2018.



meet peak demand plus a margin to account for uncertainties. RA methods and tools are being enhanced and refined to account for ongoing changes to the resource mix.[8, 9] For example, impacts of recent extreme weather events triggering an increase in failure rates due to a common condition have highlighted the need to consider such issues in RA studies,[10] as well as consider broader regions in a more coordinated fashion.

Models used in national decarbonization pathway studies treat RA with varying degrees of rigor. Most ensure sufficient capacity to meet an exogenously specified or endogenously determined annual peak, with an additional margin to ensure adequacy. Some, such as EPRI's US-REGEN,[11] build capacity to ensure demand is met with typical outage rates reflected in the model, across 8,760 hours. Other analyses have paired the pathway analysis with hourly production cost model runs as a check on model results to examine ability to balance supply and demand over one or more years (e.g. the 2030 and 2035 reports by Berkeley[12] simulated the performance of projected resource builds over seven years of weather data). None of the pathway models document running full probabilistic LOLE or EUE type studies that capture high load and resource unavailability during extreme weather or other outlying events, nor do they include such analyses to directly inform the capacity expansion process. Events such as extreme heat or cold that impact outage rates of equipment, or long wind or solar lulls, are particularly important in this context. In more detailed planning studies (such as traditional utility planning studies), capacity expansion is followed by LOLE type analysis that is then reflected in the resource buildout. As a result, decarbonization pathway studies may miss capacity that would be required to ensure adequacy.

Ensuring sufficient energy is available during periods of high stress is becomingly an increasingly important aspect of adequacy studies.[13, 14] Recent supply deficiency events in California, Texas, and other locations in the US and globally have illustrated the potential impact of extreme weather. In these cases, extreme (though not unprecedented) weather events exposed increased reliance on generation resources susceptible to common cause issues. These events highlight the need to adjust resource operational requirements for extreme conditions and to assess RA needs with more detailed models that represent increased unavailability of resources in extreme weather conditions, consider energy requirements across all hours including high risk net load hours, model interregional capacity and energy availability of resources during high risk periods, and consider issues that impact many resources at once such as gas pipeline failures. This will need to occur in the context of increased reliance on electricity given electrification, which requires an evolution in consideration of tail events. As well as data and tools, this may require revisiting of standards and criteria used to assess adequacy, with policy makers considering the inherent trade-offs between maintaining reliability under extreme conditions and costs. Demand side resources may also be able to provide adequacy, though models need to be updated to characterize the different nature of such resources. Decarbonization pathway capacity expansion models are not designed to consider all these operational details, though they could potentially be extended to do so.

A fuller consideration of adequacy implications may increase costs associated with resource procurement and infrastructure development, and may also shorten timelines for which firm, dispatchable resource technologies that meet emission reduction requirements need to be available.

None of the pathway models documents running full probabilistic LOLE or EUE type studies that capture high load and resource unavailability during extreme weather or other outlying events, nor do they include such analyses to directly inform the capacity expansion process.

8 EPRI, Resource Adequacy Challenges: Issues Identified Through Recent Experience in California, Oct 2020, available at https://www.epri.com/research/products/000000003002019972

9 D. Stenclik, Five Principles of Resource Adequacy, ESIG Blog Post, Aug 2020, available at https://www.esig.energy/five-principles-of-resource-adequacy-for-modern-power-systems/

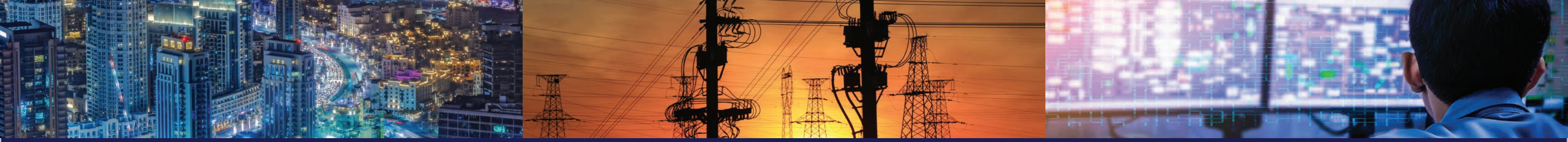
10 S. Murphy, L. Lavin, J. Apt, Resource adequacy implications of temperature-dependent electric generator availability, Applied Energy, Volume 262, 2020

11 Model documentation and public analysis conducted with US-REGEN are at: https://esca.epri.com/models.html.

12 https://www.2035report.com/

13 NERC, Ensuring Energy Adequacy with Energy Constrained Resources, December 2020 White paper

14 E3, Capacity and Reliability Planning in the Era of Decarbonization, Aug 2020, available https://www.ethree.com/wp-content/uploads/2020/08/E3-Practical-Application-of-ELCC.pdf



Transmission Infrastructure Adequacy

Most energy system capacity expansion models examine the buildout of transmission between the regions represented based on a simple economic transmission model.[15] Some models can also provide consideration of localized transmission needs by modeling more regions, representing transmission explicitly, or by including a transmission cost adder that represents the cost of connecting new renewable projects to the regional grid. As such, the main uncertainty that needs to be addressed related to transmission is whether and how the decarbonization pathway models do not fully capture the transmission needed to deliver energy to load.

For interregional transmission, multi-region capacity expansion models typically identify additional transmission capacity that would be economic by comparing the cost of building the interregional line with differences in regional energy cost.[16] Examining various recent studies shows a general trend for significant additional interregional transmission. Studies with fewer interregional additions tend to assume lower costs for balancing resources such as battery storage and higher costs to move energy between modeled areas. The EPRI Powering Decarbonization study, which models 16 regions of the US lower 48 states, projects demand for at least 20 GW-miles of inter-regional transmission (on top of existing approximately 110 GW-miles) by 2030. The Vibrant Clean Energy ZeroByFifty, which also incorporates intra-regional transmission, shows a need to double transmission by 2050,[17] while the Princeton Net Zero America study showed an expansion of the current system of 60% by 2030 (most of these additions are intra-regional), and potentially over five times the current transmission by 2050.[18] Note that these studies differ significantly in projected electricity demands and their builds of wind and solar resources.

In terms of building out such transmission, a coordinated plan may provide benefits to enabling decarbonization pathways when compared to an ad hoc buildout or the use of current practices. This would require close coordination of resource and transmission planning processes, often involving multiple organizations and regulatory frameworks, that would signal for transmission expansion to support changing resource mix. Recently, the high-level concept of a "macrogrid", consisting of a network of high voltage ac and dc transmission across the US,[19] [20] [21] has gained some traction and may be examined in more detail. Aggregate continent-wide models don't typically consider the additional intra-region transmission that is required to facilitate the large inter-regional buildout and connect regional loads and generation. A considerable number of devices that support transmission infrastructure (e.g. shunt devices) will also be needed to manage reactive power, though their investment costs will not be as significant as the cost of upgrading and building transmission.

As an example of a more detailed planning study for transmission, MISO's Renewable Integration Impact Assessment[22] shows that the type of incremental transmission needed changes as a function of the renewable share of generation. This transmission is required to connect renewable resources to load and to provide intra-regional capacity across the

KEY KNOWLEDGE GAPS:

What additional resources might be needed to ensure capacity, energy, and flexibility adequacy in light of the changing nature of the resource mix? Should additional resources be considered to cover extreme common cause type events?

[15] Referred to as a "pipe and bubble" model, transmission is thought of as having a cost per mile and a capacity that limits throughput and a constant loss fraction of flow. No physics, engineering considerations, outages, or dynamics are modeled.

[16] Electric Power Research Institute, US-REGEN model documentation, EPRI, Palo Alto, 2020. 3002016601

[17] Vibrant Clean Energy, "ZeroByFifty," presentation at the Energy Systems Integration Group technical workshop (online), November 11, 2020, https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf

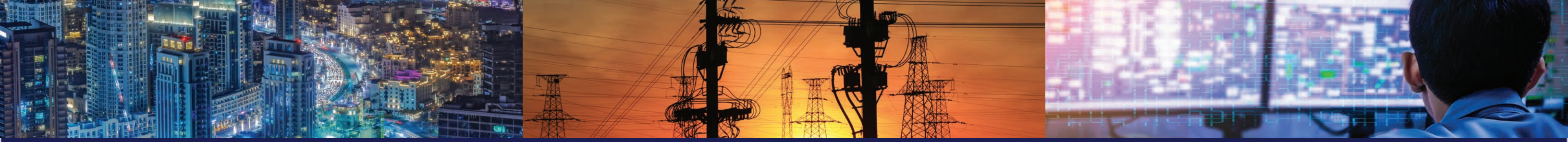
[18] https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/

[19] ESIG, Transmission Planning for 100% clean electricity, available https://www.esig.energy/transmission-planning-for-100-clean-electricity/

[20] Brown and Botterud, "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System," Joule, 5(1), at 115-134

[21] Bloom, A. et al. "The Value of Increased HVDC Capacity Between Eastern and Western US Grids: The Interconnections Seam Study: Preprint." (2020).

[22] MISO Renewable Integration Impact Assessment, available https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment#t=10&p=0&s=&sd=



system. At lower renewable penetration, most of the additional transmission would be at lower transmission voltages, with some higher voltage transmission, as summarized in Figure 1. Adding additional renewables increases the need for higher voltage ac and dc transmission, while reducing the need for lower voltage transmission.

Distribution Infrastructure Considerations

Many decarbonization pathway studies show distributed energy resources (DER), electrification of transportation, and increase in building heating increasing significantly. For example, in EPRI's Powering Decarbonization study, the results show an increase from about 32GW of customer sited solar PV (including rooftop and commercial) in 2020 to 200GW by 2050.[23] A more recent analysis of the US 2030 target (a 50-52% reduction in greenhouse gas emissions from 2005 levels) projects that 45-75% of new light-duty vehicle sales by 2030 will be electric—20 to 30 times current levels—along with substantial changes in electric home heating.[24]

Distribution utility planning and operations practices are evolving to maintain reliability and power quality in light of the rapid growth of DER and electrification.[25] In a companion paper, EPRI has explored the shift that may be seen at distribution utilities to move from a DER agnostic grid to a DER leveraging or DER dependent grid. Very few of the models summarized in Appendix A for decarbonization pathway studies consider the distribution system operational details envisioned there, or the resulting infrastructure investments

KEY KNOWLEDGE GAPS:

How much interregional transmission is required and where will it be built out?
What is the value of proactively planning and coordinating interregional transmission to provide resilience and improve diversity?
How does the need for more local intra-regional transmission differ among various pathways?

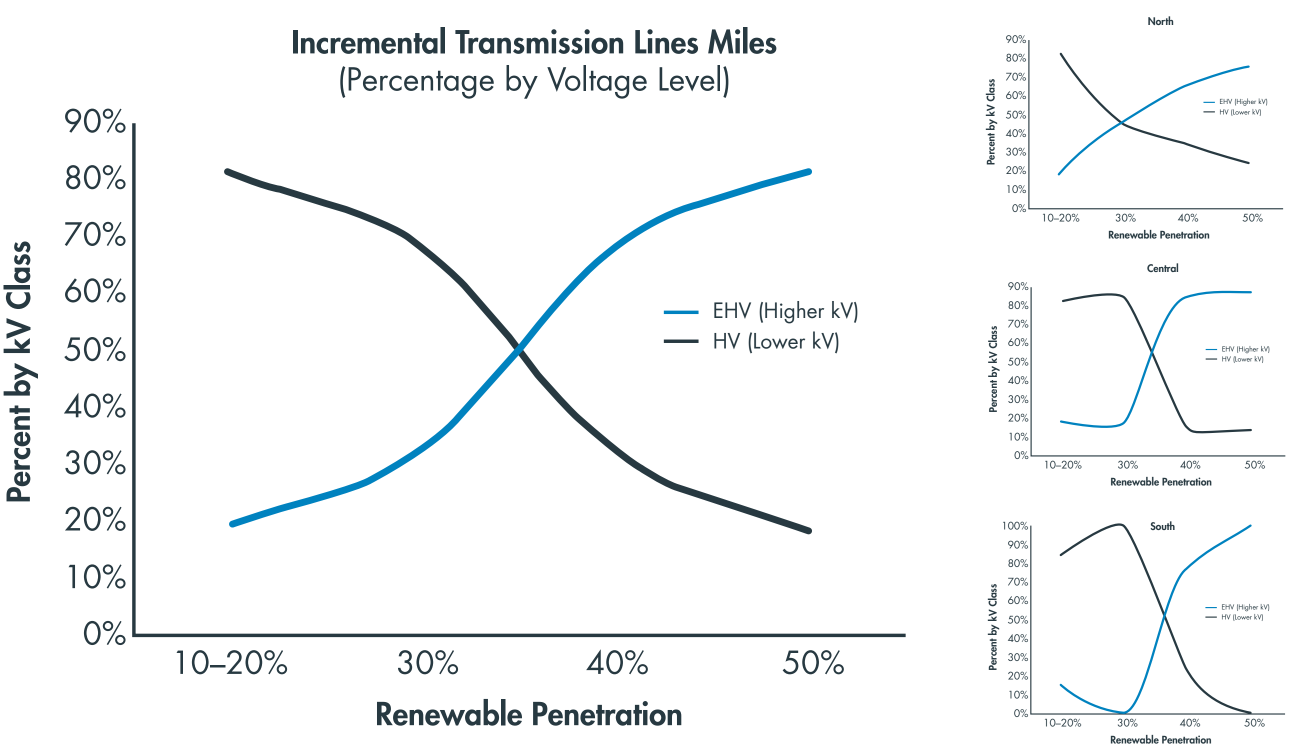


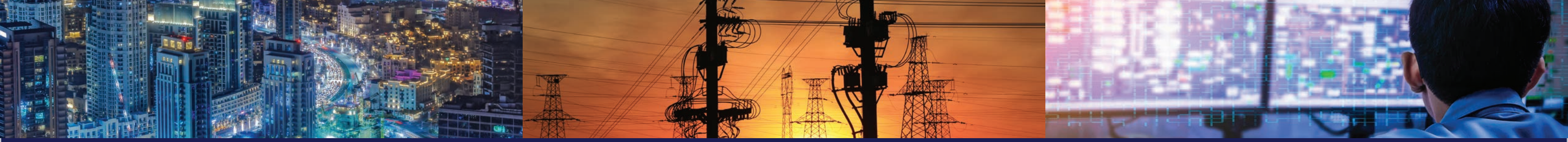
Figure 1: *Ratio of incremental high voltage (230kV and below) and Extra High Voltage (345kV and above) transmission at each renewable penetration level from the MISO RIIA study*[26]

[23] Powering Decarbonization: Strategies for Net-Zero CO2 Emissions. EPRI, Palo Alto, CA: 2021. 3002020700.

[24] Reference 50x30 analysis paper.

[25] Reference the DER paper.

[26] MISO, Renewable Integration Impact Assessment, Summary Report, Feb 2021 available at https://cdn.misoenergy.org/RIIA%20Summary%20Report520051.pdf



or changes to operational practices that may be required to support growth in DER and electrification. Therefore, detailed companion studies should be conducted to assess the limitations of the distribution system, evaluate investments and technologies to remediate these limitations, and assess the cost impact to any overall decarbonization pathway.

In regions where DER have deployed quickly such as Germany, Australia, California, and Hawaii, planning and interconnection practices have shifted to a certain degree to address the emerging distribution system limitations in feeders that are dominated by DER. When the number and total aggregate size of DER interconnections were relatively low, distribution utilities were able to minimize the impacts on the overall distribution system operations. But as the amount of DER has grown, numerous distribution system issues have emerged that have the potential to limit the additional amount of DER that can be hosted.[27] These include aspects related to voltage, protection, and power quality.

Often the most significant and costly constraints on distribution system infrastructure are equipment thermal loading limits (transformers and conductors) which are typically not uniform along the backbone of the medium voltage system and restrict the delivery of power in the forward and reverse directions. Thermal constraints may be resolved with equipment upgrades/replacement or through centralized control of DER to mitigate the constraint.

To support the level of DER observed in many decarbonization pathways, investments will be required to upgrade the backbone conductors of many distribution feeders to full feeder capability, evolving beyond the practice of tapering the conductor sizes from the substation out to the end of each feeder.[28] In some cases, alternatives to infrastructure upgrades may also be cost effective solutions. For example, implementing a Distributed Energy Resource Management System (DERMS) can enable interconnecting additional DER capacity as a managed resource that may be subjected to constraints when necessary to avoid violations under infrequent worst-case conditions. This is an area of active research and as it develops may allow for some upgrades to be deferred or avoided.[29]

Additional physical investments in the distribution system will be required to evolve the protection and monitoring capabilities of the grid required to manage the dispatch and control of variable DER assets.[30] These investments will specifically include:

- Distribution Protection Upgrades – Transitioning distribution substation protection relay and control systems from analog to intelligent electronic devices (IEDs) will allow for more complex controls, adaptive controls, distributed controls, forensic analysis, and situational awareness that are critically necessary.
- Distribution Control and Communications – Deployment of SCADA or other communications to all distribution substations, as well as to a large number of distribution devices (both DA switches and Volt/VAR devices), will be necessary to ensure the grid can sense, communicate, analyze, and act to changes in load and equipment condition.
- Distribution Switching Flexibility - Additional SCADA controlled distribution automation switches will be required to provide operational switching flexibility beyond what is necessary and economically warranted for restoration switching.
- Advanced metering infrastructure (AMI) may become necessary to better monitor/model customer demand, enable load flexibility, as well as to enable monitoring/modeling of DER supply that does not require active SCADA monitoring.

KEY KNOWLEDGE GAPS:

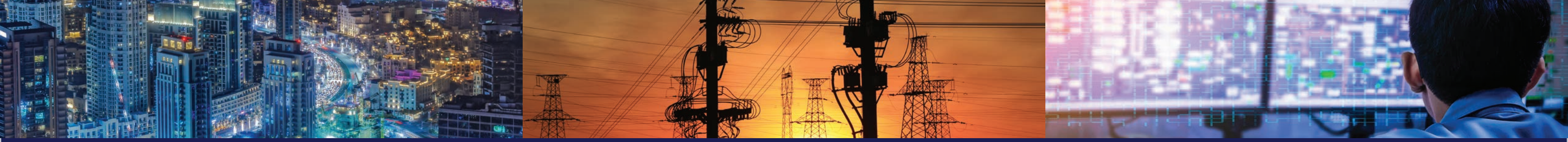
What distribution upgrades are needed to ensure customer reliability in the future? How can grid modernization support the future system needs for various pathways? What investments are needed to best enable customers to provide the flexibility needed in future distribution systems? How can this flexibility be aggregated to provide services to ensure the continued reliable operation of the bulk system? How do distribution protection schemes and designs need to change? What types of protection modeling and planning tools (existing and new) are necessary to support?

[27] New York State Energy Research and Development Authority (NYSERDA). 2019. “Mitigation Methods to Increase Feeder Hosting Capacity,” NYSERDA Report Number 19-45. Prepared by Electric Power Research Institute (EPRI), Palo Alto, CA. nyserda.ny.gov/publications

[28] EPRI, Feeder Design Practices to Enable Distributed Energy Resources (DER). EPRI, Palo Alto, CA: 2020. 3002018815.

[29] EPRI, Implementing DERMS to Manage Grid Constraints, EPRI, Palo Alto, CA. 2021. 3002022194

[30] Southern California Edison, Reimagining the Grid, https://www.edison.com/home/our-perspective/reimagining-the-grid.html



Operational Reliability: Balancing and Flexibility

Operational reliability requires the ability to balance supply and demand in timeframes from seconds to hours to days. Some of the models used in decarbonization pathway studies ensure hourly supply-demand balance and consider the variable nature of renewable resources such as wind and solar. They typically do not, however, explicitly consider more detailed requirements to manage variability and uncertainty, including intra-hour balancing, management of ramping and forecast error, and other short-term operational flexibility and operating reserve requirements. Nor do most consider longer term balancing and flexibility needs to manage extreme periods of low wind or solar output. When those are considered, they are typically in the form of requiring additional reserve margin in every hour using simple heuristics (e.g. 7% of peak demand). The deliverability of these resources across the system is often not well considered.

This may have a knock-on effect of underestimating the costs associated with operating the system and the value of investing in flexibility resources used to meet these requirements. In full planning studies, such issues would typically be analyzed in more detail using production cost models, most of which now simulate five-minute dispatch and can replicate day-ahead decisions, energy storage operations, and demand response participation. Short of running such studies, there may be some questions as to whether and by how much balancing costs will matter.

As traditional sourcing of balancing and flexibility are replaced with lower-emitting resources, it will be critical to identify clean sources of flexibility including emerging resources like energy storage and demand flexibility. While both storage and demand response are growing in application and can provide benefits such as short development times and modularity, there are still technology development, demonstration, and deployment needs for both resource types to expand their availability and application for balancing and other grid services in a decarbonized grid.

As systems decarbonize, most decarbonization studies predict there will be a reliance on gas to provide balancing services initially, with the majority of balancing shifting to other resources such as energy storage (batteries, pumped hydro, and longer duration technologies), demand-side flexibility, and dispatchable, zero-carbon resources.

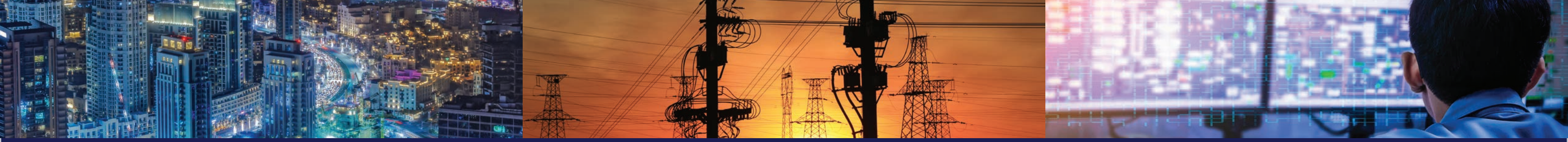
Much has been written about the increased costs associated with balancing the system in high renewable penetration regions. Integration costs of renewable resources are often studied and, for the most part, these costs are relatively small, on the order of less than $5/MWh of production,[31] though they do increase once a balancing area's annual energy penetration grows beyond approximately 40%-60%,and depend on the rest of the resource mix and loads. As systems decarbonize, most decarbonization studies predict there will be an initial reliance on gas to provide balancing services, with the majority of balancing shifting to other resources such as energy storage (batteries, pumped hydro, and longer duration technologies), demand-side flexibility, and dispatchable, zero-carbon resources – identifying the characteristics required for the latter is an important research need. In general, the balancing challenge is something that is well understood in terms of operational mitigations,[32] but the cost of employing these balancing and ramping solutions is likely to increase as renewable resources increase in penetration.[33]

For systems with new or existing flexible resources available to provide operational balancing, the additional costs are likely to be small. It would only be in cases where resources would need to be built, or kept from retiring, specifically to provide this type of balancing, that additional costs may be incurred that would need to be considered in different pathways. That may be most important in very high renewable cases (greater than 70% or more annual penetration). In such situations, batteries and other resources may be required to meet this need, and so the integration costs may be significant. Another potential option would be to develop markets

[31] Holttinen, Hannele, et al. "Summary of experiences and studies for Wind Integration: IEA Wind Task 25." 12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, WIW13. Energynautics GmbH, 2013.

[32] Paul Denholm, et al, The challenges of achieving a 100% renewable electricity system in the United States, Joule, Volume 5, Issue 6, 2021, Pages 1331-1352, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2021.03.028.

[33] H. Holttinen et al., "System impact studies for near 100% renewable energy systems dominated by inverter based variable generation," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2020.3034924



that compensate existing resources that might otherwise retire to provide such balancing services. These additional flexibility resources would need to be studied and the costs of providing such services quantified using detailed simulation models of system operations, including representation of operational solutions to mitigate some of the implications.

Operational Reliability – Grid Stability

Grid stability is the ability of the system to maintain voltage and frequency within an acceptable range for credible operating conditions and to withstand sudden disturbances to or unanticipated loss of synchronous components.[34] At the time of writing, EPRI is unaware of any models used in national-level decarbonization pathway studies that consider the extent to which the future power system can maintain grid stability in any level of detail.

As synchronous rotating generation is replaced by inverter based resources (IBRs), the future system is likely to have reduced inertia and grid "strength." Grid strength refers to the ability of the grid to handle small perturbations, such as changes in load or switching of equipment or large disturbances such as tripping of a component. Lower grid strength, combined with the variability introduced by renewables, is expected to result in a more dynamic system with larger and faster variations of electrical characteristics.[35]

As well as traditional types of stability – voltage, frequency, and rotor angle–two additional types of stabilities need to be considered in systems with high IBR penetration.[36] ***Resonance stability*** refers to sub-synchronous (below 60Hz or 50Hz nominal frequency) resonance that can generate either mechanical modes that impact synchronous resources or electrical modes that may result in damage to wind turbines. ***Converter-driven stability*** is unique to IBRs, which have fast-acting controls to ensure appropriate current injection as well as slow-acting controls for voltage regulation. Both control types are vulnerable to instability as IBR penetration increases. Weak grids are especially vulnerable to converter-driven instability, due to lack of a proper network voltage reference that the converter controls can track, or the inability of the converter to inject power in a network with high impedance. Interconnection requirements, informed by planning studies, need to continue to evolve to address such concerns.

Grid stability can be ensured as we transition to a clean electricity supply, but it will require investment and/or development of new resources and capabilities including the following:

- **Grid stability assessment methods.** Stability concerns and needed mitigations must be identified using power system dynamic models and study tools. Model development must evolve to represent new technologies, such as grid-forming controls, energy storage applications, and demand response. The use of electromagnetic transient (EMT)-based tools is likely to increase significantly to model details of various control schemes that cannot be modeled or can only be approximately modeled in positive sequence tools used widely at present for stability analysis.[37]
- **New sensing, controls, and protection technologies.** As instantaneous IBR levels increase and approach 100 percent, system dynamic speed will increase significantly. Tuning of existing IBR controls and development and deployment of grid-forming inverter controls (discussed in the next section) will be required to mitigate potential instability of the IBRs, particularly in weak systems. The system will also need faster sensing and relaying capabilities to mitigate cascading events.

KNOWLEDGE GAPS:

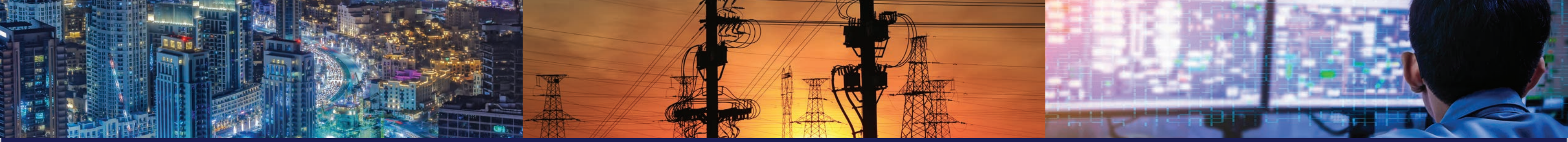
Are additional resources required to provide balancing and ancillary services within the hour? Is the value of flexibility underestimated in different pathways such that it would change the resource mix? What are the additional costs associated with balancing the system?

[34] Kundur, Prabha, et al. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions." IEEE transactions on Power Systems 19.3 (2004): 1387-1401.

[35] From H. Holttinen et al., "System impact studies for near 100% renewable energy systems dominated by inverter based variable generation," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2020.3034924

[36] Hatziargyriou, Nikos, et al. "Definition and classification of power system stability revisited & extended." IEEE Transactions on Power Systems (2020).

[37] Global Power Systems Transformation, Inaugural Research Agenda, available at https://globalpst.org/wp-content/uploads/042921G-PST-Research-Agenda-Master-Document-FINAL_updated.pdf



- **Resources providing grid stability services.** As rotating synchronous generators are replaced with IBRs, resources must be available to provide stability-supporting grid services such as reactive, inertia, and short circuit capability. This may come from traditional resources, such as maintaining some synchronous rotating machine generation, or converting to synchronous condensers, from emerging clean technologies such as gas with carbon capture and storage, or from new control capabilities on emerging resources such as batteries or renewable plants themselves. Regardless of the source, the additional resources may require additional investments.

Table 2, adapted from MISO's Renewable Integration Impact Assessment (RIIA), summarizes the overall concerns related to dynamic stability and weak grid.

DEVELOPING TECHNOLOGIES AND OPERATIONAL CAPABILITIES TO RELIABLY MANAGE DECARBONIZED SYSTEMS

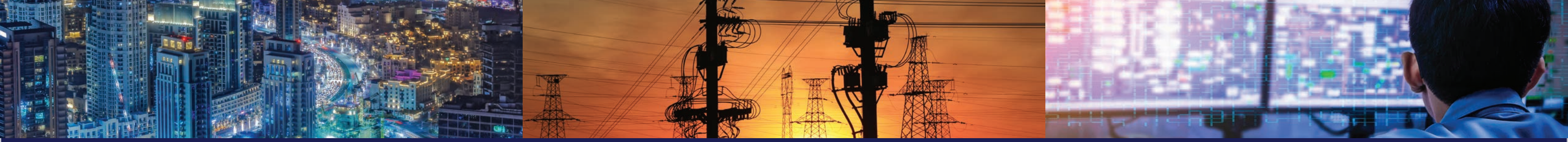
The grid reliability challenges noted as the resource mix transitions to less dispatchable, synchronous generation and more variable and decentralized inverter-based wind and solar will require new operational paradigms and technologies. This may include increased emphasis on decentralized control, changes to protection and restoration practices, deployment of new inverter control and grid enhancing technologies, increased interactions across energy systems, and other grid modernization strategies. Some of these capabilities are well developed and understood, though not widely deployed at present. Others still require additional research, development, and demonstration before playing a major role in the energy transition. All can support the achievement of future pathways while maintaining system reliability and efficiency.

KEY KNOWLEDGE GAPS:

Does the resource mix provide the reliability services to ensure grid stability? What additional technologies may need to be deployed? How must inverters behave to ensure that stability issues are mitigated, and does that impact the buildout of transmission required? How do we update models and simulation tools to ensure we can study the range of issues?

Table 2. *Summary of Concerns Related to Dynamic Stability and Low Grid Strength (adapted from MISO RIIA Study)*

STABILITY ISSUE	PERFORMANCE METRIC	SCOPE OF IMPACTS	POSSIBLE MITIGATIONS	IMPACT OF RENEWABLE PENETRATION
Control stability – Inverter-based instability and voltage instability in weak areas	SCR-based metrics, undamped voltage and control oscillations, controls interactions	Localized but observed at multiple substations	• Tuning of converter controls • Synchronous condensers • STATCOM • HVAC w/synchronous condensers • VSC-HVDC • Grid-forming controls	Very Significant, likely the first instability issue to be encountered
Frequency stability	Frequency nadir,Rate of change of freq (RoCoF),NERC obligations	Interconnection-wide	• Online headroom • Batteries	Significant, more pronounced as the penetration increases
Rotor angle stability – small signal	Damping ratio of low frequency oscillations	Interconnection-wide	• Must-run synchronous units with power system stabilizers • Power oscillations dampers (POD) on IBR, SVC, STATCOM • Specially tuned batteries	Significant, likely to be experienced right from initial stages
Rotor angle stability – large disturbance	NERC planning criteria, TO's local planning criteria	Local area	• Faster excitation systems • Fast-valving of turbines • Faster protection schemes	Mixed – may improve in some parts but deteriorate in other parts of the system
Resonance stability	Impedance scans at POI	Local	• Supplemental controls	Low, more pronounced as the penetration increases



Advanced Grid Control and Situational Awareness, including Grid Edge Visibility

Existing centralized and siloed grid monitoring and control schemes may not be able to provide the faster, localized control actions needed to ensure grid reliability with a high penetration of IBRs and exponentially higher number of resources down through distribution to the grid edge. New grid control approaches and commercial software implementations must leverage emerging high-resolution sensors, fast-acting IBR controllability, and local computing and control capabilities to obtain critical grid reliability services such as frequency and voltage support that traditionally were obtained from synchronous generation. These new control implementations are also needed to fully support DER aggregation and participation in markets as envisioned by FERC Order 2222.[38]

As shown in Figure 2, this new scheduling and control paradigm must integrate control across the transmission energy management system (EMS), distribution management system (DMS), DER management system (DERMS), customer and microgrid control systems, and autonomous device controls to optimize provision of required grid reliability services. This requires that local controllers act fast based on high-resolution data and coordinate with slower regional- and system-level controls for economic and efficient security-constrained operation of the power system. A federated architecture requires a communication and control architecture that supports ubiquitous sensing and data transfers across many more devices than in the past and information flows and interactions across transmission, distribution, microgrid, and market operator systems.[39] In such a scheme, intelligence would be placed at the optimal level, considering necessity, performance, cost, readiness/availability, scalability, and sustainability.[40] Such a system must also have cybersecurity provisions built into the design of the communications and data interface architectures rather than attempting to retrofit to mitigate potential vulnerabilities. These communications and cybersecurity issues are important factors to consider, though not examined in detail in this paper.

A federated architecture requires a communication and control architecture that supports ubiquitous sensing and data transfers across many more devices than in the past and information flows and interactions across transmission, distribution, microgrid, and market operator systems.[38]

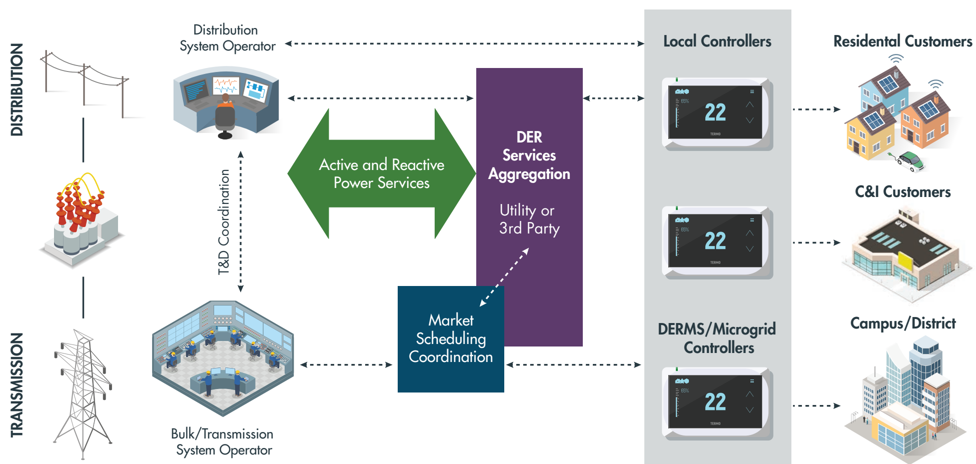
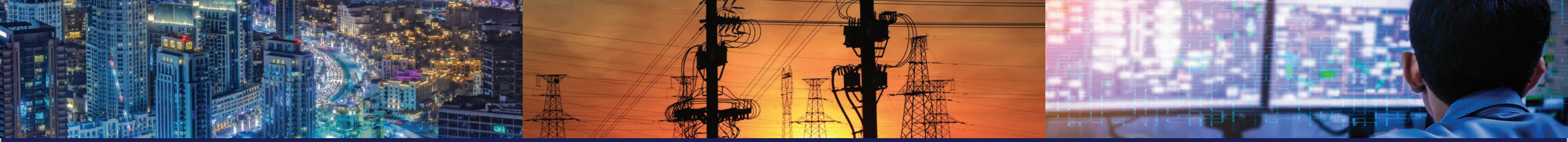


Figure 2. *Control Paradigm with Increasing Penetration of Distributed Energy Resources*

[38] EPRI, Distributed Energy Resource Aggregation Participation in Organized Markets: Federal Energy Regulatory Commission Order 2222 Summary, Current State-of-the-Art, and Further Research Needs 3002020586, Feb 2021.

[39] Southern California Edison, Reimagining the Grid, https://www.edison.com/home/our-perspective/reimagining-the-grid.html

[40] EPRI, Federated Architecture for DER Integration, EPRI, Palo Alto, CA. 2020. 3002019424



While there are many ongoing research efforts to develop aspects of integrated, decentralized control methods,[41] [42] there is still much development and demonstration at scale required before commercialization and deployment can begin. Once commercialized, typical control installations take two-four years to fully implement. As such, accelerating further development and demonstration of the needed control approaches should be a priority for achieving decarbonization objectives.

Inverter Capabilities

Inverter based resources (IBRs) are likely to make up an increasingly large share of the supply side, whether as part of large transmission connected plants or on the distribution system. Ensuring we can utilize these resources to provide system services is increasingly important and the capabilities expected to be available need to be considered in studies of the future system as they continue to develop.

Grid Forming Inverters (GFM)

Today most grid connected IBRs are grid following inverters that assume the grid is providing a stable frequency and voltage for the inverter controls to follow. As noted in the previous T&D reliability discussion, the dependence of such inverters on grid voltage in a grid with high renewable levels can lead to instability in weak areas of the system with limited inertial response. Grid Forming (GFM) inverters, where the voltage and phase angle are generated by the inverter, are a potential solution for such situations. The GFM inverter can support functions such as frequency, inertia, smoothing power generation at dc side, and black start.[43] These capabilities will become increasingly important as the generation mix becomes more decentralized. While GFM technology is available today (e.g. for microgrids and in demonstration projects[44]), seamless operations of large numbers of units at the T&D level will require standards and functional requirements to be developed, use cases identified, and the technology demonstrated at scale before widespread adoption can take place.[45]

Autonomous Grid Interactive Functions

IEEE Std 1547™-2018[46] outlines a variety of autonomous reactive and active power functions (volt-var, volt-watt, fixed power factor, etc.) that are becoming available in modern DER. This functionality has the potential for DER to mitigate steady state and short-term voltage and thermal violations on a distribution feeder while also providing voltage ride-through and frequency response during bulk system abnormal events. Studies have demonstrated that targeted application of reactive power absorption can significantly increase hosting capacity where the dominant constraint is steady state voltage.[47] Active power functions, such as volt-watt, can also be used to limit power output to maintain voltage. If fully leveraged by utilities, such "smart" inverters are positioned to help distributed PV play a more meaningful role in maintaining grid reliability (see Figure 3).

Such a system must also have cybersecurity provisions built into the design of the communications and data interface architectures rather than attempting to retrofit to mitigate potential vulnerabilities.

[41] EPRI, Next-Generation Grid Monitoring and Control: Toward a Decentralized Hierarchical Control Paradigm, EPRI, Palo Alto, CA, 2018. 3002014613

[42] EPRI, Cybersecurity Interoperability Specifications for End-to-end DER Architecture: Enable BTM DER-provided Grid Services that Maximize Customer Grid Benefits (ENGAGE), EPRI, Palo Alto, CA, 2021. 3002022403

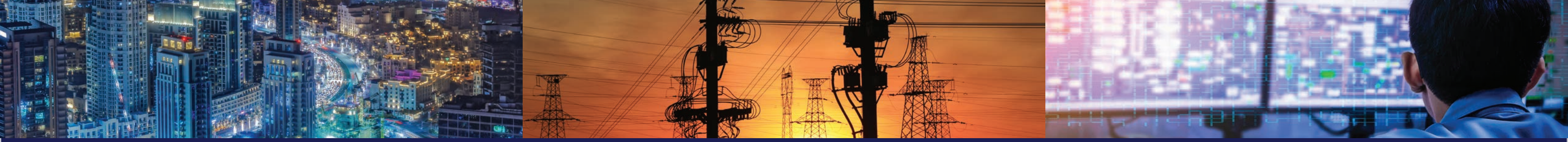
[43] Y. Lin et al, Research Roadmap on Grid Forming Inverters, NREL Technical Report NREL/TP-5D00-73476, Nov 2020, available at https://www.nrel.gov/docs/fy21osti/73476.pdf

[44] Denis, Guillaume et al. (2017). The Migrate project: Try the challenges of operating a transmission grid with only inverter based generation. A grid-forming control improvement with transient current limiting control. IET Renewable Power Generation. 12. 10.1049/iet-rpg.2017.0369.

[45] J. Matevosyan et al., "Grid-Forming Inverters: Are They the Key for High Renewable Penetration?," in IEEE Power and Energy Magazine, vol. 17, no. 6, pp. 89-98, Nov.-Dec. 2019, doi: 10.1109/MPE.2019.2933072.

[46] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), 6 April 2018.

[47] EPRI, Analysis to Inform California Grid Integration Rules for Photovoltaics: Final Results on Inverter Settings for Transmission and Distribution System Performance. EPRI, Palo Alto, CA: 2016. 3002008300.



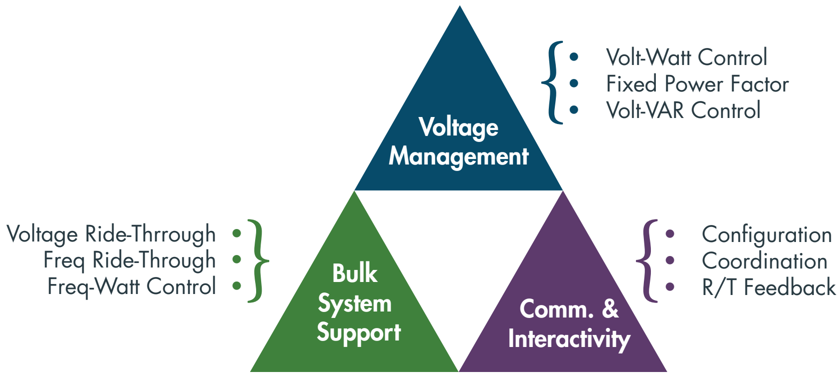


Figure 3. *Grid Supportive functions offered by smart inverters*

System Protection Considerations

The changing resource mix and significant expansion of the grid may impact system protection in multiple respects. As noted in the T&D reliability section, displacing large synchronous generation with distributed IBRs will reduce the short circuit capability in portions of the grid resulting in a weaker system. Many existing protection schemes depend on available short circuit to detect and clear system faults. Additionally, the power electronic interface of IBRs provides a fundamentally different response to system faults from traditional synchronous generators. Increased IBR levels and the ensuing changes in short-circuit behavior of the power system may mean that the fundamental principles of power system protection must evolve to mitigate potential risk of relay misoperations.

Integrating high levels of DER into distribution feeders will require application of adaptive projection schemes that can: (1) dynamically adjust minimum pickup levels to prevent relay blinding and sympathetic tripping of DER without compromising protection sensitivity; (2) adjust settings groups based on DER infeed to reduce risk of unintentional islanding; (3) adjust reclosing intervals based on fault conditions and DER infeed to avoid reclosing in the presence of DER with ride-through; and (4) adapt to changes in grid operating state such as those due to reverse power flow, actions of distribution automation schemes such as Fault Location Isolation Service Restoration (FLISR), outages, or changes related to the transmission grid operating state such as short-circuit current magnitude. While some relay vendors offer adaptive settings capabilities, these have not been widely deployed. Ongoing efforts such as EPRI's US Dept of Energy-funded PV-MOD project aims to accelerate demonstration and deployment of adaptive protections schemes.[48] Such new approaches can help eliminate complex coordinated protection settings and could transform the protection practice into a simpler, intelligent, automated and transparent process.

Fundamental principles of power system protection must evolve to mitigate potential risk of relay misoperations.

System Restoration with a Changing Resource Mix

Traditionally, power system restoration after a complete or partial blackout is carried out using transmission-connected synchronous generation. IBRs are kept disconnected during the early restoration stage and are connected only after most of the system is restored and stabilized. However, as the penetration of IBRs increases, opportunities must be explored for supporting restoration processes using battery energy storage, wind, and solar generation.

When implementing step-by-step facility energization procedures in real-time following a blackout, the power system's behavior is quite different than its behavior during normal operation. The system being restored is weak, which can produce large and unacceptable deviations in voltage and frequency, thus causing potential regression. Therefore, today's operating practices may not be appropriate in the future. If connected during the early

[48] EPRI, Expediting Adoption of Generic PV Models in Transmission Planning, EPRI, Palo Alto, CA. 2020. 3002019838

restoration stage, it is critical for IBRs to support frequency and voltage. The modern IBR installations inherently possess active power and reactive power control capabilities to provide quick support during under-frequency and over-frequency conditions as well as during overvoltage and undervoltage conditions. Power system stability performance aspects as described earlier need to be monitored carefully if IBRs are connected during the early restoration stage. If only using IBRs, the ability of IBRs to operate in "grid-forming" mode will be important to ensure restoration capabilities.

Additionally, the variability and uncertainty of wind and solar can make it challenging to utilize renewable generation during real-time restoration to maintain load-generation balance. Accurate forecasting of output for the minutes-ahead and hours-ahead timeframes can reduce the uncertainty. Another aspect that needs to be considered is the need for black start resources to be identified and evaluated in terms of their likely availability, including fuel availability, during extreme events.

To date, the use of inverter-based renewables to support system restoration has been limited to a few small demonstrations.[49] [50] Additional development and demonstrations are needed to provide procedures for future blackstart and restoration processes for high inverter-based systems.

Grid Enhancing Technologies

Grid-enhancing technologies (GET) refer to a set of hardware and software solutions to aid operational efficiency and capabilities of the transmission grid. GETs are supported by new technological advancement in power electronics, advanced metering and communication, computational processing power, and innovative optimization algorithms. GETs can in certain circumstances relieve transmission constraints, thus increasing the capability of existing transmission networks and improving the operation of new or existing transmission facilities. While there is no strict definition of GET and the specific technologies comprised within this concept, a number of technologies are commonly considered[51] as shown in the box on the next page. For all these technologies, there is a need to understand when and how they can be used and ensure that appropriate costs can be recovered. The ability to defer investment until needs are more fully established, the modularity and scalability of the resources, and the relative costs compared to benefits should all be considered when determining potential deployment of such technologies.[52]

Scheduling and Balancing Practices

Operational tools and changes in practices can be used to reduce balancing costs and flexibility needs. For example, moving from hourly dispatch to five-minute dispatch has been shown to reduce costs, with the benefits of more frequent dispatch increasing with renewable penetration.[53] Improved forecasting and use of risk based operational methods are also shown to reduce system operations costs, with recent EPRI studies showing the

[49] See for example https://www.scottishpowerrenewables.com/pages/innovation.aspx

[50] S. McGuinness, A. Kelly and V. Singhvi, "Greenstart: Protection challenges with integrating wind power parks into system restoration," 15th International Conference on Developments in Power System Protection (DPSP 2020), 2020, pp. 1-6, doi: 10.1049/cp.2020.0103.

[51] Docket No. RM20-10-000 - Electric Transmission Incentives Policy Under Section 219 of the Federal Power Act, March 2020

[52] Improving Transmission Operation with Advanced Technologies: A Review of Deployment Experience and Analysis of Incentives, Prepared by The Brattle Group for WIRES, June 2019.

[53] Milligan, M.; Kirby, B.; King, J.; Beuning, S. (2011). "The Impact of Alternative Dispatch Intervals on Operating Reserve Requirements for Variable Generation." 10th International Workshop on Large-Scale Integration of Wind and Solar Power Into Power Systems, Oct. 25–26, 2011, Aarhus, Denmark.

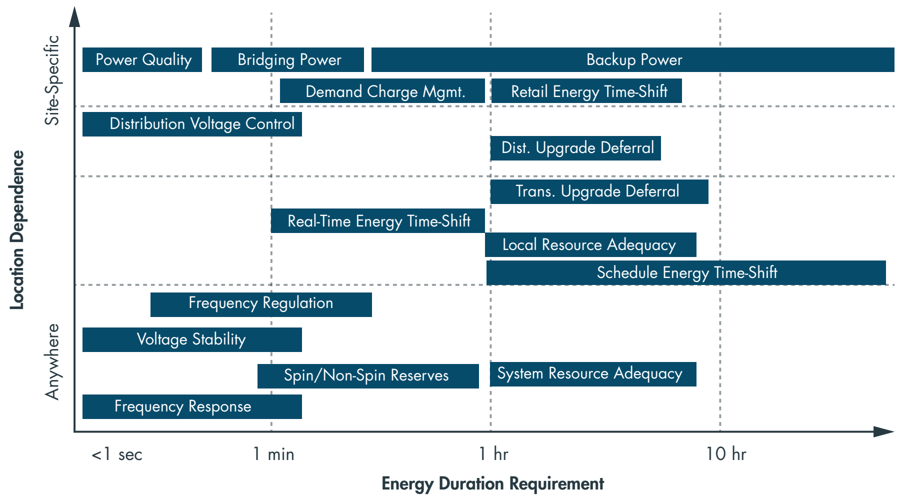


Figure 4. *Energy Storage Functions based on duration, location and service type*

GRID ENHANCING TECHNOLOGIES

Advanced line rating management: Advanced line rating methods adapt line thermal ratings to actual weather conditions to adjust line capacity, as opposed to typical current practice to take a conservative limit based on worst case ambient weather conditions. Different methods are used that vary how often line ratings are adapted to the changing ambient conditions, and the weather variables considered. While dynamic rating technologies exist and have been deployed in some regions, advances are needed for integration into system operation processes and tools for widespread adoption.

Power flow control: Power flow control (PFC) devices, versions of which have been used for many years, can alter the natural power flow through the system by different means. In recent years, new power flow control technologies have been developed that are modular and scalable, can be manufactured and installed in a shorter time, and, in some cases, are available in mobile form that can be easily redeployed.[54] PFC devices offer a potential solution to transmission congestion resulting from high renewable build-outs in regions with high quality resources.[55]

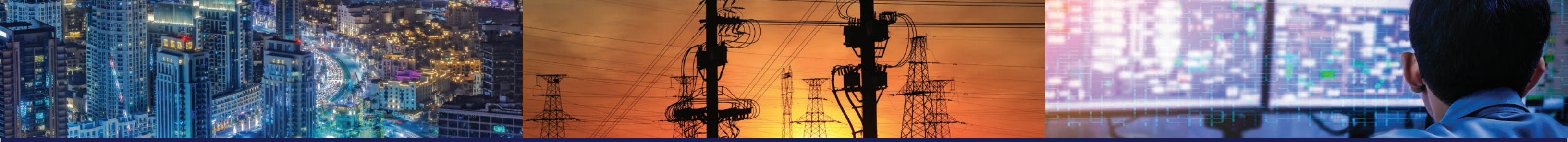
Energy Storage: Large scale energy storage devices, appropriately sited on the network, can be controlled to inject or withdraw power to eliminate transmission overloads during contingency events, thereby allowing the transmission limit to be increased. Storage can also be installed in a load pocket fed by radial transmission lines to supply the load when the capacity of the feeding lines is exceeded. If designed appropriately, energy storage systems can also provide a variety of grid and market services, largely due to technologies' flexibility and modularity, as shown in Figure 4.

Volt-VAR Optimization on the Distribution System: Traditionally, voltage regulators and capacitor banks with appropriate controls have been used to minimize reactive power flows on the distribution system and manage the voltage within limits. New requirements like conservation voltage reduction, voltage reduction for load management and loss minimization on distribution systems present challenges, and advanced volt-var control technologies are potential solutions. These technologies can help keep voltages within acceptable limits, achieve desired power factor, and minimize distribution losses. Examples include edge of network grid optimization devices, in-line power regulators (IPT), and static-var compensators (SVC).

Transmission topology control: Topology control changes the power flow in the system by strategically opening or closing certain circuit breakers. This can reduce congestion and improve economic efficiency without adversely affecting security. The concept has been used by system operators to address reliability concerns, based on system knowledge and staff experience; recently, topology optimization software has been developed to identify system reconfigurations systematically and automatically. As topology optimization is a software application, the cost can be quite low for the value received.

[54] Integration of Power Flow Controllers and Advanced Transmission Technologies: Use Cases and Solutions Design. EPRI, Palo Alto, CA: 2020. 3002018976

[55] Benefits and Value of New Power Flow Controllers. US Department of Energy. July 2016. Contract DE-AR0000554. (EPRI Product Id: 3002013930).



benefit of such methods to determine operating reserves.[56 57] Improved interaction between neighboring balancing areas has also resulted in lower integration costs, as shown by recent experiences in the western US Energy Imbalance Market,[58] as well as previous experience in the Eastern Interconnection in moving to larger balancing authorities or through reserve sharing.[59] Such operational practices can result in lowering integration costs without significant additional physical asset deployment, but rather through the deployment of advanced modeling and operational software tools.

Market designs must therefore evolve to provide revenue sufficiency for resources needed to maintain reliability and resiliency but that have sparse run time and face declining prices.

Electricity Market Revisions and Financial Considerations

Increasing amounts of near-zero marginal cost resources are envisioned in all pathways, while there will also be a need to ensure that capacity, energy, and flexibility are available from the resource mix across the range of potential conditions. Market designs must therefore evolve to provide revenue sufficiency for resources needed to maintain reliability and resiliency that have sparse run time and face declining prices. Resilience measures such as dual fuel capability and fuel storage require similar consideration. There is significant ongoing work across the world identifying and analyzing such changes to market designs; however, there is no consensus on what the final designs may be.[60] Changes to designs are likely to impact how energy is priced, particularly during high risk periods, how demand can participate in various markets, and how forward markets are developed and implemented for ensuring availability of resources. It is also likely to include changes in how reliability services are procured and valued, and may result in shifts in the relative proportion of revenue across energy, capacity, flexibility, and grid services.

[56] EPRI Journal, "A win-win for grid operators and customers", Available: https://eprijournal.com/a-win-win-for-grid-operators-and-customers

[57] M. Ortega-Vazquez et al, Operating Reserve Dimensioning Using Probabilistic Forecasts, working paper, 2021

[58] California ISO, Western EIM Benefits Report, April 29, 2021. Available https://www.westerneim.com/Documents/ISO-EIM-Benefits-Report-Q1-2021.pdf

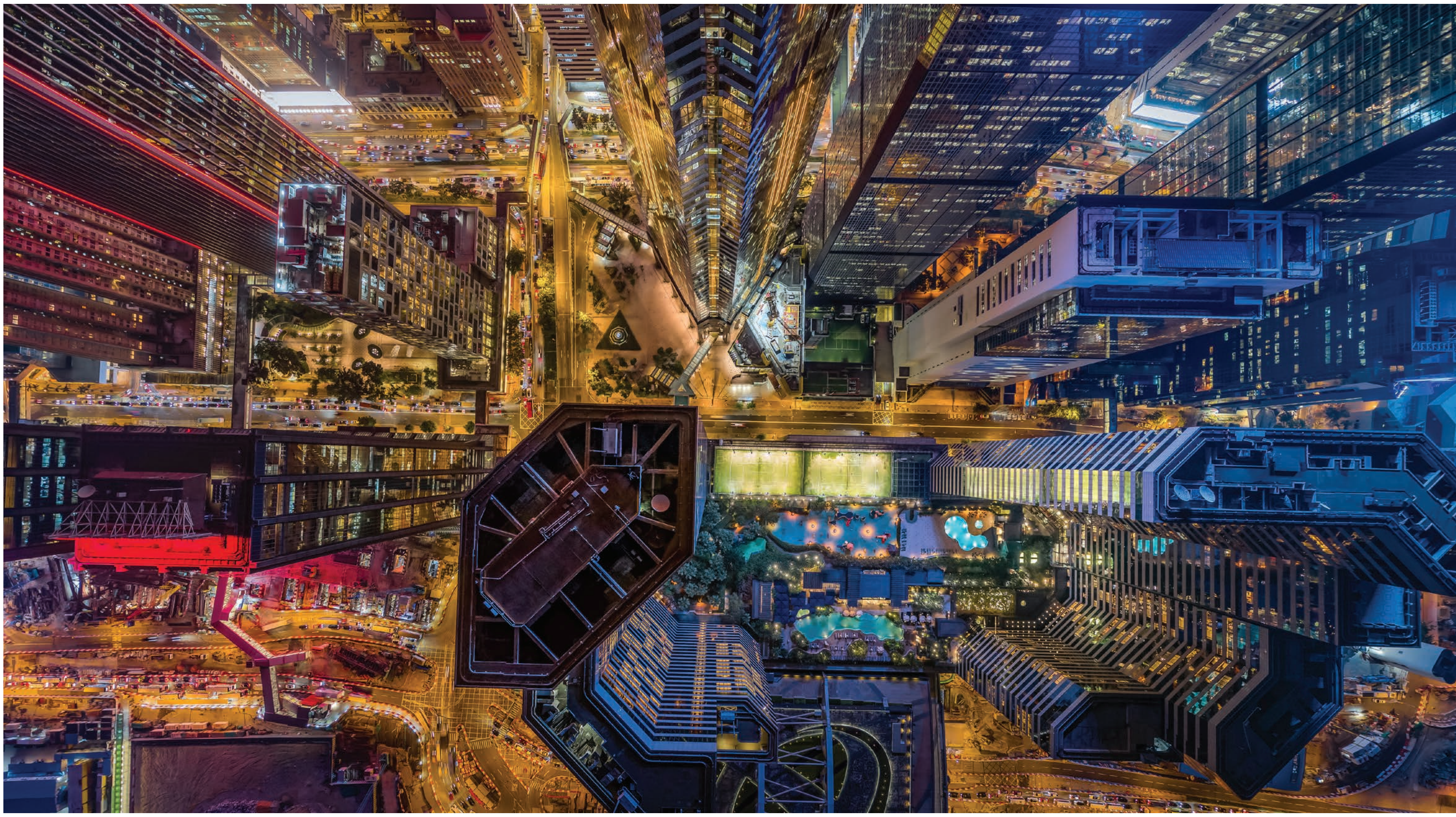
[59] EPRI, DOE: Integrating SPP Wind Energy into Southeast Electricity Markets, Final Report, 2011.

[60] E. Ela et al., "Future Electricity Markets: Designing for Massive Amounts of Zero-Variable-Cost Renewable Resources," in IEEE Power and Energy Magazine, vol. 17, no. 6, pp. 58-66, Nov.-Dec. 2019.

The timing of these market changes also influences the mobilization of capital required for low carbon resources and the timing of the investment case. Financing mechanisms must support investment for well-established technologies and must evolve to rapidly deploy appropriate capital to emerging technologies with a higher risk profile and more complex revenue structures than traditional energy sales. Mechanisms may also be needed to address stranded investments in higher emitting resources that have remaining book life beyond dates to meet reduction targets, particularly for public power where disadvantaged communities may be adversely impacted by early retirement. New cost allocation methods for transmission that identify and allocate benefits may also be needed.[61]

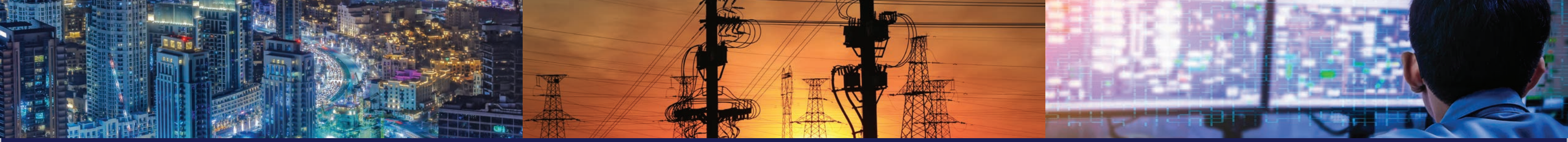
Integrated Energy Network Modeling Capabilities

Given the increased interdependency across different planning domains, including generation, transmission and distribution, as well as linkages with other energy sectors and communications, strategic investment decisions increasingly need a more integrated modeling framework. In the 2018 "Integrated Energy Network Planning" paper, EPRI identified the key needs for evolution of planning tools to address the increased complexities and challenges associated with decarbonization and other related changes.[62] The framework laid out there identified ten key challenges related to planning tool capabilities that will be needed in the future. Challenges were placed in three broad categories: modeling the changing power system, integrating forecasts, and expanding planning boundaries. EPRI is currently working on developing the capabilities to link different modeling tools across the resource expansion, production cost modeling, and transmission and distribution analysis domains in order to better answer many of these questions.



[61] ScottMadden, Informing the Transmission Discussion, January 2020

[62] EPRI, Developing a Framework for Integrated Energy Network Planning (IEN-P): Executive Summary, EPRI, Palo Alto, CA, 2018. 3002014154



Such planning tool and methodology development will be required to address many of the more detailed planning studies needed to further investigate decarbonization pathways. While not a capability that supports decarbonization in itself, the tools and models envisioned will allow for greater understanding of the potential implications of the changing resource mix, as well as providing greater insight into the need for and use of the other technologies and capabilities discussed in this section. Improved modeling tools and capabilities will also require sharing of models across seams (whether geographic between regions, between transmission and distribution, or across energy systems), and in depth interactions between tool vendors and end users to allow for rapid update of models and tools as new learnings arise.

Interactions with Natural Gas and Other Energy Systems

As the economy becomes increasingly electrified in almost all scenarios of the future system (e.g., electricity rising from 20% of final energy demand today to 50% in a low-carbon future), the links between electric infrastructure and other energy infrastructure need to be more fully considered. In the decarbonization pathway models, this linkage is considered in terms of interactions between the different energy infrastructures and how they impact supply and demand for different sources of energy and end uses. Planning decisions will require consideration of these interdependent systems to enable optimal investment for ensuring resiliency and reliability. For example, consideration of natural gas delivery system impacts on electric system resource adequacy may reveal needs for additional supply or either electric and/or gas delivery capacity. When it comes to operating the power system in the future, these interactions will have to be enhanced from their current state.[63]

Planning decisions will require consideration of these interdependent systems to enable optimal investment for ensuring resiliency and reliability.

Visibility of other systems will become increasingly important, whether due to reliance on those systems to provide services, or due to their implications on availability of electrical infrastructure. Technical challenges associated with widespread operations across multiple energy systems include computational complexity,[64] data complexity (out of date data or poor exchange), and the need to model different spatial and temporal resolutions. Coordination between network operators (transmission and distribution and operators of other energy vectors) and agreement between different types of stakeholders will also be important. Assuming such challenges can be overcome, the increased visibility and control associated with multi-energy networks has the potential to provide significant flexibility to the power system, while allowing for increased decarbonization in other energy systems.

Summary of Technology and Operational Capabilities Required

Table 3 summarizes the required technology and operational capability developments in terms of the remaining innovation needed to achieve deployment at scale, the effort required to close the remaining gaps, and the reliability or system investment that need to be addressed.

[63] G. Freeman, J. Apt, M. Dworkin, *The Natural Gas Grid Needs Greater Monitoring*, Issues in Science and Technology, Summer 2018, pp. 79-84

[64] Dall'Anese, Emiliano & Mancarella, Pierluigi & Monti, A. (2017). Unlocking Flexibility: Integrated Optimization and Control of Multienergy Systems. IEEE Power and Energy Magazine. 15. 43-52. 10.1109/MPE.2016.2625218.

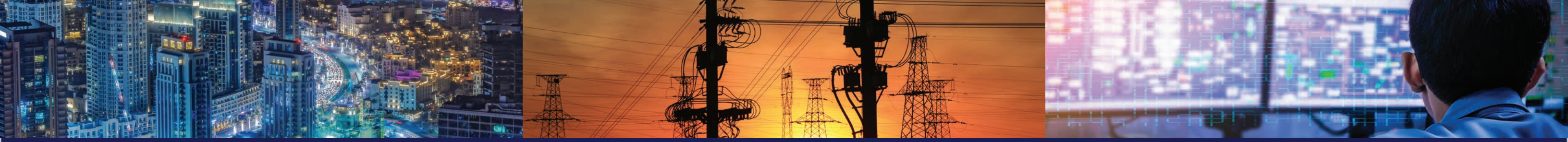


Table 3. *Capabilities required to support decarbonized electric systems*

TECHNOLOGY/CAPABILITY DEVELOPMENT	INNOVATION NEEDED	EFFORT FOR ROLLOUT AND DEPLOYMENT	CHALLENGES ADDRESSED
ADVANCED GRID CONTROL AND SITUATIONAL AWARENESS	Development of new methods; Demonstration of new methods; Standards or codes development	+++	Grid Stability; Transmission; Distribution
INVERTER CAPABILITIES	Development of new methods; Demonstration of new methods; Standards or codes development	+	Grid Stability
SYSTEM PROTECTION	Significant change from current practices; Demonstration of new methods; Deployment of existing technologies	++	Transmission; Distribution; Grid Stability
SYSTEM RESTORATION	Significant change from current practices; Demonstration of new methods; Development of new methods	++	Transmission; Grid Stability; Resource Adequacy
GRID ENHANCING TECHNOLOGIES	Deployment of existing technologies; Demonstration of new methods	++	Transmission; Distribution; Grid Stability
SCHEDULING AND BALANCING PRACTICES	Demonstration of new methods; Significant change from current practices	+	Balancing
ELECTRICITY MARKET REVISIONS AND FINANCIAL CONSIDERATIONS	Development of new methods; Significant change from current practices	++	Balancing; Resource Adequacy; Grid Stability
INTEGRATED ENERGY NETWORK MODELING CAPABILITIES	Development of new methods; Significant change from current practices	++	Transmission; Distribution; Grid Stability; Balancing; Resource Adequacy
INTERACTIONS WITH OTHER ENERGY SYSTEMS	Significant change from current practices; Standards or codes development	++	Balancing; Resource Adequacy

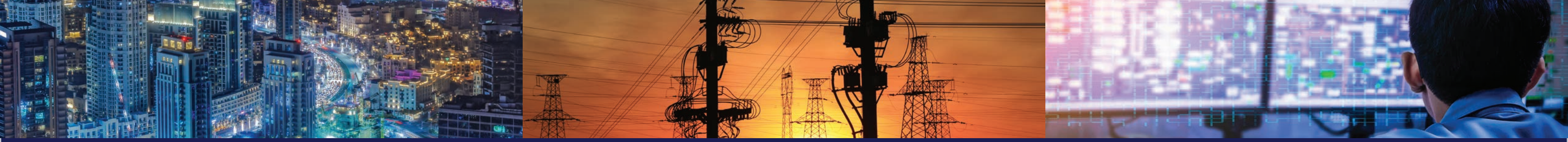
LEGEND:

- Development of new methods
- Demonstration of new methods
- Significant change from current practices
- Standards or codes development
- Deployment of existing technologies
- Balancing
- Grid Stability
- Resource Adequacy
- Transmission
- Distribution

GRID TRANSFORMATION CHANGE MANAGEMENT AND TIMELINES

Transforming existing electric systems to reliable and resilient grids that enable a net-zero economy requires wide-ranging changes in supply and delivery infrastructure and deployment of various grid operation technology, capabilities, and practices as described above. Orchestrating such change across every part of the power system requires considerable planning, conscientious management, and stakeholder collaboration. The decarbonization pathway studies that provide the compass for achieving targeted emissions reductions imply a buildout of infrastructure, deployment of new technologies, and changes to operating practices and tools on a scale and pace never before experienced for the electric grid. Achieving such an extensive transformation of the grid will require immediate consideration of timelines of many prerequisite and inter-related processes including investment planning, regulatory approval, technology innovation, and infrastructure construction.

Planning and operational practices continuously evolve in each region and between neighboring regions. Changes to operational procedures, market designs, or long-term planning analysis may range from months to years to implement, depending on the complexity of the change. Market design changes often require extensive consultation across market participants, system operators, grid owners, state and federal regulators,



and societal groups. For policy or regulatory driven processes, drafting and consultation processes typically take 18-36 months with tariff change responses due within another 12 months, followed by an implementation phase. Therefore, a policy change may only become effective in operations three to four years after the regulation is initially drafted. Like other forms of infrastructure, grid projects require extensive time for planning and deployment. A transition to net zero requires substantial capital investment. Project development timelines can range from weeks to decades when considered individually, while they also need to be sequenced to meet the overall goals. The remainder of this section describes some of the timeline and change management considerations for various aspects of the net-zero grid transformation. Figure 5 draws from these different subsections to provide typical timelines for the sequencing required when developing and deploying new assets or changing practices, standards, and processes. Note these are typical timeline ranges, realizing the processes may vary significantly based on jurisdictional specifics. Considerations for each of these steps are described in the following subsections.

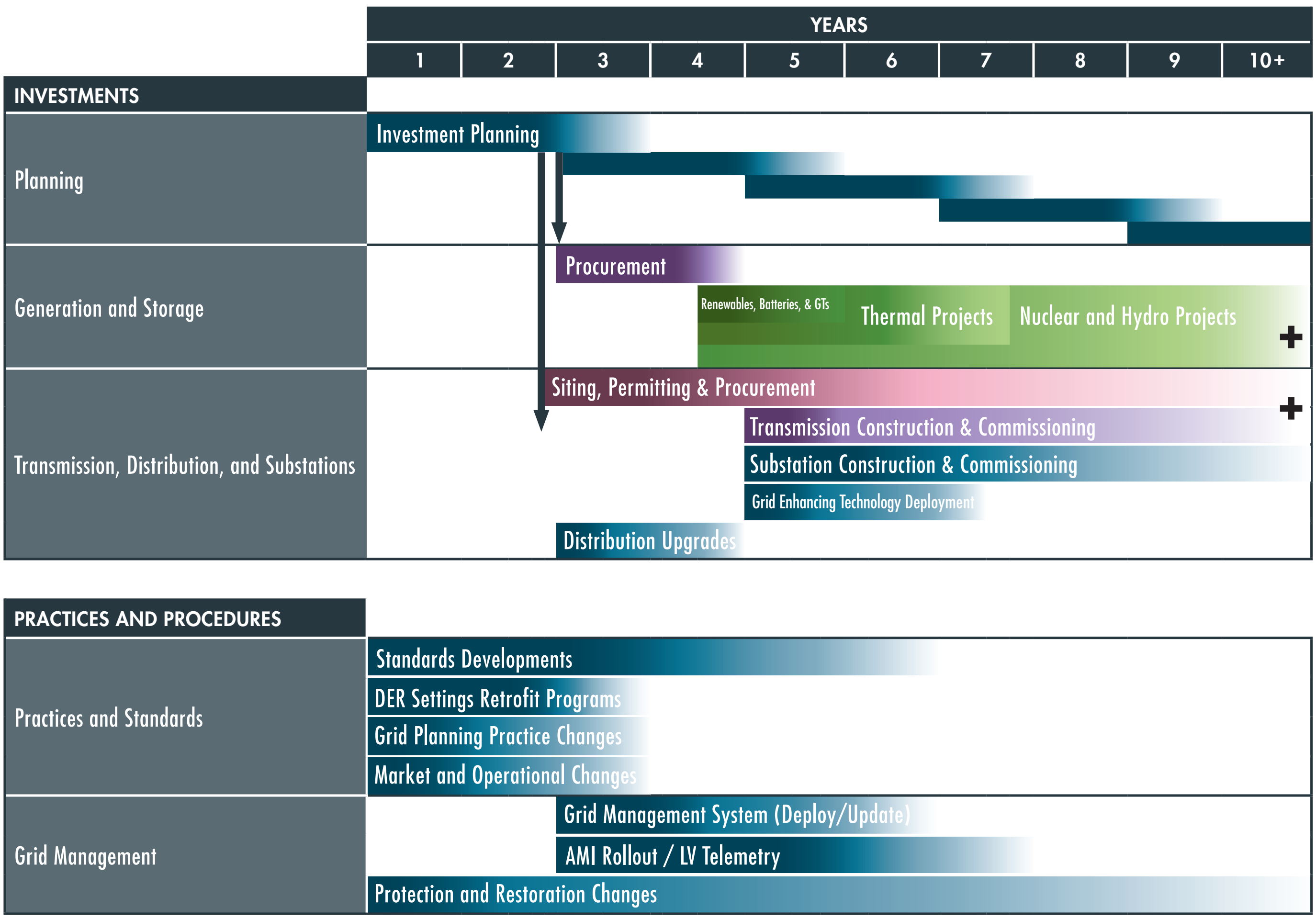
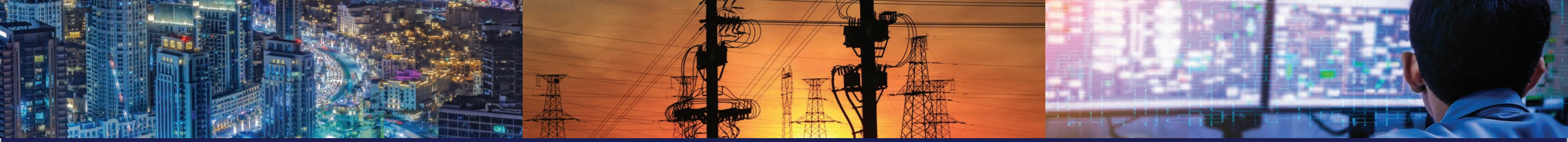


Figure 5. *Typical time requirements and sequencing for power system technology and infrastructure deployment.*



Investment Planning

The investment process commences with a planning study that identifies future supply and network reinforcement needs and recommends mitigation options for investment (e.g. Integrated Resource Planning, multi-regional planning studies). Capital projects or programs of works arising from this process face regulatory and, increasingly, societal approval. Planning occurs on a rolling basis, but individual planning exercises can be broken down into one year of assessment and a second year of approval, with potentially longer timelines for plan completion. The term "Analysis" covers a wide range of techno-economic studies required as prerequisites for project investments. Near-term planning (e.g., 2030 targets) models and strategies must also consider longer-term objectives (e.g., 2050 targets) such that optionality is important across generation, transmission, and distribution. Investment in specific infrastructure deployment or technology development that may not be fully needed for near term objectives may be optimally justified now to support future trajectories.

Generation & Storage Infrastructure Development

While residential customers may make decisions relating to home solar or storage installations in weeks, large capital projects have longer lead times. The initial phase, after completion of planning studies, of siting, permitting, and procurement can vary substantially depending on the resource type, location, and regulatory context. Once permitted, construction times range from months (batteries) to multiple years (nuclear or hydro projects). At the end of 2020, over 850 GW of generation was in the US interconnection queues[65]; commissioning and full production may be influenced by the timing of other enabling grid investments, reinforcing the need for planned sequencing of activities in a holistic process. Technology maturity, supply chain scaling, site access, and availability of labor can further influence construction and deployment time beyond the uncertainty in the siting and permitting phase.

Transmission and Distribution Infrastructure Development

All decarbonization pathways show a need to increase transmission, with the amounts of new transmission varying depending on aspects like the costs assumed for storage, limits on buildout available, and model resolution. In most studies, transmission buildouts reflect at least as much new build and upgrades as seen in the past two decades. In many cases significantly more buildout is expected across the next two decades. Transmission investments in the US have increased in the past two decades, from $9.1B in 2000 (2019 dollars) to $40B in 2019[66] with over half for new infrastructure (note that new infrastructure refers to both new lines, cables, and substations as well as uprating or replacement of aging infrastructure – the other costs are O&M). Other regions, such as China and Europe, have seen greater buildout and have significant additional buildout plans already in place.[67]

There are currently over 400,000 circuit miles of transmission in the US[68]- much of which was built prior to the early 2000s. In the past decade only 2013 has seen more than 3,000 circuit miles built in one year in the US, largely due to Texas completing their Competitive Renewable Energy Zone (CREZ) projects.[69] Most other years during that period saw between 1,000 and 3,000 circuit miles of transmission completed, most at 345 kV. Most decarbonization studies report results in MW-miles (or GW-miles), so one cannot directly compare existing or recent circuit-miles constructed with new build requirements from

In the past decade only 2013 has seen more than 3,000 circuit miles built in one year in the US.

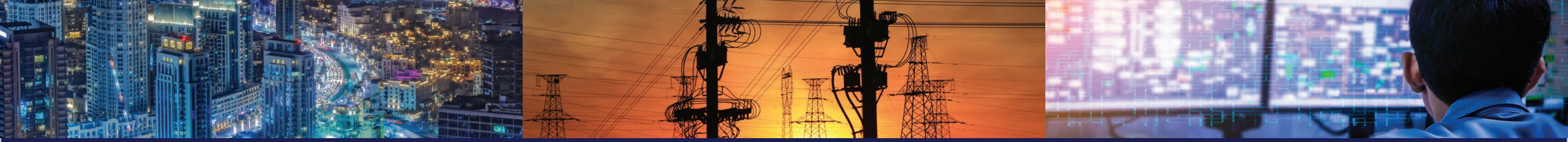
[65] Lawrence Berkeley National Lab, Generation, Storage, and Hybrid Capacity in Interconnection Queues, available at https://emp.lbl.gov/generation-storage-and-hybrid-capacity

[66] Energy Information Administration, "Utilities continue to increase spending on the electric transmission system", March 2021, available https://www.eia.gov/todayinenergy/detail.php?id=47316

[67] James McCalley and Qian Zhang, Macro Grids in the Mainstream: An International Survey of Plans and Progress, sponsored by Americans for a Clean Energy Grid, Nov. 2020

[68] Annual US Transmission Data Review, US Department Of Energy, March 2018

[69] ScottMadden, Informing the Transmission Discussion, January 2020



the decarbonization studies. While it is also difficult to estimate existing US transmission capacity in GW-miles, some estimates are on the order of 150 GW-miles in the US today. In the decarbonization pathway studies reviewed, new transmission required for interregional transmission is typically in the tens to low hundreds of GW-miles. When additional intra-regional transmission is also included to connect those interregional transmission to load and renewable resources, it is not inconceivable that at least 100 GW-miles may be needed for the future – several studies indicate significantly more, with up to a tripling of the number of GW-miles of transmission required by 2050. Regardless of the exact numbers, most of the studies estimate a very large buildout of transmission.

Buildout timescales vary; substations can be built in two to three years exclusive of planning considerations, siting, and permitting. Certain types of infrastructure, such as stations for generators or new loads, may be built faster than transmission built to relieve congestion or mitigate a specific reliability constraint. Total time for siting, permitting, and constructing new transmission lines can range from a few years to beyond 15 years with typical assumptions being in the five to eight year range.[70] For example, the ERCOT CREZ lines, with over 3,500 miles of transmission, carrying 18.5 GW of electricity, were originally directed by the Texas legislature in 2005, approved by the PUC in 2008, and built by 2013. On the other hand, examples exist of ongoing delays for smaller, seemingly more straightforward, projects. The Southline project, with 240 miles of new transmission and 120 miles of uprated transmission to provide 1,000 MW of capacity in New Mexico and Arizona, started preliminary studies in 2009 and is not beginning construction until 2021. The Transwest Express, which is over 700 miles of HVDC and HVAC from Wyoming through Utah and to Southern Nevada and will provide 1,500 MW of capacity, began planning in 2007 and is expected to start construction in 2022. These and various other examples exist where permitting (including certificate of public convenience and necessity and environmental impact assessments) have taken three or more years, with larger projects potentially taking even longer under current processes. Construction itself varies based on tower type, proportion of strain structures, topography, accessibility, proximity of existing roads, and complexity of line crossings. Reconductoring existing lines takes substantially less time.

As noted in the Technology Development section, grid enhancing technologies may provide some buffer for early stages of rapidly changing generation mix as in many circumstances GET can typically be constructed on shorter timelines and at lower cost than large capital projects.[71] However, large scale deployment may require some changes to how transmission systems are planned and operated, and investment costs are recovered and allocated.[72]

Distribution systems also require time to plan and build. Distribution modernization is a key enabler of a future with increasing distribution-connected resources, demand side participation, and customer resilience and reliability. Changes will be required to how distribution systems are planned and operated, with a need for new or adjusted grid architectures, often customized to the specific locations.[73] Grid modernization considerations for fully enabling DER are described in detail in a companion whitepaper titled "Distribution Grid Modernization Key to Unlocking DER Potential".[74] Buildout of distribution infrastructure also requires time but is typically faster than transmission development due to the more localized nature.

[70] Lawrence Berkeley National Lab, Building Electric Transmission Lines: A Review of Recent Transmission Projects, Sept. 2016, LBNL-1006330

[71] Reference upcoming EPRI paper on this topic

[72] J. Pfeifenberger, Transmission Cost Allocation: Principles, Methodologies, and Recommendations, prepared for OMS Cost Allocations Committee Meeting, Nov. 2020

[73] Southern California Edison, Reimagining the Grid, https://www.edison.com/home/our-perspective/reimagining-the-grid.html

[74] Electric Power Research Institute, Maximizing Distributed Energy Resource Value Through Grid Modernization, EPRI, Palo Alto, Nov 2021. 3002023235.

Practices & Standards

Because the grid is a massive interconnected electromechanical system, standards and operational practices tightly govern access to the grid and the mandated behavior of resources. The change in the resource mix will necessitate updating of those rules and practices. Standards development is a consensus driven exercise with multi-year time frames for drafting, and additional time required to develop testing standards that must then be adopted by each region. Standards such as IEEE 1547[75] and 2800[76] that address interconnection of distributed resources and transmission-interconnected IBRs, respectively, provide a strong basis for guiding the future grid changing resource mix, but continued refinement will be required over time. In the case that legacy settings need adjusting based on the emerging grid profile, this process can take multiple years for distributed resources as was the case in Germany and in the UK. These standards also provide an example benchmark for the time required to develop and approve new industry standards to support grid planning and operation. The revision of the 1547 standard required four years from inception to approval, with an additional two years for test procedures. Standard 2800 is still in process but has required over two years to this point, with expected publication in 2022, to be followed by test procedures. Both are expected to undergo revisions in coming years.

Grid Management

As discussed in the previous section there are new technologies that need to be developed and rolled out, including new control and protection schemes and paradigms. Significant operational system updates, such as energy or market management systems, typically take two to four years from initial planning to project completion once the new required capabilities are developed, demonstrated at scale, and commercialized. Operational tools can be developed on a scale of months to years, depending on the complexity of the task and the availability of specialists. Movement towards modular architectures for critical operating systems from monolithic, highly customized solutions offers the opportunity to reduce the time frame for minor and application upgrades. Improving situational awareness at the grid edge is a critical enabler of distributed energy deployment and network optimization. Completing advanced metering rollout and low voltage network sensors are multi-year processes but which can be targeted to the most sensitive areas of the grid based on need.

Operational tools can be developed on a scale of months to years, depending on the complexity of the task and the availability of specialists.

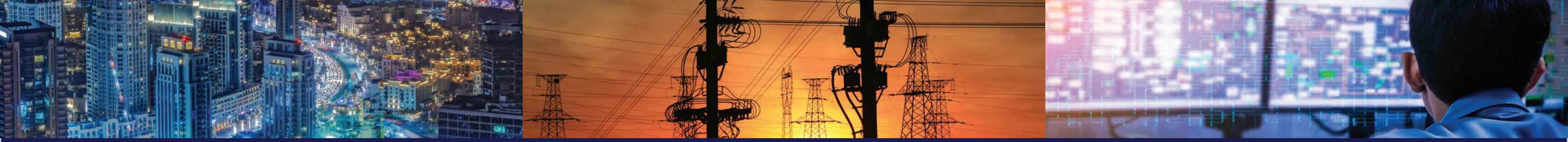
Logistical Challenges

The most significant logistical challenge in deploying the infrastructure and operational processes is creating cross-sector alignment and public acceptance of the proposed plans. Generating alignment requires effective and intense engagement, consultation, and revision by responsible entities, including a wider range of stakeholders as infrastructure expands and customers more actively engage with the electricity system.

Developing mechanisms and incentives to deliver effective cooperation is a logistical challenge to coordinate across territories, particularly in cases where the distribution of benefits is not uniform among the affected parties. As such, new approaches to interregional planning, such as the ENTSO-E Ten Year Network Development Plan (TYNDP), or other proposed means to build new transmission, are needed to enable the buildout. Examples in the US that have been successful in building large scale transmission include ERCOT's Competitive Renewable Energy Zone (CREZ) and MISO's Multi-Value Project (MVP) processes. Both examined overall needs based on changes to the system

[75] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003) pp.1-138, 6 April 2018

[76] IEEE P2800 - IEEE Draft Standard for Interconnection and Interoperability of Inverter-Based Resources (IBR) Interconnecting with Associated Transmission Electric Power Systems; more details at https://standards.ieee.org/project/2800.html



resource mix and identified candidate lines that would provide support to future needs, above and beyond typically considered transmission. A similar coordination is required between transmission and distribution, extending beyond the immediate provisions of FERC Order 2222 to incorporate planning activities. Both schemes are prerequisites to the delivery of net-zero pathways but need deliberate and accelerated activity.

Access to human resources and materials must be considered as multiple countries race to reach decarbonization goals, and this is likely to put a global crunch on resources. This includes ensuring supply of relevant equipment, for example ensuring a sufficient supply of high voltage transformers, HVDC converter stations, or subsea cables. Organizations may need to change, with different skillsets and interactions with other parts of the company. For example, distribution operations organizations will need to evolve to include operational specialists (DER Managers, Operational Planners) whose roles are to manage the operation of DER on the distribution system and manage the interaction between the TSO and DSO for flexible interconnection and dispatch of DER. Power system engineers are highly specialized, with long training times to develop the workforce, in a globally competitive market for technical skill.

Access to human resources and materials must be considered as multiple countries race to reach decarbonization goals, and this is likely to put a global crunch on resources.

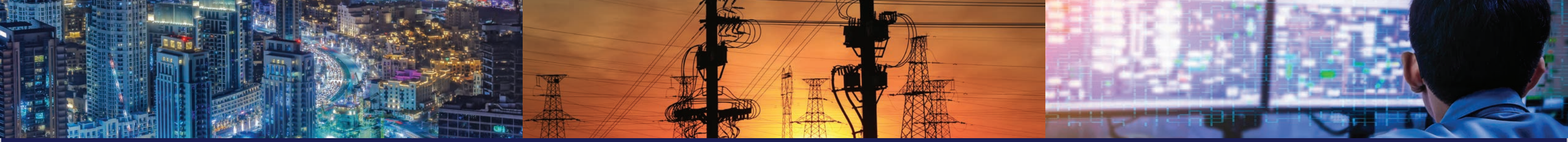
IMPLICATIONS AND NEXT STEPS

As countries across the globe develop plans to reduce GHG emissions, energy sector leaders are conducting decarbonization pathway studies to guide technology development and deployment strategies to meet targets. Most, if not all, of these strategies estimate that the least-cost pathway to achieving net-zero targets is through reducing electric sector emissions and leveraging clean electricity to decarbonize much of other energy sectors. This increased societal dependence on electricity necessitates a highly reliable and resilient supply of electricity. There are significant technology, infrastructure, and stakeholder coordination process developments required to plan, build, and operate the reliable and resilient decarbonized electric grid. Decarbonization pathway implementation strategies include the following key priorities:

- Reliability and resiliency planning. Development and application of detailed reliability and resiliency planning processes and models on a regional and national level across transmission and distribution to maximize the impact of available investment capital.
- Power system operational capabilities. Development and deployment of new grid control and protection capabilities and clean supply and demand balancing resources for reliably and efficiently operating a much more dynamic, decentralized, and inverter-based renewable resource grid.
- Markets and financial systems. Design and implementation of market, financial, and regulatory processes that incentivize investment in significant new supply, demand flexibility, and transmission and distribution infrastructure, and compensate all resources for essential grid services provided.
- Regulatory considerations. Revision of regulatory, innovation, and commercialization processes to reduce timelines for infrastructure siting, permitting, and construction and technology development, demonstration, and deployment substantially relative to historical timelines.

The innovation, collaboration, and investment required to accomplish these tasks in a relatively short timeframe are unprecedented in the power sector. The time required to achieve the above will largely determine the timeframe in which decarbonization targets can be achieved. To that end, the work must begin immediately to reach the desired destination, and collaboration will be key to getting there. EPRI is committed to conducting the independent, science-based collaborative research, development, and demonstration efforts needed to achieve these objectives, including organizing collaborative regional studies that push beyond broad pathways to identify regional strategies for resilient, reliable, affordable, low-carbon energy futures.

There are significant technology, infrastructure, and stakeholder coordination process developments required to plan, build, and operate the reliable and resilient decarbonized electric grid.



APPENDIX: SUMMARY OF NATIONAL DECARBONIZATION STUDIES CONSIDERED HERE

Note: Where specific information was not provided, EPRI made assumptions based on capabilities of software used and descriptions that were available from presentations and other public information. Note that for the most part, stability is not explicitly modeled in these tools, and distribution is only considered explicitly in one model based on information provided. Note also that there are a range of other studies that have focused more on reliability issues; however these typically are not pathway type studies and are more focused on reliability analysis of specific end points or regions.[77]

DECARBONIZATION STUDY	TOOLS USED	OPERATIONAL MODELING	TRANSMISSION MODEL
1. POWERING DECARBONIZATION	US-REGEN	Hourly balancing for subset of days	Pipe and bubble (16 regions)
2. NET-ZERO AMERICA	EnergyPATHWAYS and RIO	Hourly balancing for subset of days	Pipe and bubble (14 regions)
3. ISSUE BRIEF: THE BIDEN ADMINISTRATION MUST SWIFTLY COMMIT TO CUTTING CLIMATE POLLUTION AT LEAST 50 PERCENT BY 2030	EnergyPATHWAYS and RIO	Hourly balancing for subset of days	Pipe and bubble (16 regions)
4. CARBON-NEUTRAL PATHWAYS FOR THE UNITED STATES	EnergyPATHWAYS and RIO	Hourly balancing for subset of days	Pipe and bubble (16 regions)
5. EMISSIONS PROJECTIONS FOR A TRIO OF FEDERAL CLIMATE POLICIES	Haiku Electricity Sector Model	None	Pipe and bubble (13 regions)
6. MEETING POTENTIAL NEW US CLIMATE GOALS	USREP and ReEDS	None	Pipe and bubble (134 regions)
7. ILLUSTRATIVE STRATEGIES FOR THE UNITED STATES TO ACHIEVE 50% EMISSIONS REDUCTION BY 2030	ReEDS and PLEXOS	Hourly balancing for subset of days; further study in PLEXOS for every hour	Pipe and bubble (134 regions)
8. 2035 REPORT	ReEDS and PLEXOS	Hourly balancing for subset of days; further study in PLEXOS for every hour	Pipe and bubble (134 regions)
9. ZEROBYFIFTY (NOT YET PUBLISHED)	WIS:dom-P	Sub-hourly balancing for full study period	Ability to run nodal down to 69kV; cooptimizes aggregate representation of distribution

References to decarbonization studies

1. EPRI, Powering Decarbonization: Strategies for Net-Zero CO2 Emissions, EPRI, Palo Alto, CA. 2021, 3002020700
2. E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report, Princeton University, Princeton, NJ, December 15, 2020.
3. NRDC Issue Brief, The Biden Administration Must Swiftly Commit to Cutting Climate Pollution At least 50 Percent by 2030, March 2021
4. Williams, J. H., Jones, R., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., et al. (2021). Carbon-neutral pathways for the United States. AGU Advances, 2, e2020AV000284.
5. Resources for the Future, Issue Brief (21-02), Emissions Projections for a Trio of Federal Climate Policies, Wesley Look, Karen Palmer, Dallas Burtraw, Joshua Linn, Marc Hafstead, Maya Domeshek, Nicholas Roy, Kevin Rennert, Kenneth Gillingham, and Qinrui Xiahou
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7. Abhyankar, Nikit, Priyanka Mohanty, and Amol A Phadke. Illustrative Strategies for the United States to Achieve 50% Emissions Reduction by 2030. Lawrence Berkeley National Lab, 2021.
8. UC Berkeley, 2035 Report, Plummeting Solar, Wind, and Battery Costs Can Accelerate our Clean Electricity Future, June 2020
9. Vibrant Clean Energy, ZerobyFifty Study, ESIG Transmission Workshop, Nov 2020: https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf

[77] Examples of more detailed studies that examine specific reliability issues include the MISO Renewable Integration Impact Assessment study and the LA100 study. These types of studies are not the focus of this paper, which is focused on national decarbonization studies that address policy goals.

About EPRI

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

Together, we are shaping the future of energy.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com