ANL-24/07

Research Priorities and Opportunities in U.S. Wholesale Electricity Markets

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Market Design under Deep Decarbonization

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prepared by
Todd Levin,[1] Bethany Frew,[2] Alexandre Moreira,[3] Erik Ela,[4] Mahdi Mehrtash,[5]
Abe Silverman,[6] Audun Botterud,[1] Zhi Zhou,[1] Nongchao Guo,[2] Miguel Heleno,[3]
Ryan Schoppe,[4] Robin Hytowitz,[4] and Benjamin Hobbs[5]

[1] Argonne National Laboratory
[2] National Renewable Energy Laboratory
[3] Lawrence Berkeley National Laboratory
[4] Electric Power Research Institute
[5] Johns Hopkins University
[6] Columbia University

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ACRONYMS AND ABBREVIATIONS

CAISO	California Independent System Operator
CEAC	clean electricity attribute certificate
DEFR	dispatchable emission-free resource
DER	distributed energy resource
DOE	U.S. Department of Energy
DSO	distribution system operator
DSR	demand-side resource
EERE	Office of Energy Efficiency & Renewable Energy
ERCOT	Electric Reliability Council of Texas
FACTS	flexible alternating current transmission system
FCEM	forward clean energy market
FERC	Federal Energy Regulatory Commission
GEP	generation expansion planning
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
ICCM	integrated clean capacity market
ISO	independent system operator
ISO-NE	ISO New England
LDES	long-duration energy storage
LSE	load-serving entity
MISO	Midcontinent Independent System Operator
NREL	National Renewable Energy Laboratory
NWA	non-wires alternative
NYISO	New York Independent System Operator
PJM	PJM Interconnection
RA	resource adequacy
REC	renewable energy certificate
RTO	regional transmission operator
SOC	state of charge
SPP	Southwest Power Pool

T&D	transmission and distribution
TEP	transmission expansion planning
VAr	volt-ampere reactive
VRE	variable renewable energy

1 INTRODUCTION: ELECTRICITY MARKETS UNDER DEEP DECARBONIZATION

The Biden administration has set an ambitious goal to generate 100% of electricity in the United States from carbon-free energy sources by 2035. It is important to understand not just which technologies can be deployed to achieve this goal cost-effectively, but also whether and how wholesale electricity markets must evolve to enable these deployments while maintaining reliable, resilient operations through 2035 and beyond. A transition to zero-carbon power may motivate fundamental paradigm shifts in existing market designs and procedures, and in the tools used to operate and plan these power systems. On the other hand, existing market structures may instead prove largely sufficient to meet the challenges posed by decarbonization and therefore continue to evolve incrementally. In either case, research is needed to better understand the value competitive wholesale electricity markets can provide in a deeply decarbonized future and how they may evolve to support economically efficient short- and long-term decision making by market participants while also meeting other societal goals.

Over the past decade, there have been extensive discussions on market design needs, challenges, and proposed solutions for deeply decarbonized power systems. Many of these assume that future low-carbon power systems will be dominated by variable renewable energy (VRE) resources. However, there is no consensus on the optimal path forward for market design. Market design studies have included a wide range of possible impacts, such as reliability and economic efficiency, as well as proposed market design options ranging from incremental to more fundamental changes. In the following discussion, we briefly summarize a selection of this existing literature.

Several studies have reviewed challenges associated with using competitive markets to maintain physical system reliability and market efficiency in deeply decarbonized systems, providing broad guiding principles for future enhancements (e.g., Ela et al. 2021, 2019, 2014; Hogan 2022, 2010; Zhou et al. 2022; Aggarwal et al. 2019; Olsen et al. 2021). Multiple studies suggest that increasing market participation from zero-fuel-cost resources does not fundamentally alter the core economic principles of competitive wholesale markets (Tarel et al. 2022; Zhou et al. 2022), and therefore argue that current core market structures should be preserved (Leslie et al. 2020; Olsen et al. 2021). Others highlight potential problems associated with incremental reforms to current markets (Pierpont and Nelson 2017), focus on approaches to maintain efficient interactions between short-term market prices and long-term market mechanisms driven by regulatory considerations (Aggarwal et al. 2019; Batlle et al. 2021), or raise questions as to whether current market designs are compatible with public policy goals (Joskow 2019). Some propose concrete changes in market design. These include a combination of a long-term energy market and a real-time delivery market (Pierpont and Nelson 2017); a standardized, fixed-price-forward contract approach (Wolak 2021); and market design enhancements that would operate in parallel to today's energy markets (Corneli 2020). Several others focus on perspectives in specific regions—such as Europe (Newbery et al. 2018) or California (Tierney 2018)—that may be broadly applicable elsewhere. Alternatively, some compare current market frameworks in the United States and Europe in the context of maintaining resource adequacy (RA) throughout the transition to decarbonized systems (Botterud and Auer 2020). Distinct from forward-looking discussions of market needs based on economic principles and modeling studies, some empirical analyses have also reviewed the historical impacts of VRE resources on wholesale market outcomes (for example, in the United States [Wiser et al. 2017] and Australia [Rai and Nunn 2020]).

This report contributes to the body of literature by reviewing key challenges for competitive wholesale electricity market design in deeply decarbonized power systems and establishing potential solutions and associated research needs. We provide a long-term perspective on ways in which competitive wholesale electricity markets can evolve to ensure that they still operate efficiently throughout the transition to a deeply decarbonized future. In this report, we use the term “deep decarbonization” to refer broadly to systems that generate nearly all their electricity from zero-carbon or carbon-neutral resources, while recognizing that there are many potential configurations of such systems. We also stress that many of these issues will arise to varying degrees as systems move toward full decarbonization, even if they are not truly 100% carbon-free.

In ongoing debates about changes in electricity policy, there is an important distinction between two basic features of electricity markets: (1) *market design*, which establishes definitions of market products, price formation mechanisms, and auction features; and (2) *market structure*, which establishes roles and responsibilities related to decision making, allocating risk, and pursuing social objectives. Both design and structure may evolve due to regional or national policy choices or in response to technological and financial drivers (Aggarwal et al. 2019).

The first six sections of this report focus on research needs in market design, emphasizing technical and economic challenges and solutions; the general assumption is that market structure may remain broadly similar to its construct today. Those sections are organized around the same topics as our earlier report, Sun et al. (2021), which focused on near-term market design challenges but did not specifically consider long-term power system decarbonization goals. The following six topics were identified through a review of publications from independent system operators (ISOs), regional transmission operators (RTOs), industry reports, and academic literature: (1) reliability and flexibility services, (2) market integration of emerging technologies, (3) adequacy and resilience, (4) wholesale price formation, (5) interactions between transmission and distribution (T&D) systems and wholesale and retail markets, and (6) transmission planning. Section 2.7 introduces a seventh topic: a closer look at how clean energy regulations and policies may affect market structure under deep decarbonization. Figure 1 summarizes the key challenges highlighted across all seven topic areas. Each section leads with a brief introduction, then provides additional narrative with further context and discussion across a range of related challenges and opportunities. The section then concludes with a table summarizing these challenges, potential solutions, and associated research needs.

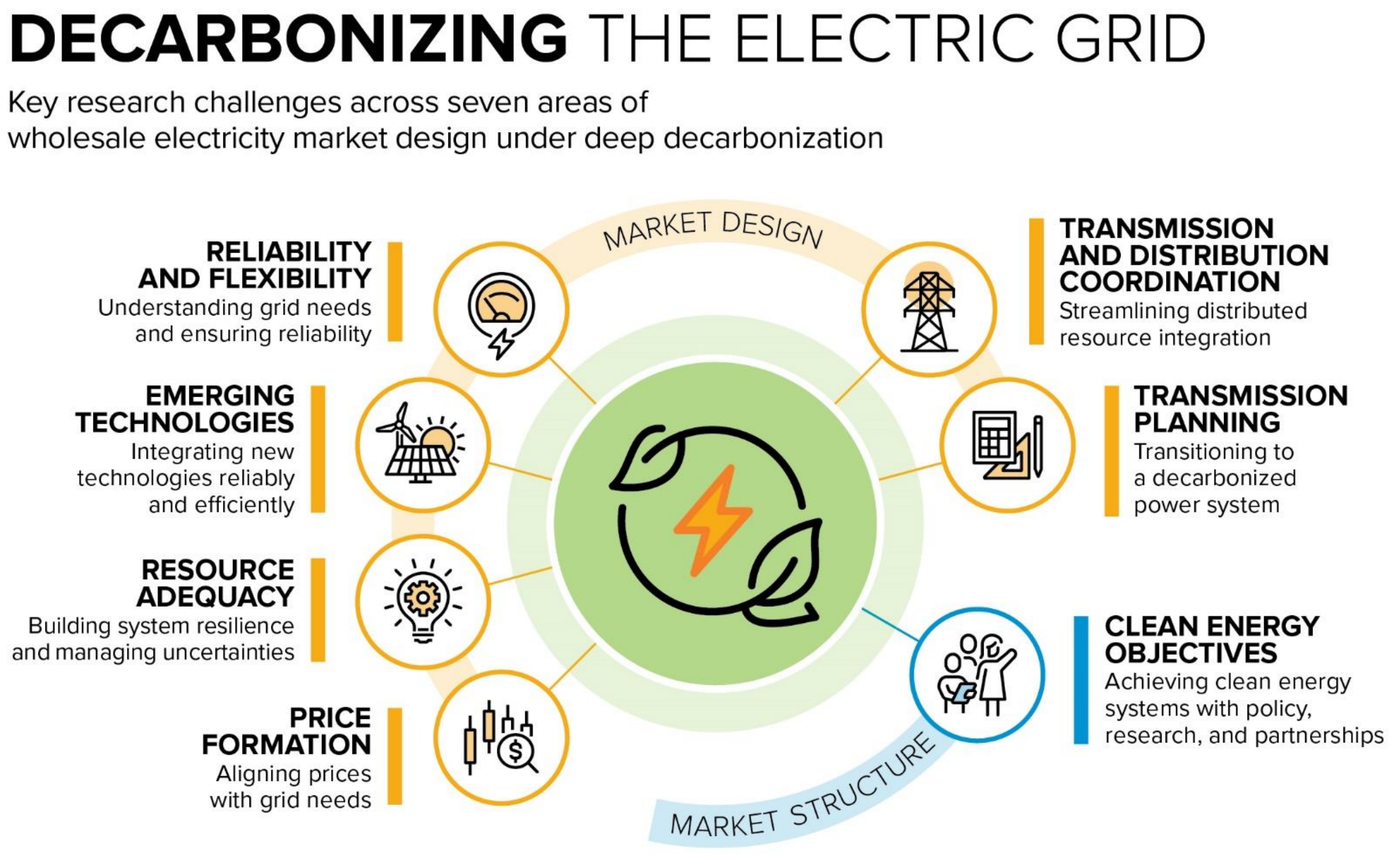

Figure 1. Key Research Challenges across Seven Areas of Wholesale Electricity Market Design under Deep Decarbonization

2 RESEARCH PRIORITIES

2.1 INCENTIVIZING RELIABILITY SERVICES AND OPERATIONAL FLEXIBILITY

Independent of decarbonization goals, short-term operations of a power system must ensure that demand and supply are always balanced, while maintaining power flows within physical limits and meeting reliability requirements. Wholesale market operators in the United States are critically important; to ensure bulk power systems operate reliably, they provide market signals that incentivize resources to provide energy, operating reserves, and other grid services when and where they are needed. Currently, centralized wholesale power markets in the United States conduct short-term operations through day-ahead and real-time (balancing) markets for energy and a suite of ancillary services. These market frameworks are generally successful at providing short-term operations and flexibility. However, the operational needs of the system are continuously evolving in response to technological changes, increasing reliance on variable generation and inverter-based resources, growth in energy storage resources, increasing participation from responsive customer demand, and increasing controllability of distributed resources. As a result, the market mechanisms that provide signals to procure existing and new grid services may need to evolve as well. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 1.

2.1.1 Changing Reliability Needs and Grid Requirements

A deeply decarbonized electricity system will have needs that are very similar to those of today's system, but the deeply decarbonized system may also have new reliability requirements and market products. Meeting changing reliability needs may require changes to market design, grid codes, standards, software, and operational strategies. New grid services may need to be established to provide system attributes that have traditionally been widely available (e.g., inertia). Definitions of existing grid services may need to be updated to better reflect system needs, or adapted to facilitate procurement through wholesale markets. New incentive mechanisms may also be needed to efficiently procure these services through wholesale and retail market structures.

2.1.2 Economic Procurement of Grid Services

System reliability can be maintained by acquiring services through competitive short-term auctions, interconnection requirements, centralized procurement through request for bids, or cost-of-service reimbursement. In the future, some services that are currently procured through cost-of-service mechanisms may be obtained more cost-effectively through spot markets or competitive long-term auctions, while the converse may hold true for other services currently obtained through competitive processes (O'Neill et al. 2008). For example, it remains to be seen whether technologies that are needed to support a potential transition from mostly synchronous generation to inverter-based resources will be incentivized through competitive auctions, grid codes, cost-of-service regulation, or other methods.

New market processes should also explicitly balance the value and cost of services to provide appropriate incentives, for instance through demand curves for operating reserves and system flexibility (Mehrtash et al. 2023). Another possibility that has been explored is transitioning away from a centralized unit-commitment process to something that aligns more closely with the resource mix change. Many features of current day-ahead electricity markets, including lead times, commitment constraints, and three-part offers with startup and no-load costs, were developed in response to the characteristics of traditional thermal generation technologies. In a future dominated by different resource types, it may no longer be important for market clearing processes to capture these costs and constraints. One option could be a transition to day-ahead markets with one-part offers, while providing market participants with more opportunities to adjust their positions—as is currently the case in many European markets. Another option may be a market clearing tool that focuses on storage operation, such as the security-constrained optimization process for storage resources.

2.1.3 Deliverability of Grid Services

New procedures may also be needed to ensure that grid services can be delivered when and where they are needed as the composition of the power system changes. Specifically, it will be important to account for a transmission system that is more heavily constrained through more diverse siting of resources across a network, especially when the transmission system is not able to keep up with new builds. In addition, changes in grid dynamics introduced by inverter-based resources and fuel delivery interdependencies (e.g., hydrogen) can affect locational needs across the network. The same challenges may arise on the distribution system, particularly when distributed energy resources (DERs) provide large amounts of energy and other grid services to the transmission system via wholesale market interactions. Market solutions may also be applied directly to distribution systems, using competition to motivate innovative approaches to provide grid services (Andrianesis et al. 2022).

2.1.4 Reliable Operations during Extreme Events

The changing climate will likely lead to increased periods of extreme weather, which will alter demand profiles and stress system infrastructure (IPCC 2021; Zobel et al. 2017). Market solutions may help efficiently prepare for and recover from those events. Customer-sited backup power sources and robust microgrids can support system reliability and resilience when events such as wildfires or hurricanes impact the bulk power system’s ability to deliver energy (Brown and Muehlenbachs 2023). Such resources could be integrated into market operations to ensure that these resources are used efficiently. However, regulators must also help to ensure that these types of options are available to all consumer classes, including vulnerable populations. Markets could also aim to support reliability under extreme weather conditions by explicitly incentivizing investment in long-duration energy storage (LDES) technologies and other resources with extended energy supply, as well as improvements to harden supply-side resources (for example, winterization). Finally, new grid models and data are needed to capture the impacts of future climate conditions and to better capture the links between power systems and other energy networks that may face highly disruptive common-mode failures during certain types of extreme weather events.

2.1.5 Increasing Demand Response Participation

Many studies show that large increases in responsive demand-side participation are essential to meet energy needs alongside a supply fleet dominated by VRE (O'Shaughnessy et al. 2022). Flexible demand can facilitate continual matching of supply and demand across time and space, and in some cases can also provide specific reliability services. Flexible demand participation can be further enhanced by better understanding how the value of lost load varies across customer classes and end uses. These preferences can then be used to enhance price signals to better reflect the marginal cost and value of energy at a specific time. To efficiently incentivize flexible demand through wholesale market mechanisms, it will be important to clearly define reliability needs, identify sources of operational flexibility, and improve representation of customer preferences and responses in market operations and planning procedures. It will be important for wholesale market operators, retail rate designers, and regulators of both systems to work together to understand what types of incentives are best signaled through retail rates and which are more important to provide through wholesale prices. This will require stronger coordination between wholesale and retail markets to ensure that services are not double counted in payments, as well as T&D system coordination (see Section 2.5).

Table 1. Market Challenges, Potential Solutions, and Research Needs Related to Incentivizing Reliability Services and Operational Flexibility

Challenge	General Solutions	Specific Research Areas
Satisfy evolving reliability needs and grid requirements	• Tailor grid services to ensure reliability in systems dominated by variable, inverter-based, and energy-constrained resources. • Incentivize provision of reliability services to align with actual T&D benefits and costs.	• Analyze system and market participant impacts of alternative grid service products under future grid conditions. • Adapt services to support evolving resource portfolios. • Ensure new products consider the welfare of both sellers and buyers and reflect equitable cost allocation methodologies and allocate costs equitably.
Procure reliability services efficiently	• Develop cost-effective solutions for providing reliability and flexibility services in future systems. • Provide needed services without duplicating efforts or introducing excessive or unnecessarily complex products. • Explicitly balance the cost and value of services to provide appropriate incentives.	• Assess whether existing products are better procured through competitive auctions or regulated cost of service. • Analyze services that are currently unpaid and assess whether payments will be required in future systems to guarantee their provision. • Understand the role of new grid services and whether components of those products can be integrated within wholesale electricity market designs. • Analyze the impacts of centralized vs. decentralized unit commitment decisions. • Develop improved optimization and simulation tools that account for the full range of costs and benefits of reliability services.
Ensure deliverability of reliability services	• Ensure new and existing ancillary services can be delivered cost-effectively through market mechanisms, while considering a constrained T&D network.	• Develop improved algorithms that account for reserve deliverability in scheduling, dispatch, and market clearing. • Consider economically efficient and reliable solutions of maintaining deliverability on the distribution system for DER-provided grid services.
Maintain reliable operations during extreme events	• Ensure cost-effective, equitable provision of electricity services under extreme weather events. • Support proactive and reactive decision making for operations during and after events driven by extreme weather and common-cause outages.	• Develop grid model inputs that link with weather data and climate projections to capture the potential impacts of extreme weather events. • Implement grid–climate linked models to identify energy services and corresponding resource needs under extreme operating conditions. • Identify flexible resource characteristics that can support emergency operations (e.g., black-start resources) and determine proper compensation. • Understand links with other energy networks to determine whether new products or methods are needed to ensure reliability during extreme events.
Facilitate increased demand response	• Reflect demand characteristics in market participation models for load. • Create incentives for demand participation through emergency response products, passive engagement, and active response through wholesale or retail incentives.	• Investigate market efficiency improvements from demand response under different market participation models and incentive schemes. • Assess past product designs for demand response to understand participation incentives and to learn from successes and failures. • Evaluate the role of retail rates in incentivizing customer demand response and assess the associated efficiency benefits and tradeoffs across wholesale and retail markets, and the elimination of double payments.

2.2 INTEGRATING NEW AND EMERGING TECHNOLOGIES INTO WHOLESALE MARKET OPERATIONS

Deep decarbonization of the electric sector will likely require the adoption of a host of emerging technologies that may interact with wholesale markets differently than traditional technologies. These technologies include alternative forms of renewable energy resources (e.g., geothermal, biomass, marine hydrokinetic), dispatchable low-emissions resources (e.g., carbon capture and storage, hydrogen, flexible and modular nuclear), new types of energy storage (e.g., new battery chemistries, LDES technologies), grid controls (flexible alternating current transmission system [FACTS] devices, other power flow control technologies, transmission switching optimization), electric vehicles and other mobile assets, DERs, and new types of flexible demand, among others. High penetrations of such emerging technologies will introduce new market challenges that must be overcome to ensure that future systems can be planned and operated both cost-effectively and reliably. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 2.

2.2.1 New Market Participation Models

Current market participation models may not always ensure that the full suite of costs and benefits of emerging technologies are reflected in operational decision-making and long-term planning. Therefore, research is needed to inform the development and implementation of new market participation models that are either tailored for specific technologies or sufficiently generalized to provide incentive compatibility for all technologies participating in the market. Market designs should ensure incentives that are compatible with efficient, reliable operations and a level playing field across all resources.

As an example, energy storage resources face opportunity costs during dispatch that are not present in traditional supply-side resources. Batteries are subject to substantial capacity degradation that depends on how the specific assets are operated. Energy storage resources require consideration of longer sequential time periods in order to accurately determine opportunity costs and operational dispatch strategies. Capturing these characteristics can drastically change storage operations, reduce costs, and improve reliability, but may require fundamental changes in participation models and analytical tools (Levin 2023).

2.2.2 Improved Technology Representation in Scheduling and Dispatch

New tools may also be needed to reflect the specific characteristics of emerging resources that influence market clearing outcomes. It is important to properly capture these characteristics in models, planning processes, operational practices, business practices, and market clearing software. For instance, energy storage technologies require algorithmic development and proper business rules to ensure that these resources are dispatched cost-effectively to support reliability objectives while also maintaining sufficient state-of-charge during all operating conditions. LDES technologies introduce additional complexity to scheduling and dispatch, which current day-ahead and real-time markets may not be able to capture. It is also challenging to minimize the possibility of infeasible dispatch outcomes for energy storage. Finally, storage operations in rolling horizon market processes risk inflicting financial losses when prices turn out differently than anticipated; on the other hand, providing insurance against such losses through bid-cost recovery methods may provide an implicit subsidy and advantages to storage that are unavailable to other resources that are not subject to energy limits. There is also limited experience around the new technical constraints and costs of other emerging technologies such as hydrogen or carbon capture, use, and storage.

2.2.3 Cross-Technology and Cross-Sectoral Coordination

New infrastructure and coordination mechanisms may be needed to support emerging technologies with cross-sectoral applications, such as across electricity, natural gas, water, heating, and transportation systems. For instance, if hydrogen becomes a more prominent as a fuel source, capturing the complex dynamics of the entire hydrogen fuel cycle becomes important—such as how hydrogen is produced (e.g., electrolysis with renewable electricity) and distributed, and what competition exists for its end use across other energy markets and sectors (e.g., heating and transportation). Capturing synergies between different energy sources, carriers, and infrastructure systems will become increasingly important under economy-wide decarbonization, as decarbonized economies will likely require a tighter coupling between energy sectors.

This trend is also challenging from a regulatory perspective; different entities are typically in charge of overseeing these complex energy infrastructure systems. There has been limited success over the past decade in coordinating gas supply management and power system operations because regulatory systems are fragmented (Ericson et al. 2019) and there is a lack of tools to manage multi-energy systems (Mancarella 2014). Both of these difficulties must be addressed in future research.

2.2.4 Adequate Mechanisms for Managing Investment Risk

A related challenge is the need for markets and institutions that allow for systematic comparison and consistent evaluation of investments in generation, transmission, storage resources, and demand management. Services provided by these different investment options can substitute for one another but are procured by very different regulatory and market processes (see Section 2.7). For instance, both grid reinforcements, such as substations or new lines, and energy storage can facilitate delivery of energy from remote VRE resources. However, centralized, cost-recovery-based transmission grid planning is inefficiently coordinated with market-based procurement of storage, and methods and market structures are needed to enable direct comparisons (Lau and Hobbs 2021). Emerging technologies may also increase the need to revisit a long-standing challenge in electricity markets: providing adequate contracts and mechanisms for investors to hedge their financial risks (see Section 2.3.1). Capacity expansion models can also be enhanced to capture heterogeneous investor and technology risks as well as long-run economic and policy uncertainties when they are applied to identifying optimal infrastructure investment pathways.

2.2.5 Market Power Monitoring and Mitigation

Some emerging technologies present new challenges for market power monitoring and mitigation. In particular, opportunity costs for batteries and other energy storage technologies, which determine their operational strategies, may be subjective and dependent on operator risk tolerance, making it more challenging to identify and mitigate instances when such resources exhibit noncompetitive behavior.

Overall, to ensure competitive outcomes, procedures and metrics will need to be revisited to address market power in future deeply decarbonized electricity markets. New market power metrics are also needed to better reflect the characteristics of emerging technologies. For example, such metrics should capture the impacts of resource opportunity costs, which are non-observable, and consider factors beyond direct variable costs when determining benchmarks for competitive bidding. To this end, improved and standardized methods will be required to determine opportunity costs for different technologies under varying and uncertain system conditions.

2.2.6 Equitable Technology Deployment

Finally, as recognition grows about the importance of developing and operating power systems in a manner that equitably allocates costs and benefits across market participants and consumers, it will be important to establish market rules, regulations, and policies that maintain reliability, reduce environmental impacts, and create economic opportunities for historically marginalized groups. Emerging technologies may be a key enabler to achieve this goal. For example, DERs such as rooftop solar or battery storage can improve localized reliability and provide direct economic benefits to communities where they are installed. They can also reduce reliance on emitting resources that may continue to disproportionately impact disadvantaged communities throughout the clean energy transition (Goforth and Nock 2022).

Therefore, research is needed to develop pricing schemes that account for localized environmental externalities, while also conducting targeted analyses to identify policy and regulatory mechanisms that can support efficient and equitable deployment of emerging technologies. Furthermore, planning models and procedures may need to be updated to ensure that they appropriately reflect emerging energy equity objectives Finally, new equity metrics are needed to rigorously assess how policies, regulations, and investments impact just energy outcomes for individual communities.

Table 2. Market Challenges, Potential Solutions, and Research Needs Related to Integrating New and Emerging Technologies into Wholesale Market Operations

Challenge	General Solutions	Specific Research Areas
Implement new market participation models	• Tailored market participation models for a wider range of specific technologies. • Generalized technology-neutral market participation models.	• Design incentive compatible market participation models for all technologies. • Develop simulation tools to analyze different participation models. • Analyze impacts of different participation models.
Improve technology representation in scheduling/dispatch	• Highly resolved technology representation in ISO/RTO tools. • Market participants are empowered to manage technology constraints efficiently.	• Develop computationally efficient tools to manage state-of-charge and capacity degradation in batteries. • Establish methods to avoid infeasible dispatch of energy storage and other technologies with inter-temporal constraints.
Enhance cross-technology and cross-sectoral coordination	• Simultaneous coordination and optimization across multiple technology classes. • Simultaneous coordination and optimization across multiple energy sectors.	• Develop new tools and methods that capture interactions and substitution effects between multiple technology classes (e.g., generation, transmission, storage, demand response). • Develop new tools to facilitate analysis and data exchange across interconnected energy sectors (e.g., electricity, gas, hydrogen, water, heating, transportation).
Manage and mitigate investment risk	• Improved liquidity in long-term energy markets. • New contract designs that account for characteristics and needs of emerging technologies.	• Develop new market products and contracts to help technologies hedge price and quantity risks, thereby lowering capital costs. • Improve consideration of technology risk in capacity expansion models.
Monitor and mitigate market power	• New market power metrics that consider characteristics of all technologies. • Opportunity cost is adequately accounted for in market power monitoring.	• Identify market power metrics that move beyond variable cost as a benchmark for competitive bidding. • Establish market power metrics that account for opportunity costs and the behavior of energy-limited resources. • Improve and standardize methods to determine opportunity costs under uncertainty.
Deploy technologies equitably	• Incentivize investments (technologies, locations) that improve reliability and reduce environmental exposure for marginalized groups.	• Develop locational pricing schemes that account for environmental externalities. • Identify regulatory mechanisms that enable technology deployment that is more equitable. • Enhance planning models to capture social objectives and develop new rigorous energy equity metrics to assess impacts.

2.3 RESOURCE ADEQUACY (RA) AND SYSTEM RESILIENCE

Ensuring adequate resources is a core objective of power system planning and operations. This includes RA, which ensures that the system maintains sufficient supply- and demand-side resources (DSRs), as well as resilience, which reflects the system's ability to withstand and recover from extreme events. RA and resilience traditionally have been considered separately; however, there is a growing need for RA assessments to consider additional stress cases and resilience events, namely increasingly frequent extreme weather events that affect power systems.

In competitive electricity markets, there is a critical link between RA and revenue sufficiency, the latter of which reflects the opportunity for needed reliability resources to recover both fixed and variable costs from revenue streams available in the market. Ideally, market designs provide efficient price signals across the full set of market products to enable revenue sufficiency for resources needed for RA, while those that are not needed receive appropriate market exit signals. In practice, different market areas have different market paradigms for RA, each with different degrees of linkages to revenue sufficiency. In energy-only markets (e.g., the Electric Reliability Council of Texas [ERCOT]), prices for energy and ancillary services are—in principle and with limited exceptions—entirely responsible for incentivizing the new resource investments that are needed to maintain RA. Alternatively, these operational prices can also be supplemented through mandatory centralized capacity markets (e.g., PJM Interconnection [PJM], New York Independent System Operator [NYISO], ISO New England [ISO-NE]), or other capacity remuneration mechanisms (e.g., Midcontinent Independent System Operator [MISO], Southwest Power Pool [SPP], California Independent System Operator [CAISO]).

New challenges related to revenue sufficiency and RA will likely arise in a deeply decarbonized future with extremely high penetration of zero-marginal cost, weather-driven, variable resources; energy-constrained resources; and fundamentally different load profiles. These emerging system attributes collectively increase the complexity and variability of the system for which RA must still be assessed and maintained. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 3.

2.3.1 Revenue Sufficiency and Risk Allocation

Enhanced, economically efficient market design and operational mechanisms may be needed to help ensure revenue sufficiency and RA in a deeply decarbonized future. Some examples of such potential market enhancements include long-term forward contracts for energy and and/or clean energy, capacity markets for clean energy, capacity requirements and improved credit quantification, new market mechanisms to support market participation of reliability-enabling emerging resources (e.g., price-responsive demand, DERs, and long-duration storage), and changes to ancillary service markets (e.g., overall design, price formation, and/or scarcity pricing mechanisms). A key challenge is determining which, if any, of these mechanisms are most efficient and effective under different system conditions.

Any of these market changes, if implemented, would directly affect many market participants, who may respond to market signals in a variety of different ways. The uncertainty surrounding future market design changes has important consequences for long-term investment decisions, which can directly impact RA. One important consideration is the potentially evolving allocation of risk between market participants under different RA mechanisms (see Section 2.2.4). Research is needed to assess the ability of different long-term bilateral contracting mechanisms and financial products to hedge evolving investment risks under various RA frameworks.

2.3.2 Supply-side Uncertainty and Variability

Many supply-side decarbonization options have a range of operational characteristics that impact RA in new ways, for example, weather driven variability, time-varying and unit-based forced outage rates, and fuel or energy system dependencies. These characteristics introduce supply-side uncertainty and variability, which makes assessing RA contributions challenging. Thus, a key challenge is ensuring that RA assessment tools can capture the implications of these new resource attributes and uncertainties. Models and tools will also need methods, data, and metrics that consider greater spatial and temporal resolution in order to assess RA in such systems. Specifically, it is crucial to develop new RA metrics and/or criteria that are not solely based on installed or unforced capacity or anticipated availability during periods of peak demand. Existing metrics that properly capture the critical dimensions of outage frequency, magnitude, duration, and timing should also be better incorporated into power system planning and resource assessment processes.

2.3.3 Demand-side Uncertainty

Demand-side uncertainty is similarly increasing, as load electrification will affect both the magnitude and shape of future demand profiles. However, certain responsive loads (including electric vehicle charging and residential batteries) can provide flexibility and support grid reliability. Therefore, improved data are needed to capture the uncertainty of DSRs with high temporal and spatial resolution. Such data needs include detailed load projections under electrification futures with various degrees of load flexibility, time-varying outage rates for generators and transmission, and more granular spatial representation of the transmission network. Enhanced computational methods may be required to ensure that models using these more granular data inputs are tractable.

2.3.4 Extreme Weather Events and Infrastructure Interdependencies

As discussed in Section 2.1.4, the frequency and severity of extreme weather events are expected to continue increasing under the impacts of climate change. These changes may result in periods of high electricity demand (heat waves), constrained fuel supply (cold events), or limited availability of renewable resources (IPCC 2021; Zobel et al. 2017). Extreme weather events can also introduce sustained common mode failures across generation resources and interconnected energy infrastructure (e.g., natural gas or hydrogen supply, transportation, heating). Enhanced methods may be needed to account for these events in RA assessments and mitigate their impacts in decarbonized futures, particularly those with significantly more weather-dependent resources. In particular, it is important to consider how the impact of a reliability event scales across time and space (e.g., widespread, sustained outages are typically more impactful than localized, short outages).

These metrics will require enhanced historical datasets that contain information on weather-dependent resource availability, as well as improved forecasts across multiple horizons. Metrics should also consider climate-change-adjusted impacts, the implications of low-probability high-impact extreme events, weather-correlated generator and transmission outage rates, and infrastructure interdependencies that may lead to common mode failures. Today’s power systems also have resources whose outage probabilities are correlated, strong intertemporal interconnections due to energy storage, large amounts of VRE resources, growing transmission congestion, and increasing demand response participation. Research is needed to develop new tools that capture these characteristics and correctly estimate the reliability of diverse resource portfolios.

Table 3. Market Challenges, Potential Solutions, and Research Needs Related to RA and System Resilience

Challenge	General Solutions	Specific Research Areas
Ensure revenue sufficiency and mitigate financial risk	• New market products and contract mechanisms that ensure revenue sufficiency for technologies needed for RA. • New market and contract mechanisms that minimize financial risk and ensure low cost of capital for investments in infrastructure assets needed for RA.	• Develop new or improved market designs to support resource adequate investments (and retirements) in VRE-dominated systems. • Develop effective RA mechanisms for a changing resource mix, considering both energy and capacity needs and the full set of available resources (i.e., emerging technologies, DSRs, supply-side resources). • Investigate the potential role of long-term contracts in achieving RA and revenue sufficiency. • Investigate how market design and contract mechanisms impact cost of capital, risk, and in turn investment and/or retirement decisions and RA.
Manage increasing supply-side uncertainty and variability	• Metrics and criteria capture impacts related to frequency, magnitude, duration, and timing of outages. • Metrics and criteria account for evolving resource mix, system impacts, and consumer preferences. • Improve data to capture uncertainty and variability with larger buildouts of weather-dependent resources.	• Define new metrics that capture the RA implications of variable and uncertain generation supply. • Establish new methods to use reliability metrics to inform RA planning. • Analyze the impact of new metrics and/or criteria on investment and retirement decisions. • Develop improved, multi-year, time-synchronous resource time series data including multiple forecast horizons and "actuals" to better represent uncertainties in operational timescale.
Manage increasing demand-side uncertainty	• Models/metrics account for future load uncertainty due to electrification. • Models and metrics account for demand-side flexibility and consider price responsiveness.	• Create forward-looking electrification-adjusted demand projections to serve as inputs for planning tools. • Capture anticipated changes in total demand, shifting temporal profiles, and the ability of flexible demand to support RA.
Capture impacts of increasing weather dependence and extreme events	• Models and metrics account for the reliability impacts of anticipated future weather conditions and extreme weather events. • Metrics capture weather-dependencies, correlated outages, and infrastructure interdependencies.	• Improve representation of low-probability, high-impact events in reliability assessment and capacity expansion tools to assess RA. • Create forward-looking datasets adjusted for climate change for input into planning tools. • Enhance models of unit-level thermal generator outages, considering temporal variations in outage rates. • Analyze the ways in which common mode failures across multiple infrastructures can affect the RA of electricity systems.

2.4 PRICE FORMATION

By design, short-term wholesale market outcomes provide economic signals that align incentives with resource availability to support system operational reliability. Short-term market prices are also important to inform long-term investment decisions. Price formation, the process by which prices are determined through a competitive market clearing process, has been a complex topic for electricity markets since their inception. For example, bids in United States markets include generation costs, unit commitment costs, and unit commitment constraints. These same markets produce prices that are based on the incremental energy bid and capped due to market power concerns. This combined approach to market participation and price formation supports operational efficiency across the regional markets, but has also led to several challenges including: (1) misaligned incentives, (2) weakened price signals during times of true scarcity, (3) the need for substantial uplift payments to ensure cost recovery, (4) a lack of co-optimization, and (5) a lack of transparency. At the same time, the provision of energy and other grid services is not always fully co-optimized. These shortcomings can lead to cost-recovery challenges and the need for separate side payments. These five price formation issues may become more complex when zero-fuel cost resources dominate a system and when additional characteristics of emerging technologies (e.g., state of charge [SOC] for energy storage) are considered in market clearing (Zhou et al. 2022). Several related challenges, potential solutions, and prospective research areas are outlined in Table 4.

2.4.1 Improved Scarcity Pricing

Scarcity pricing is crucial in forming short-term prices; however, representations of scarcity prices can be very coarse, often using a single price that does not vary over either time or geography. Because bid and price caps or market mechanisms may fail to trigger true scarcity pricing when loads are curtailed, the resulting price may be much less than the actual value of power to consumers during times of scarcity. As power systems approach higher penetrations of low-carbon resources with zero fuel cost, scarcity pricing may become increasingly important in dictating revenues for resources and driving investment and retirement decisions. Therefore, it will be important for administratively determined scarcity pricing mechanisms to accurately capture and convey the true cost of scarcity conditions through resulting market prices.

Because demand-side participation in wholesale markets remains relatively low, administrative demand curves for operating reserves are being implemented in most ISOs and RTOs, in part as a substitute for demand response (Mehrtash et al. 2023). As demand-side market participation becomes increasingly prominent, it is important to improve social science–based understandings of consumer choices. Ideally, this framework will also enable consumers to signal their own reliability preferences; however, it is important that the potential price formation and equity implications of such changes are well understood by market operators, regulators, and consumers alike.

2.4.2 Enhanced Market Mechanisms for Emerging Technologies

Current price formation mechanisms may be unsuitable for the needs of systems that increasingly rely upon emerging technologies such as wind, solar, storage, and demand response (see Section 2.2.1). For example, markets are often not cleared with sufficient temporal resolution to capture the complex operational dynamics and interactions of emerging technologies and market products.

In particular, there are a number of price formation challenges specific to energy storage resources. One specific consideration is that opportunity costs and anticipated degradation influence resource supply curves. However, in the case of opportunity costs, owners have extremely diverse price expectations that may be inconsistent with system conditions. Market clearing models run by operators can manage SOC efficiently by coordinating across resources, but real-time market processes with shortened time horizons can misvalue stored energy. Meanwhile, market software and participation models may either not consider or highly simplify degradation costs, not recognizing their complex dependence on depth and rate of discharge. In general, ISOs/RTOs may not adequately capture either category of costs for energy storage (McPherson et al. 2020; Sioshansi et al. 2022; Torbaghan et al. 2021).

Therefore, price formation mechanisms may need to evolve to better consider battery degradation and opportunity costs, while continuing to mitigate market power and ensure revenue sufficiency (see Section 2.2.5). Possible improvements include enhancing current price formation methods for ancillary services that are currently based primarily on lost opportunity costs. Specifically, it is important to understand how changes in ancillary service price formation will affect the value of these services under different future system conditions. Price guarantees for energy storage resources, and LDES in particular, may also be considered by regulators or market operators.

2.4.3 Uncertainty Representation in Price Formation

Work is needed to establish to what extent approaches that consider uncertainty can be implemented within market clearing algorithms. Stochastic models could be applied to understand how to revise existing market procedures to improve the efficiency of resource scheduling and dispatch under increasing uncertainty. Other changes in market structure may also be considered, such as increasing the frequency of market clearing intervals, adjusting current three-part bidding structures, or adjusting or eliminating the day-ahead market along with its unit commitment process. This is especially relevant for energy-constrained resources (e.g., energy storage and hybrid resources). For example, the existing two-settlement market clearing framework, comprising day-ahead and real-time markets, is primarily tailored to systems dominated by conventional thermal generation resources that have significant capacity constraints and considerations around the supply of fuel (e.g., natural gas). This design aims to mitigate uncertainties associated with load forecasting and system contingencies through forward-looking unit commitment. However, this approach may not fully capture the uncertainty, dynamic capabilities, and operational constraints of energy-constrained resources, which are characterized by their rapid response and flexibility. As a result, the system may not be able to capture the full flexibility of the resources in real-time operations.

2.4.4 Capturing Social Objectives in Prices

Government entities are implementing diverse policies and regulations to achieve their social objectives, such as reducing greenhouse gas emissions or increasing investments in clean technologies. Price-formation mechanisms must evolve to ensure that these social objectives are appropriately represented in price signals. However, because wholesale electricity markets often span multiple states or policy jurisdictions, market operators face the challenge of ensuring fair and just market conditions for participants operating under different policy paradigms (see Section 2.7.1).

Jurisdictional interactions, such as carbon boundary adjustments, are likely to become more pronounced as decarbonization targets become more ambitious. Furthermore, differing policies could lead to different short-term market outcomes, even with similar rates of investment (Levin et al. 2019). Interactions between environmental policy and electricity market design will pose a range of challenges for ISOs and RTOs. If mismanaged, the result may be reliability challenges and costs that are and higher than necessary, without significant environmental improvements (Xu and Hobbs 2021). Furthermore, if the cost of decarbonizing becomes higher than necessary, or system reliability degrades, the result may be slower progress and perhaps weakening of public support for decarbonization objectives.

Table 4. Market Challenges, Potential Solutions, and Research Needs Related to Energy Price Formation

Challenge	General Solutions	Specific Research Areas
Improve scarcity pricing	• Scarcity pricing that captures true costs of scarcity conditions. • Scarcity pricing mechanisms that are dynamic depending on time, location, and customer class. • Enable customers to signal their reliability preferences through market/contract mechanisms.	• Analyze how different scarcity pricing mechanisms affect system operations and price formation. • Analyze interplay between scarcity pricing and RA mechanisms. • Investigate the relationship between voluntary demand response and administrative scarcity pricing. • Assess the market power impacts of different scarcity pricing schemes.
Enhance market mechanisms for emerging technologies	• Markets that are cleared with sufficient time resolution to capture the full value of existing and new reliability services. • Include additional continuous stages in market clearing. • Adequately balance detail and transparency in offer formats. • Improve representation of energy storage cost and performance characteristics in market clearing.	• Analyze desirable time resolutions for market clearing of different energy and ancillary service products. • Assess the benefits of co-optimization and more frequent market clearing. • Investigate the market efficiency impacts of different offer formats. • Analyze the ability of different technologies to reflect the full range of costs/constraints, including non-convex costs and opportunity costs in markets. • Investigate cost-recovery challenges and the need for uplift payments under different market designs.
Improve uncertainty representation in price formation	• Capture the impacts of uncertainty in price formation.	• Develop market clearing, scheduling, and pricing schemes that better account for uncertainty to achieve system cost improvements while maintaining incentive compatibility for market participants. • Test alternative deterministic market clearing formulations (e.g., deploying dynamic operating reserves). • Investigate the benefits, costs, and feasibility of stochastic market formulations.
Reflect the value of clean energy and carbon emissions reductions in prices	• Capture the values of clean energy attributes and carbon externalities in price formation. • Market designs that accommodate state, local, and regional policies and remain incentive compatible.	• Investigate how different incentive schemes for clean energy and carbon emission reduction can affect price formation. • Analyze the ways in which clean energy incentives and carbon policy interact with the formation of electricity prices. • Assess issues presented by differing policies that are implemented across overlapping markets and jurisdictions.

2.5 TRANSMISSION AND DISTRIBUTION (T&D) SYSTEM COORDINATION

Bulk power systems were originally designed to serve inelastic and reasonably predictable demand by dispatching firm generation through a high-voltage transmission grid that served distribution system customers. This paradigm is being increasingly upended as VRE penetration increases at both the T&D levels.

The regulatory framework established by Federal Energy Regulatory Commission (FERC) Order 2222 is also leading to much more active participation of distribution system resources in wholesale electricity markets. The rapid anticipated future growth of DERs will require better coordination between T&D operations to manage two-way interactions between these systems. In Sections 2.5.1 through 2.5.5, we consider DSRs to be a subset of DERs and highlight key issues that are specific to DSRs. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 5.

2.5.1 Coordinated T&D Planning

Coordinating T&D infrastructure operations and planning will be critical to unlocking the bulk power system benefits of resources that are near consumers, for example accessing the full range of system flexibility provided by DERs. Improved T&D coordination is also needed to overcome challenges such as misaligned price signals, operational infeasibilities, and a lack of representation of network bottlenecks across the T&D interface.

To this end, research is needed to identify current and potential future regulatory and technological barriers that might prevent ISOs and RTOs from coordinating their transmission planning decisions with distribution systems in their jurisdictions. This research must also define the data requirements necessary to improve T&D coordination. New models and algorithms must be developed to manage uncertainty from variable resources in coordinated T&D planning. These tools will need to be flexible enough to be adapted to the different circumstances of various ISO and RTO regions.

2.5.2 Improved Market Participation Models for DERs and DSRs

Recent rapid growth in DERs is leading to a paradigm shift in power systems, in which an increasing portion of energy production occurs on the distribution grid. This introduces a fundamental challenge to improve and extend market participation models that were historically designed for a small number of large power plants. Such models must instead encompass millions of small-scale assets, including load modifying technologies such as virtual power plants that are owned and managed by numerous entities and spread across T&D systems. Specific to DSRs, system operators currently lack insight into the willingness of customers to reduce or defer their consumption as well as the differentiated value that they place on reliability. This challenges traditional market-based frameworks, which may be replaced or supplemented by a decentralized, bilateral decision-making paradigm to incentivize DER investments and operations.

Specifically, research is needed to evaluate the cost-benefit tradeoffs between two primary paradigms: (1) centralized dispatch optimization conducted by an ISO or RTO, or (2) local optimization conducted by a distribution system operator (DSO) and assess the circumstances under which each can optimally facilitate active participation of DERs in wholesale markets while leveraging the flexibility of distribution systems. A comprehensive evaluation of alternative DER scheduling policies, structures, and technologies should also be performed.

2.5.3 Communications, Controls, and Dispatch Software

Widespread adoption of DER has tremendous potential to provide economic and reliability benefits to power systems—for instance, by flattening load profiles, reducing losses, decreasing distribution investments, and providing supply and storage services when and where needed by the grid. However, market scheduling software, metering practices, communications, and control technologies, as well as retail and grid access pricing structures, must evolve to provide sufficient means and incentives to realize those benefits.

From an operational perspective, new enabling technologies and communications and data management protocols are needed to support DER aggregation. DER management systems must also be developed to enable hierarchical control strategies for aggregated DER resources that provide multiple services.

2.5.4 Policy and Regulatory Structures for DER Integration

To enable the goals of FERC Order 2222, more work is needed to identify optimal regulatory and technological approaches to large-scale DER integration. Specifically, research must identify which, if any, new market products will be necessary to facilitate T&D coordination in futures with significant DER participation in wholesale electricity markets. To this end, it will also be critical to develop concepts and methodologies to compute locational marginal prices for distribution grids (Andrianesis et al. 2022) and define best practices for DER aggregation. Efforts are also needed to help streamline policy structures for DERs across multiple jurisdictions and help ISOs and RTOs develop and implement optimal pathways to satisfy evolving regulatory requirements.

2.5.5 Capturing Reliability Contributions from the Distribution System

Processes and mechanisms must be developed and implemented to assess the collective reliability of T&D systems while considering both the uncertainty and reliability contributions of DERs. New methods are also needed to coordinate TSO and DSO responses during emergencies. In particular, it is important to improve methods for determining the RA contributions of DERs that exhibit supply-side variability and uncertainty (see Section 2.3.2).

Table 5. Market Challenges, Potential Solutions, and Research Needs Related to T&D System Coordination

Challenge	General Solutions	Specific Research Areas
Improve coordination in T&D planning	• Establish priorities and timelines for coordinated and cooperative T&D planning that are well-defined. • Improved computational solutions to support coordinated and cooperative T&D planning.	• Identify the main regulatory and technological barriers that prevent ISOs/RTOs from coordinating T&D planning decisions. • Define data requirements for exchange of information between T&D. • Develop models and algorithms that consider renewable uncertainty while optimizing coordinated T&D planning decisions.
Streamline market participation models for DERs and DSRs	• Participation models that allow DERs to provide grid services. • DER dispatch preferences that are integrated into wholesale market clearing. • New wholesale market products that capture the value of DERs. • Market participation models that accommodate price/reliability preferences of customers.	• Determine which new products (e.g., reactive power, voltage support) will be necessary to facilitate wholesale market participation of DERs. • Analyze the extent to which DERs can provide current market products. • Identify and define best practices for aggregation of DERs. • Develop methods to compute locational marginal prices for distribution grids. • Analyze cost-benefit tradeoffs of different market structures, considering central optimization by the ISO or local optimization by the DSO or any potential structure in between. • Investigate the value of reliability and lost load for different consumer classes.
Enhance communications, controls, and dispatch software	• Improve management and communication architecture.	• Develop communication and data management protocols for information exchange between T&D entities. • Improve DER management systems to allow hierarchical control strategies for aggregated DER resources that provide multiple services. • Enhance processes to coordinate TSO-DSO interactions during emergency response, including granular load curtailment strategies.
Implement policy and regulatory structures for DER integration	• Policies and market structures that support distribution system flexibility. • Guarantee deliverability of services provided by DERs.	• Create test cases to evaluate the impacts of different policies, structures, and distribution technologies on system flexibility. • Gather and analyze data on existing wholesale market participation of DERs. • Evaluate the effectiveness of different policy and regulatory mechanisms at promoting DER adoption and market participation.
Capture reliability contributions from the distribution system	• Appropriately represent DERs in long-term reliability studies of the bulk power system.	• Assess the historical reliability contributions of DERs. • Develop optimization and simulation methods that consider DER contributions to T&D system reliability. • Develop improved methods to assess the reliability contributions of DERs.

2.6 TRANSMISSION PLANNING

The transition to a decarbonized power system presents new challenges, needs, and opportunities for transmission systems. This is especially true because most ISOs and RTOs still rely on traditional transmission expansion planning (TEP) methods that do not adequately consider some factors that drive new transmission expansion, such as the need for new transmission infrastructure to support deep decarbonization objectives (Lau and Hobbs 2021). New transmission infrastructure may be necessary to connect generation resources that are distant from loads, and thereby capture benefits from geographic resource diversity (i.e., reducing system-wide uncertainty and volatility in VRE availability). Under traditional planning paradigms, these transmission needs have not been as significant as they will be in the future, because large thermal units were often connected directly to the grid with the expectation that their generation would largely be consumed by local loads. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 6.

2.6.1 Multi-regional Coordination

Within each of the three large interconnections in the United States, there are multiple independent regional entities, each of which engages in its own TEP processes. This can diminish incentives for beneficial grid investments or lead to duplicative, unnecessary investments. These issues become more critical in the context of deep decarbonization targets that require significant investment to both develop new transmission lines that span two or more regions, and reinforce existing ones. It is therefore important to improve intraregional coordination of TEPs across these entities. However, individual regions maintain separate rules and planning procedures, which introduces a host of cost allocation challenges; FERC Order 1000 acknowledged these challenges, but it has not resolved them. New algorithms and methodologies may need to be developed and implemented to establish system optimal solutions while respecting the information privacy of individual planners (Mehrtash et al. 2019).

2.6.2 Coordination with Generation Expansion Planning (GEP)

In most power systems, GEP and TEP are generally conducted independently or iteratively. However, in a deeply decarbonized future, ISOs and RTOs will need to improve coordination and integration between TEP and GEP, while also considering projected investments that are external to their system (Krishnan et al. 2016).

There are several ways to improve coordination between ISOs or RTOs and generation companies (Lau and Hobbs 2021): TEP/GEP co-optimization models, bi-level proactive transmission planning models that anticipate energy market reactions, and two-stage stochastic TEP models in which future installations are treated as an uncertain parameter modeled from datasets of generation interconnection queues. However, while the theory behind these methods has been established, more work is needed to improve their computational efficiency, demonstrate their practical utility, and translate them into practice.

2.6.3 Interconnection Reform

The current interconnection request process in the United States has led to backlogs in VRE development. At the end of 2022, over 2,000 GW of generation and storage resources were seeking connection to the grid (over 90% of which is for zero-carbon resources like solar, wind, and battery storage). This number will likely continue to grow (Rand et al. 2023). One problem is that resource developers often submit multiple interconnection requests to reserve a queue position—irrespective of a commitment to eventually build the resource—which leads to artificial congestion in the interconnection queue.

Interconnection processes should be reformed to expedite the interconnection of economically viable wind, solar, and battery storage capacity into the transmission system. One potential solution is to implement a first-ready, first-served cluster study process instead of a serial first-come, first-served process (Boemer et al. 2022). Other options, such as connect-and-manage, which involves quickly connecting new generation resources and then relying on congestion management to maintain reliability, or other new interconnection paradigms may be necessary as the amount of new generation proposed continues to increase.

Project-by-project screening of candidate transmission expansion projects should also eventually be replaced by optimization-based TEP methods that consider multiple candidate options (e.g., volt-ampere reactive [VAr] compensators, high-voltage direct current [HVDC], and non-wires alternatives [NWAs]) simultaneously. Work is needed to evaluate the relative advantages and challenges associated with implementing each of these approaches.

2.6.4 Robust and Equitable Cost Allocation

Work is also needed to develop and implement new cost-allocation measures that support beneficial investments and allocate costs to market participants in a manner commensurate with the benefits market participants receive. Specifically, new methods are needed to co-optimize energy and reserves in both short-term operations and long-term planning with high spatial resolution. At the same time, these methods should consider uncertainties, and thereby inform fair allocation of new transmission costs across multiple beneficiaries.

2.6.5 Consideration of HVAC, HVDC, and Non-wires Alternatives (NWAs)

HVDC transmission lines may provide an economic option for moving large quantities of energy over long distances, but current TEP models do not properly account for the benefits of high-voltage alternating current (HVAC) and HVDC candidates. Other emerging technologies such as NWAs can defer investments in new transmission lines, but it is challenging to quantify the contributions of these technologies and allocate their costs accordingly. The same challenges are present for other supporting technologies that can reduce the need for new transmission lines or upgrades, such as power flow controls, dynamically rated lines, FACTS devices, advanced conductors, and superconductors.

Current TEP methods largely overlook considerations related to reactive power and voltage stability. FACTS devices, such as phase-shifting transformers or reactive power compensators (VAr compensators), can be deployed to alleviate congestion at a lower cost than installing new transmission lines (Lumbreras and Ramos 2016). More research is needed to ensure that the reactive power benefits of FACTS and other flow controls are captured in TEP processes.

2.6.6 Transmission Siting

Co-optimization frameworks should also ensure that the benefits of siting new resources, including DERs and energy storage, are captured in TEP processes. Specifically, TEP models should be extended to explicitly determine whether NWAs can effectively defer investments in new transmission lines. Furthermore, dynamic line rating technologies can be implemented in congested locations to expand line capacities when weather conditions permit. To implement these technologies, sensors will need to be installed near existing transmission assets to collect conductor temperatures in real time. Traditional TEP models and procedures should also be extended to consider both AC and HVDC candidate lines. Current transmission siting processes may not properly account for the benefits of developing infrastructure, such as existing rail lines, where rights-of-way already exist.

Table 6. Market Challenges, Potential Solutions, and Research Needs Related to Transmission Planning

Challenge	General Solutions	Specific Research Areas
Improve multi-regional coordination	• Collaborative TEP algorithms that can identify interconnections that are beneficial to all participating systems. • Improve coordination in national transmission planning studies.	• Develop TEP software that can efficiently identify multiple candidate solutions for participating systems to consider. • Ensure that TEP methods are scalable to very large systems and capture the full range of potential future operating conditions and decarbonization scenarios.
Enhance coordination between TEP and GEP	• Stochastic TEP models that consider uncertain resource capacities. • Coordinate TEP procedures with capacity market design.	• Develop new algorithms that proactively plan transmission, considering the benefits of improved resource investment as well as operations. • Analyze future deep decarbonization scenarios that require rapid transmission expansion to facilitate the integration of renewables.
Reform interconnection processes	• Streamline interconnection request processes. • Capture system-wide cost and reliability implications of individual interconnection decisions.	• Analyze the impacts of an interconnection process reform in which ISOs/RTOs will perform a first-ready, first-served cluster study process. • Develop new interconnection processes to assess the performance and verify the conformity of transmission service provider before and after commissioning to ensure plants operate continuously and reliably.
Ensure robust and equitable cost allocation	• Cost-allocation that promotes cooperation. • Cost-allocation processes that consider all technical contributions, economic benefits, and environmental impacts of transmission reinforcements.	• Establish standardized methods to quantify the benefit of one or more new transmission lines by co-optimizing the provision of energy and reserves with and without the lines. • Develop a wide range of operational scenarios to robustly quantify the benefit of adding new transmission lines.
Improve consideration of HVAC, HVDC, and NWA	• Extend TEP models to consider HVDC, HVAC, and NWA options. • Alternative financing and participation models that reflect the full value of NWAs.	• Evaluate the costs and benefits of a U.S. macro-grid with HVAC and/or HVDC. • Develop software for specific HVDC applications, such as offshore wind transmission studies. • Investigate the tradeoffs between required transmission expansions and NWAs for deep decarbonization. • Analyze the technical advantages of alternatives to new line construction (e.g., FACTS and VAr compensators) in post-processing analysis.
Overcome barriers to transmission siting	• Use existing transmission corridors and other infrastructure (e.g., rail lines) to overcome barriers to implementing new transmission infrastructure.	• Analyze the costs and benefits of TEP that prioritizes upgrades to existing lines over the construction of new lines. • Analyze the relative costs and benefits of a TEP that sites new transmission lines where rights-of-way already exist.

2.7 ACHIEVING CLEAN ENERGY OBJECTIVES

Investments in next-generation clean energy are increasingly being driven by state clean energy policies and the private consumer demand for clean energy. One challenge of the clean energy transition will be interactions between electricity market outcomes and state-driven public policies. State public policies can affect wholesale market price signals by accelerating the retirement of existing emitting resources, or they can result in increasing investment in non-emitting generation resources. While state regulators view these actions as necessary to meet state policy, subsidized new entry can make investment more difficult for non-subsidized resources. Steps must be taken to ensure that wholesale market price signals are harmonized with policy mandates and social objectives, particularly given the jurisdictional divide between federal and state policymakers. Sections 2.1 through 2.6 primarily focus on market design, and the challenges and priorities in Sections 2.7.1 through 2.7.4 are primarily related to market structure. Several specific challenges, potential solutions, and prospective research areas are outlined in Table 7.

2.7.1 Split Jurisdiction between State and Federal Policies

The split jurisdiction between federal and state regulators creates major challenges for future market design. State regulators generally have jurisdiction over the selection of generation resources, while federal regulators have jurisdiction over wholesale energy markets (*FERC v. Electric Power Supply Association* 2016). FERC and each regional market will need to establish optimal approaches to manage these regulatory interactions while maintaining system reliability. These tensions threaten to become more pronounced as some states trend toward 100% renewable portfolio standards, implement clean energy requirements, or mandate the retirement of emitting resources.

In addition, state and regional policy and regulations—both implemented and proposed—to support power sector decarbonization can differ significantly from jurisdiction to jurisdiction. Analysis is needed to evaluate the diverse federal, state, and local policy landscape for economic efficiency, reliability impacts, cost allocation implications, vulnerability to carbon leakage, social impacts, and biases for or against particular technologies.

2.7.2 Emerging Clean Energy Market Mechanisms

Investments in new resources may increasingly be driven by policies and incentives rather than market signals. This has important implications for future market designs and raises the central question of whether markets should be restructured to help achieve clean energy objectives or whether electricity markets should remain technology and outcome agnostic (Silverman et al. 2021).

One possible approach is for deep decarbonization objectives to be facilitated by centralized clearing and contracting of new clean energy resources. Load-serving entities (LSEs) and other voluntary buyers (e.g., municipalities, corporations) could be given the option to contract for renewable energy credits through a centrally cleared, multi-year forward market structure (Schatzki et al. 2022).

LSEs may also wish to purchase a co-optimized mix of clean energy attributes and RA products through emerging market structures in order to establish a low-cost, reliable resource mix that meets their social objectives. Examples include the forward clean energy market (FCEM) or integrated clean capacity market (ICCM) frameworks currently being considered in PJM and ISO-NE. Research is needed to understand the extent to which these approaches may reduce the transaction costs of bilateral contracts, facilitate financing of clean energy infrastructure, enable smaller voluntary buyers to procure clean energy, and support system reliability.

Another potential approach is for a state or region to adopt a clean capacity constraint. The clean capacity constraint would allow a state or other regulator to mandate that a percentage of the region’s RA needs must be served by clean resources. Such an approach allows for distinct prices for conventional capacity and capacity from non-emitting resources. The grid operator would then procure the mandated amount of non-emitting resources as part of its least-cost, reliable, system mix.

2.7.3 Objective Compatible Policies and Regulations

Additional challenges are introduced when policies do not perfectly align with social objectives. For example, a jurisdiction may elect to provide incentives for specific generation technologies as opposed to using market-based mechanisms to reward generators that result in decreased emissions. As additional forms of net-zero generation become technically feasible (including new nuclear, carbon capture, storage, biogas, net-zero hydrogen, virtual power plants, etc.), it may be advisable to switch the traditional renewable energy certificate (REC) to a clean electricity attribute certificate (CEAC). The CEAC better reflects the federal goal to decarbonize the electricity sector by 2035 and allows for a broader market response to zero-carbon mandates than promoting investment in specific zero-carbon technologies.

Another active area of research is to consider whether REC markets should better account for variability in the carbon intensity of the grid when clean energy is produced. Current renewable energy credit programs typically provide for a static value for all RECs, regardless of when those RECs were produced or the location of production (within any mandated geographic footprint for eligibility). Imposing carbon-indexing could result in clean energy producers receiving enhanced payments for production that occurs during times of high marginal carbon emissions on the grid and lower levels of compensation during times of low marginal carbon emissions.

2.7.4 Maintaining RA and Operational Reliability

Many state-based REC programs incentivize production of electricity, without accounting for when or where the electricity is being produced. New approaches may therefore be needed to ensure that operational reliability (see Section 2.1) and RA (see Section 2.3) are maintained when significant clean energy incentives are present. Specific classes of clean technologies, such as dispatchable emission-free resources (DEFRs), may provide reliability benefits during multi-day or seasonal shortfalls of weather-dependent generation. Many DEFRs have either high capital costs and low marginal costs (e.g., small modular nuclear reactors) or low capital costs and high marginal costs (e.g., combustion turbines with green hydrogen). The differing economics across these classes of technologies will impact their interactions in competitive markets and may make it challenging for owners and operators to assess market entry opportunities, thereby introducing investment risks. This issue is particularly pressing as certain states implement restrictive policies around dispatch of fossil fuel generation, where forward reliability considerations will require RA mechanisms to explicitly recognize state environmental and clean energy policies. Research is needed to understand how centralized markets can evolve to accommodate these technologies and policies to ensure least-cost, reliable outcomes that respect both mandated and voluntary demand for clean energy.

Table 7. Market Challenges, Potential Solutions, and Research Needs Related to Achieving Clean Energy Objectives

Challenge	General Solutions	Specific Research Areas
Resolve split jurisdiction between state and federal policies	• State and federal policy makers need to collectively drive investment in resources sufficient to meet clean energy objectives.	• Investigate how to structure future markets to cost-effectively and reliably integrate resources that are supported by policy. • Identify market structures that result in lower total costs of achieving clean energy targets within organized markets. • Explore mechanisms for transitioning existing markets to an FCEM, ICCM or comparable structure.
Improve coordination across policies	• Ensure optimal price and environmental outcomes even as clean energy investments are driven by voluntary purchases. • Improve coordination between clean energy incentive programs and carbon abatement objectives.	• Explore implications of switching from renewable energy credits to clean energy attribute credits, which can be produced from any net-zero generation resource. • Develop standards for incorporating relative carbon abatement value into renewable energy credit markets. • Examine whether markets can better account for localized co-benefits associated with carbon abatement policies, with a particular focus on environmental outcomes in marginalized communities.
Implement objective compatible policies and regulations	• Explore policy mechanisms that incent net-zero carbon emission generation rather than technology-specific requirements.	• Explore allowing LSEs to signal their willingness to pay for clean energy or clean capacity that may result in more efficient procurement and dispatch. • Determine who will contract with or otherwise procure clean firm resources (beyond voluntary measures), necessary to meet reliability targets and how LSEs will be assigned those obligations.
Maintain RA and operational reliability	• Ensure that clean energy incentive contracts are structured to reward projects with high reliability value.	• Compare cost and reliability profile of meeting clean energy demand in a centralized versus bilateral market structure. • Evaluate whether markets can be co-optimized to allow LSEs to meet reliability and clean energy targets at a lower cost than procuring products separately.

3 CONCLUSIONS AND PATH FORWARD

This report highlights a non-exhaustive list of challenges that may emerge in competitive wholesale electricity markets as power systems become increasingly decarbonized. Many of these challenges are already being experienced to some degree in current markets and may become more pronounced in the future. Others may not materialize to a significant extent until deeper decarbonization levels have been achieved. Still others may prove to never seriously disrupt the status quo, depending on which technologies and policies are used to achieve decarbonization.

We have organized our discussion across seven primary topic areas. This follows the convention used in a previously published companion report that broadly reviewed competitive market challenges across six topic areas within a shorter time horizon and without specific consideration of decarbonization (Sun et al. 2021). Here, we focus on challenges and research opportunities associated with future decarbonized power systems within these same six topics, while also adding an additional seventh topic to address issues related to cost-effectively achieving clean energy objectives through market frameworks. These categories are not mutually exclusive and many of the challenges, solutions, and associated research needs that were discussed could easily fit into two or more of these sections.

Importantly, there will not be one single optimal approach to collectively address the challenges discussed above. Rather, the best path forward will depend on market objectives, social objectives, available energy resources, and interactions with policies that have been or will be implemented to support the clean energy transition. Hence, regional solutions are likely to emerge in response to the electricity market challenges that follows from power system decarbonization. Furthermore, it will be important to revisit many of these challenges and proposed solutions as power systems and electricity markets continue to evolve, and as industry, researchers, regulators, and policymakers gain new insights along the way.

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Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Lemont, IL 60439-4854

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