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Electricity Sector Policy Reforms to Support Efficient Decarbonization

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ABSTRACT

The final version of this paper will appear as Chapter 8 in the forthcoming MIT Energy Initiative study, The Future of Storage. *Chapters referred to in this paper will be included in that study when it is published.* In future decarbonized electric power systems, wind and solar generation will be much more important than in current systems. Unlike thermal generators, the outputs of wind and solar generators are intermittent: they vary over time and are imperfectly predictable. Storage technologies, if efficiently deployed and utilized, can play an important role in maintaining system reliability and controlling system costs in the face of generation intermittency. This paper considers how alternative regulatory rules and policy regimes will affect the ability of storage to contribute to reliable, cost-effective, and equitable power system and economy-wide decarbonization. The focus is mainly on the United States, though the general issues discussed are relevant in other developed regions. The basic conclusion is that future decarbonized power systems will differ from current systems in fundamental ways that will render today's governance arrangements increasingly inadequate. We recommend a number of steps that should be taken now by regulators and others to deal with this challenge. Because effective governance of future decarbonized power systems will require development and deployment of new tools as well as reform of rules and regulations, research has an important role to play.

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8.1 Introduction

The overall goal of this study is to address the roles of energy storage in reducing the total cost of future deeply decarbonized electric power systems.[1] This chapter considers how alternative regulatory rules and policy regimes will affect the ability of storage to contribute to cost-effective and equitable power system and economy-wide decarbonization. We focus primarily on the United States, though the general issues we discuss are relevant in other developed regions. Our basic conclusion is that future decarbonized power systems will differ from current systems in important ways that will render today's governance arrangements increasingly inadequate. We recommend a number of steps that should be taken now by regulators and others to deal with this challenge. Because effective governance of future decarbonized power systems will require development and deployment of new tools as well as reform of rules and regulations, research has an important role to play.

In future decarbonized power systems, wind and solar generation will be much more important than today. For example, in a recent study of global decarbonization pathways, the International Energy Agency (IEA) projects that wind and solar generation will account for almost 70% of global electricity generation by 2050, up from 9% in 2020 (IEA 2021, Table 3.2). Wind and solar generators, often collectively labeled VRE (variable renewable energy), are intermittent: their output is both variable and imperfectly predictable because it is primarily determined by variations in wind and solar resource availability rather than by system operators' decisions to balance supply and demand by moving up and down a reasonably stable bid-based or marginal-cost-based economic dispatch curve as demand varies (the way system operators now manage output from mostly fossil-fuel generation resources). (See Figure 8.1, below.) In contrast, in a system with high VRE penetration, supply will vary widely and possibly quite suddenly over time due to exogenous changes in wind conditions and solar irradiation. As a consequence, future systems will need to cope with unprecedented supply fluctuations to balance supply and demand reliably. Existing systems are used to coping with weather-induced demand fluctuations; in the future, weather-induced fluctuations will affect both supply and demand; those effects will

[1] Total cost includes investment and operating cost as well as the cost of any involuntary blackouts or load shedding, conditional on satisfying carbon emissions constraints.

generally be correlated; and these correlations will also vary with weather conditions. For example, very hot days may be associated with both increased demand for air conditioning and reduced output from wind generators. On days when there is heavy cloud cover over a large region, the output from all solar generators on the system will be reduced, creating a high correlation between all solar generators on the system; a correlation between generators that is largely absent in conventional thermal systems. Energy storage will play an important role in balancing supply and demand reliably in systems with high VRE penetration by filling the gaps between exogenous variations in VRE supply and demand.

Economy-wide electrification of various end-uses, a core element of most economy-wide decarbonization scenarios, may worsen this problem. Some uses of electricity, for example to charge electric vehicles (EVs) or produce hydrogen via electrolysis, could potentially help balance supply and demand by reducing operations in response to decreases in electricity supply. Others, such as increased electrification of space heating, could result in new peak loads that may be correlated with weather variations that reduce VRE generation at the same time,[2] making it more difficult to balance supply and demand.

Because of the key role storage can play in balancing supply and demand and thus maintaining reliability in systems with high VRE penetration, and because of substantial projected declines in the costs of storage technologies, storage should be much more important in future decarbonized power systems and play a larger variety of roles than it does today. The methods used by today's system operators and the associated regulatory rules and policy regimes that constrain them were developed for power systems that relied primarily on dispatchable generators and in which storage was of negligible importance. As we discuss in this chapter, investing in and operating storage so that it effectively plays appropriate roles in future decarbonized power systems will pose novel operational and financing challenges. It will also pose challenges in terms of regulation and market design—the focus of this chapter.

[2] The Texas power crisis of February 2021 dramatically illustrated this possibility. Weber (2021) provides a brief discussion.

In today's competitive electricity markets, wholesale prices reflect generators' marginal costs of producing electricity at each potential level of demand. When demand is low, the system's marginal cost is relatively low, reflecting the marginal cost of the lowest-cost generator. When demand is very high, the marginal cost of the highest-cost generation needed to balance supply and demand can be very high. In short, the economic dispatch curve is upward sloping and reasonably stable, as illustrated in Figure 8.1. The challenge for the system operator is to adjust dispatchable generator output along the economic dispatch curve as demand varies from hour to hour, day to day, season to season, etc. There is no storage in the classical economic dispatch model for systems with dispatchable thermal generators.

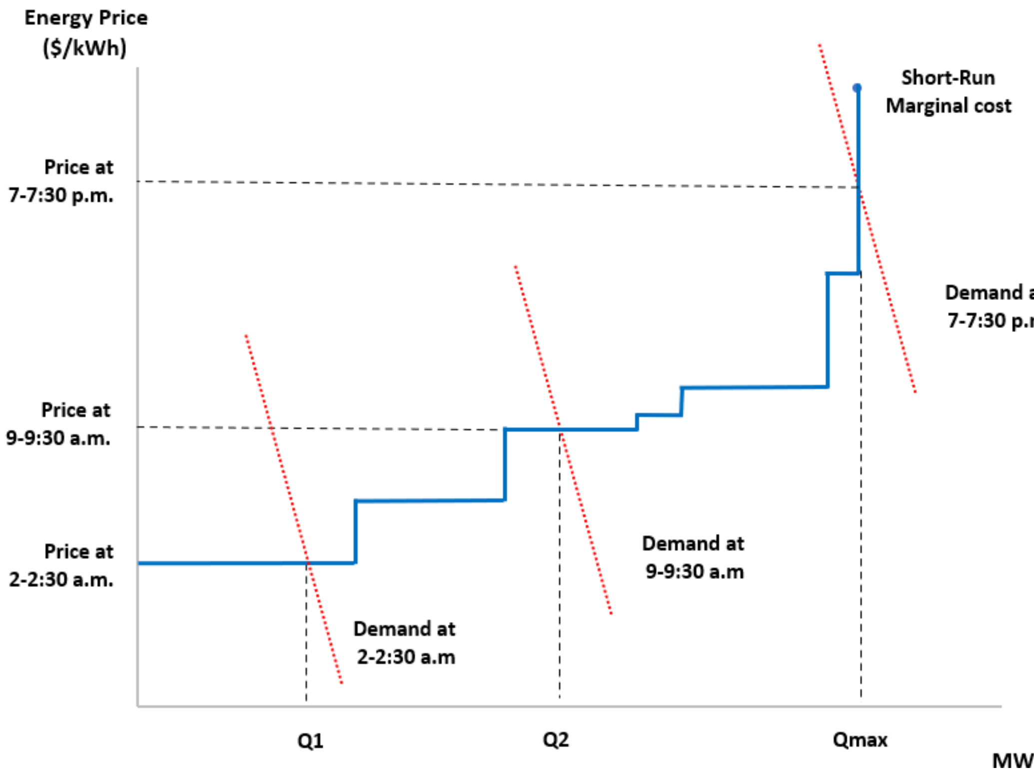

Figure 8.1: A contemporary electricity market in the short run.

In contrast to the system depicted in Figure 8.1, which is built upon dispatchable generators with stable marginal costs (reflecting different thermal efficiencies and fuel costs), the supply of VRE generation varies up and down based on sometimes wide and rapid exogenous changes in wind and solar conditions. Thus, there is no simple equivalent of the economic dispatch curve depicted in Figure 8.1. Moreover, the short-run marginal costs of wind and solar generation are always close to zero. Markets dominated by such generators present market design challenges: how to deliver wholesale and retail price signals that reflect the marginal cost of production while still yielding expected revenues that cover both investment and operating costs.[3] Moreover, as discussed in Chapters 1 and 6, many storage technologies also have near-zero marginal operating costs and lose relatively little energy in charge/discharge cycles. These technologies thus raise similar market design issues. In addition, the operating characteristics of electricity systems that are dominated by VRE and storage technologies raise significant equity and risk-tolerance issues that must be addressed in devising future retail pricing regimes.

This chapter is organized as follows. The next section, Section 8.2, discusses requirements for overall power system efficiency, both in general and in light of the modeling results presented in Chapter 6. Section 8.3 provides a brief overview of the wide variety of organizational structures and regulatory frameworks within the U.S. electric power sector and of their evolution. In the two subsequent sections we consider two polar opposite structures described in Section 8.3 at the bulk power (wholesale) level. Section 8.4 considers barriers to least-cost production in the first of these: the traditional structure of a regulated investor-owned firm that provides generation, transmission, and distribution and has a monopoly within its state-designated service area. Section 8.5 then considers the polar opposite case in which generation, transmission, and distribution functions have been separated, and generation has been horizontally disaggregated to support competitive wholesale markets. In systems of this general sort, organized wholesale markets play key roles in guiding resource allocation in both the short run and the long run—consequently, market design challenges are present that do not arise in vertically integrated structures, which lack organized markets.

Finally, Section 8.6 considers the challenge of designing equitable retail rate regimes in either structure that guide efficient investment and consumption decisions without imposing excessive risks on households and small firms. In most of the country a single regulated entity

[3] Systems with high VRE penetration face other challenges as well. For example, how to manage a system reliably where supply can fluctuate widely and rapidly in response to exogenous changes in weather. Responding to these challenges will likely require additional market design changes, especially in ancillary service products. However, we do not discuss this type of operational challenge in this study.

sets retail rates, but about nineteen U.S. states have allowed competition in marketing electricity to some or all retail customers.[4]

8.2 Efficiency in High-VRE Power Systems

There are two general requirements for overall power system efficiency in a decarbonizing economy.[5] First, and most obvious, electricity should be produced and delivered at the lowest possible total cost, including the cost of any involuntary blackouts or load shedding, compatible with satisfying applicable carbon constraints and given the available technologies and their costs. This requirement, which is often termed *productive efficiency*, means production and delivery costs must reflect the efficient uses of available technologies given their costs and production attributes. It is the focus of Sections 8.4 and 8.5. Two novel challenges to productive efficiency deserve emphasis.

First, productive efficiency requires achieving carbon constraints through policies that support efficient investment and operating decisions at all levels in the system. As economists have argued for decades, a central element of an efficient approach to reducing carbon emissions is to place an appropriate price on carbon emissions, either in the form of an economy-wide tax on carbon emissions or a comparable cap-and-trade regime with the same economy-wide scope.[6] In what follows, we assume that carbon pricing policies are in place, as they are in our modeling exercises in Chapter 6, since it is simply not possible to deal with the consequences of the host of politically more popular but less efficient policy alternatives that can be—and, indeed, have been—widely deployed. Use of any of these alternatives—which include renewable portfolio standards, clean energy standards, investment tax credits and production tax credits, feed-in tariffs, and net metering policies applied to generation and storage facilities on customers' premises—instead of carbon pricing raises the cost of electricity unnecessarily and

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[4] https://competitiveenergy.org/consumer-tools/state-by-state-links/ accessed February 20, 2022. Retail competition has been a political issue at the state level, and the number of states that allow it has changed from time to time.

[5] Throughout this chapter we assume, consistent with public policy in the United States and elsewhere, that retail electricity rates must produce revenues sufficient to cover all investment and operating costs for the system as a whole.

[6] Hafstead (2019) provides an accessible overview of carbon pricing. A recent (2021) World Bank report finds that 64 carbon pricing initiatives had been implemented as of late July 2021, covering just over 21% of global carbon emissions. Sadly, even though both major political parties' presidential candidates endorsed carbon pricing in 2008, prospects for carbon pricing at the national level in the United States have dimmed considerably since then.

thus works against reaching economy-wide decarbonization goals via electrification. That said, the recommendations developed in this chapter are generally desirable even in the face of inefficient policies for achieving decarbonization, though their benefits, in the context of inefficient carbon policies, will be reduced. Since we focus on 2050 in our modeling work, we hope that public policy will evolve by that time to rely primarily on more efficient mechanism to provide incentives for decarbonization.

A second novel and complex challenge to achieving the least-cost production and delivery of electricity is that, as noted above, existing markets and institutional arrangements were not designed to make efficient use of energy storage. While the modeling analysis described in Chapter 6 concentrates on the potential to use storage to perform intertemporal energy arbitrage—effectively moving VRE generation from one time period to another—storage can also, as we discuss in Chapter 1, perform a variety of other functions in power systems. Least-cost production and delivery of electricity requires that investment and operations decisions involving storage reflect the value of all those functions. In addition, some battery storage technologies (notably lithium-ion batteries) can be deployed relatively efficiently at small scale. Batteries in homes, commercial buildings, or industrial facilities can also efficiently deliver a variety of services at the wholesale level, but existing utility regulations, wholesale power markets, and retail pricing regimes are not designed to facilitate their efficient participation at the wholesale level.

The second requirement for overall power system efficiency is related: "retail prices"—that is, prices faced by end-use electricity consumers and service contracts that may be made available to them and that might provide incentives for third-party control of some appliances, vehicle charging, or other electric loads—should support short-run and long-run decisions on energy use that reflect marginal cost or, more generally, the marginal value of energy.[7] This requirement for *allocative efficiency* means that energy use should be discouraged in the short run when electricity is expensive on the margin, but it should be encouraged when electricity is

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[7] This distinction reflects the fact that the cost of supplying electricity from storage is mainly an opportunity cost, the foregone opportunity of supplying it later, rather than an out-of-pocket cost like the fuel used in thermal generation.

cheap—for instance, when available VRE generation exceeds demand. The marginal value of energy should guide decisions on investment in and operation of small-scale generation and storage assets located on customer premises, as well as investment to enable demand to respond to short-run price changes. Retail rates that support allocative efficiency, the focus of Section 8.6, are critical to support least-cost economy-wide electrification as a key component of economy-wide decarbonization.

Despite its limitations, the optimization analysis in Chapter 6 has important implications for the features of high-VRE power systems that produce and deliver bulk power efficiently.[8] Our optimizations seek to minimize total system cost subject to a constraint on carbon emissions.[9] All decisions are optimally driven by a single variable: the marginal value of electric energy, a shadow value that reflects the cost of incremental supply from generation and/or storage in each time interval. In theory, one can translate the results of these optimization analyses into market equilibria under perfect competition in a system with only energy markets by treating the marginal value of energy as the actual spot price. In an optimized system, the marginal value is used as a market price would be used under conditions of perfect competition: to guide dispatch and other operating decisions as well as all investment decisions.

Two features of the efficient systems modeled in Chapter 6 have particularly important implications for the design of markets and governance institutions. First, the modeled distribution of (shadow) spot wholesale prices for energy is very different from current distributions of spot prices. Even when storage is optimally deployed to "buy low and sell high"—thus moving electric energy from periods of abundance to periods of scarcity—there are many more hours of very low prices than at present, along with more hours of very high prices.[10] This reflects the variability of

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[8] Importantly, that analysis assumes perfect foresight with respect to both demand and supply of renewable generation and we do not model so-called ancillary services (such as frequency regulation) or load-uncertainty-related resource adequacy challenges. Both enormously simplify the analysis. The assumption of perfect foresight removes the need for reserve margins and, along with the assumption of constant returns to scale, ensures that all technologies optimally deployed earn zero economic profits.

[9] The limit on carbon emissions is specified as a constraint on carbon emissions per megawatt-hour (MWh) of output, and the shadow price on that constraint gives the carbon price that would need to be imposed under competition to ensure satisfaction of the emissions constraint.

[10] As we discuss below, many of today's wholesale energy markets have low price caps that limit the variability of spot energy prices. The comparison in Chapter 6 between the price distributions produced by our model of Texas in

VRE supply with near-zero short-run marginal cost, the excess supply of VRE generation at some times in the optimal solution, and demand-side variability.

Translating the solutions of our optimization exercises into market equilibria in a system with only an energy market implies that generators and storage facilities would earn a disproportionate share of the revenues needed to recover investment costs during only a few hours every year (or every few years) when prices are very high. In the world of the model, end-users who actually have to pay marginal system costs for all the electricity they demand at each point in time would, in theory, face correct incentives for efficient consumption and investment. In practice, however, the price risks to end-users in this scenario would be enormous and, for households and small businesses, likely intolerable. These risks were made visible in the February 2021 energy crisis in Texas.[11] Luckily, as we discuss in Section 8.6, a complete pass-through of wholesale prices into retail rates is not necessary to induce efficient behavior by producers and consumers.

The second feature of high-VRE systems that has significant governance implications is that storage, both grid-scale and at customer premises, is a potential substitute for, or complement to, essentially all other elements of a power system. Efficient governance must enable least-cost choices among all these elements. As shown in Chapter 6, optimal storage deployment in high-VRE systems complements VRE, increasing its value by reducing the need for curtailments and mitigating the consequences of intermittency.[12] Tighter constraints on carbon emissions reduce the possible use of natural gas generation, which substitutes for long-term storage, and thus increases the value of storage. The ability to reduce load in times of supply scarcity through demand response reduces the optimal amount of storage deployed.

A stronger regional and inter-regional transmission network permits access to better wind and solar resource sites and enables broader geographic diversification, which reduces average

2050 and the distribution of 2018 and 2019 wholesale prices in ERCOT (the Electric Reliability Council of Texas), which operates a wholesale market covering most of the state of Texas with a very high price cap, provides strong support for this statement.

[11] See Blumsack (2021) for a brief discussion.

[12] We do not discuss the properties of alternative curtailment mechanisms here: we simply assume that when curtailments are necessary to balance supply and demand, they are implemented efficiently.

variability and allows, for example, solar generators in the west to help meet evening loads farther east.[13] Increased transmission capacity also reduces the optimal amount of storage deployed. Finally, Chapter 7 reveals that for systems experiencing rapid growth, storage can reduce costs by delaying the need to expand transmission or distribution systems.

8.3 Market and Institutional Structures

As noted above, U.S. bulk power systems exhibit a wide range of market and institutional structures.[14] Traditionally, most electricity was generated by vertically integrated, investor-owned utilities, which mainly sold to ultimate customers pursuant to retail tariffs regulated by state regulatory commissions. In a vertically integrated (VI) system, a single organization ("the VI utility") owns and controls the generation, transmission, and distribution facilities to serve retail consumers within the organization's geographic footprint. In addition, some sales were made by vertically integrated utilities to cooperatives and municipal utilities that, in turn, sold to ultimate customers under wholesale contracts or tariffs regulated by the Federal Energy Regulatory Commission (FERC).[15]

In the Southeast, Southwest, and much of the West, the traditional, VI-utility model still dominates.[16] Accordingly, the next section (Section 8.4) considers the efficient governance of a regulated, vertically integrated, investor-owned utility that owns or contracts for all generation, transmission, bulk storage, and distribution assets.[17] This utility does not own generation or

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[13] This is discussed in Chapter 6 and several references cited there.

[14] For a useful brief overview, see Cleary and Palmer (2020).

[15] In some regions, federally owned utilities, notably the Tennessee Valley Authority in the Southeast and the Western Area Power Administration and Bonneville Power Authority in the West, had significant shares of generation and regional transmission capacity. These federal utilities by law sold almost exclusively to cooperatives and utilities owned by state and local governments. Cooperatives and municipal utilities have remained important in some regions. In 2019, 856 cooperatives and 2,003 government-owned utilities served 28% of all U.S. customers, supplied approximately 15% of all the electricity delivered to U.S. end-users from generating plants they own, and produced approximately 10% of all the electricity generated in the United States (American Public Power Association, 2021).

[16] For a brief overview of regulatory structures in the various regions, see https://www.ferc.gov/electric-power-markets.

[17] We recognize that even vertically integrated utilities may engage in some short-term bilateral wholesale transactions with interconnected utilities, may participate in more organized short-term energy markets (as in the Western Energy Imbalance Market), or may be integrated into organized wholesale markets. However, it is useful to consider this pure case since, even in these other contexts, state regulation typically plays the central role in resource planning, resource adequacy determinations, revenue determinations, and retail rate design.

storage assets on customer premises. It is regulated at the state and federal levels, with state regulation being more important. There is no competition in the provision of electricity to final customers, and retail customers pay for the electricity they consume according to the utility's regulated retail tariffs. In this polar case structure, there are no transparent wholesale market prices. Absent transparent wholesale prices, efficiency requires that the short-run marginal cost of supplying electricity should drive decisions, even though, traditionally, time-invariant retail rates were set to cover utilities' average costs. When the system's supply is constrained, and supply–demand balance must come from the demand side, the relevant marginal cost and spot price is the value of unserved load—referred to as the value of "lost" load (VoLL)—or, if there is an active, price-sensitive demand side, the relevant price is the price that clears the market without implementing involuntary load curtailments (Joskow and Tirole 2007).

Beginning in the 1990s, the electric power sector in much of the United States (and in many other nations) was restructured to increase reliance on competitive wholesale markets to supply energy and so-called ancillary services such as reserve capacity and frequency regulation. The basic idea was that the actual spot price of electricity in these markets would guide all bulk power operation and investment decisions, as the shadow value of electricity does in our optimization model. Seven regional entities, called independent system operators (ISOs) or regional transmission organizations (RTOs), now operate those markets and regional transmission systems and engage in some regional planning.[18] (For simplicity, we refer to all of them as ISOs in the discussion that follows.) ISOs manage about 60% of U.S. electricity supply.[19]

In some U.S. regions, though not all, electric sector restructuring was accompanied by the vertical separation of generation, transmission, and distribution, as well as by additional, horizontal disaggregation of generation. These changes and the entry of merchant generators led to a far greater role for non-utility generators, which accounted for about 47% of U.S. electricity supply in 2020.[20] In addition, fourteen states have allowed retail competition for all retail

[18] For a discussion and a map of service territories, see https://www.ferc.gov/electric-power-markets. All of the ISOs except ERCOT, which has a service territory entirely within Texas and no substantial connections with other states, are regulated by FERC.
[19] https://www.eia.gov/todayinenergy/detail.php?id=790, accessed February 21, 2022.
[20] Edison Electric Institute (2021).

customers.[21] In these states, the physical distribution of electricity remains a regulated monopoly, but competitive retail providers can purchase electricity in the wholesale market and resell it to retail customers. A few additional states allow some but not all retail customers access to competitive suppliers.

Developing competitive wholesale power markets for energy and ancillary services was more complicated than many had anticipated, but in today's systems that primarily rely on dispatchable fossil-fuel generation resources, these markets now have good operational performance under most conditions. Energy prices have been capped at levels well below reasonable estimates of VoLL, however, and bulk power system reliability standards have been set that are often excessive from an economic perspective.[22] ISOs sometimes engage in "out of market" actions to respond to situations in which the system's supply–demand balance is stressed and to manage associated reliability concerns. As a result, revenues from energy and ancillary service markets have generally not provided adequate incentives for generation investments at the level needed to meet applicable reliability standards. This gives rise to what is often called the "missing money" problem.[23] Similarly, because they constrain price variability, energy and ancillary service markets with low price caps would likely lead to sub-optimal investment in energy storage.

In response to the "missing money" problem and the reliability concerns raised by potential underinvestment in generating capacity, most restructured regions in the United States have added markets for capacity or related "resource adequacy" mechanisms to supplement energy and ancillary service market revenues in order to ensure that capacity is adequate to meet reliability standards.[24] More recently, climate and clean energy policies, including mandates for VRE generation and storage, have led to additional regulatory interventions in investment decisions within restructured regions. This has resulted in so-called *hybrid* systems in which

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[21] https://competitiveenergy.org/consumer-tools/state-by-state-links/, accessed February 20, 2022.

[22] That is, the value of lost load implied by these reliability standards is typically implausibly high. For example, Astrape Consulting (2013) estimates that the common 1-event-in-10-year standard corresponds to an implied VoLL of $300,000/MWh—one or two orders of magnitude higher that typical estimates of VoLL.

[23] https://www.nrel.gov/docs/fy15osti/64324.pdf accessed July 29,2021

[24] ERCOT, which serves most of Texas, is a notable exception, but it does have a mechanism embedded in the energy market that provides supplemental payments for energy supplies in the real-time market when operating reserves fall below specified levels: http://www.ercot.com/services/training/course/109606.

wholesale markets guide operations, but investment decisions are heavily affected by resource adequacy policies, government decarbonization commitments, government mandated VRE and storage procurements, and associated regulatory decisions (Roques 2021). The rules commonly applied to energy, ancillary service, and capacity markets in these systems were not designed with storage in mind, however, and the owners of existing assets are not eager to encourage competitive storage. As discussed below, efforts to reform those rules are underway at the federal level and in several states. These efforts are important and should be encouraged.

Section 8.5 considers the polar case of a fully restructured bulk power system with merchant suppliers of generation and grid-level storage. In this structure, transmission and distribution remain regulated and an ISO develops rules for, and operates, wholesale markets for energy and ancillary services, subject to federal (FERC) oversight. As in the contrasting polar case of a vertically integrated utility with no wholesale markets, customers make investment and operating decisions for distributed generation and storage facilities on their premises. Both state and federal regulation are important in this structure. ERCOT, which serves most of Texas, probably comes closest to exemplifying this model, but electricity systems in the northeastern United States (specifically, the PJM, NYISO, and ISO-NE systems) have also been largely restructured, using similar wholesale energy market designs but with added capacity markets. [25]

8.4 Regulated, Vertically Integrated Bulk Power Systems

In principle, regulated, vertically integrated systems can minimize total system costs at the bulk power level, thus attaining productive efficiency, with system marginal costs and the value of unserved load (VoLL) standing in for a wholesale market spot price. In practice, however, even if productive efficiency is one of the integrated utility's objectives, achieving it is difficult, for several reasons. The cost-containment discipline provided by competitive markets is mostly absent, regulatory oversight is imperfect and subject to interest group politics, and VRE generation and storage at scale pose new problems for operations and investment decision-making.

[25] See https://www.ferc.gov/electric-power-markets.

As noted in Chapter 6, neither vertically integrated utilities (nor ISOs that manage wholesale markets and transmission in restructured systems) have much experience operating high-VRE systems in which storage plays multiple, significant roles. Similarly, most utilities and system operators have historically had separate planning processes for generation (including purchased power), transmission, and distribution and have little experience with including grid-level storage in planning. Because high-VRE systems with storage will pose new operational and planning challenges, Chapter 6 recommends that utilities and system operators, with the support of state and federal regulators, engage in cooperative research with universities, national labs, and other institutions to develop the tools needed to operate high-VRE systems with storage and to better integrate generation, transmission, storage, and distribution options in their long-term planning processes.

High-VRE systems with storage will also pose significant new challenges for state and federal regulators. Since utilities respond to the incentives created by regulation, it is important that regulatory agencies have the expert staff and resources necessary to devise and implement efficiency-enhancing incentives appropriate to a rapidly changing environment. At present, most agencies lack sufficient technical and economic expertise to respond effectively to these challenges. To decarbonize the power system and the wider economy without incurring excessive costs, these deficiencies must be remedied.

Recommendation 8.1: Staffing and budgets for state and federal regulatory agencies should be substantially increased to enhance these agencies' capabilities to design and implement regulatory mechanisms that can guide the transition to least-cost high-VRE systems with storage.

Because FERC regulates transmission and wholesale energy and capacity markets in the United States, whereas states regulate retail rates and everything else, regulated, vertically integrated utilities may have incentives to exploit differences between state and federal regulation (this practice is sometimes called regulatory arbitrage) in ways that lead to inefficient investment decisions. On the other hand, there may be value in having FERC and states experiment with a variety of organizational and regulatory approaches. Greater communication among regulatory agencies may have considerable value as all stakeholders in the electric power sector head into uncharted waters.

In many cases, storage assets located "behind the meter" on customer premises can provide grid-level and generation-related services cost-effectively, particularly if they are operated by aggregators.[26] Regulated utilities, however, will prefer to employ storage assets that they own. State regulators should attempt to ensure that this preference does not lead to uncompetitive, excessively costly outcomes.[27] On the other hand, restrictions on the ownership of storage (and other state interventions to influence the amount and type of storage installed) may increase overall costs by preventing storage options from capturing all wholesale, wires, and customer-related value streams.

Recommendation 8.2: State regulators should develop rules that allow owners of storage (and generation) assets installed on customer premises to sell services to vertically integrated utilities under appropriate terms and conditions that facilitate efficient investment in and use of "behind-the-meter" generation and storage.

Ensuring "appropriate terms" for storage services provided by devices installed on customer premises will likely require enabling purchases and sales of energy from these devices at system marginal cost (or at VoLL when there is unserved load).

Rather than owning and operating facilities that are subject to traditional rate-of-return regulation, it will often be efficient for a regulated, vertically integrated utility to use competitive bidding to procure generation, storage, and transmission capacity, or, preferably, to use technology-neutral bidding for services that could be provided by different types of assets (without specifying the asset types to be employed) through long-term contracts with third-party VRE and storage suppliers. These contracts should involve fixed payments if performance criteria

[26] See, for example, Green Mountain Power's Home Battery program (From Pilot to Permanent: Green Mountain Power's Home Battery Network Is Here to Stay | Greentech Media) under which the utility now controls several thousand Tesla Powerwall batteries sited in customers' homes. For a general discussion of programs of this sort, with a focus on New England, see Comments of the Energy Storage Association to the Public Utility Commission of New Hampshire, January 11, 2021, available at https://www.puc.nh.gov/Regulatory/Docketbk/2020/20-166/LETTERS-MEMOS-TARIFFS/20-166_2021-01-11_ESA_COMMENTS.PDF.

[27] The California Public Utilities Commission and the California Independent System Operator have been engaged on this issue for some time. See, respectively, CPUC (2018) and CAISO (2019).

(e.g., availability) are met, since the system-wide marginal cost of producing more or less electricity from the facilities involved will frequently be close to zero. Contracts that tie payment directly to the quantity of energy supplied by VRE generation or storage at prices above the facility's marginal cost (e.g., $70/MWh supplied when the marginal cost is close to zero) will raise system costs by distorting dispatch decisions and should therefore be avoided.

8.5 Restructured and Hybrid Bulk Power Systems

Competitive markets generally provide stronger cost-minimization incentives than cost-of-service/rate-of-return regulation, and the possibility of merchant entry into various functions can be a powerful force for static and dynamic efficiency. Existing rules in organized regional wholesale power markets were not designed for high-VRE systems in which storage is important, however. In addition, incumbents (including owners of thermal generators) are not eager for the entry of new competitors in the form of storage providers. FERC Order 841 (FERC 2018), which required ISOs to enable the participation of storage providers in regional markets, was an important first step. FERC took another important step with Order 2222 (FERC 2020), which required ISOs to remove barriers to the participation, through aggregators, of distributed energy resources (including behind-the-meter storage) in regional markets.

These orders need to be translated into workable market rules and aligned with state regulations, particularly with respect to integrating wholesale markets and the distribution and customer-side values of storage. In California, the public utility commission (CPUC) and the ISO (CAISO) have already done much work on this kind of integration, perhaps helped by the fact that CAISO is a single-state ISO with an integrated, single-state regulatory framework and climate-policy regime to guide its actions. This sort of integration may be more challenging for multi-state ISOs.

Devising state and federal rules that are aligned and provide incentives for efficiency will not be simple, but it will be essential for the high-VRE systems of the future, in which avoiding unnecessary costs will require that storage play an important role. At a minimum, storage providers must be able to buy and sell energy at the wholesale spot market price. When charging, storage facilities should be treated as negative supply, not as another form of ultimate customer load. This means storage providers should not be burdened with the recovery of fixed costs for transmission or distribution or for out-of-market payments unless there is a clear rationale, based on cost-causality considerations, for doing so—for example, if the addition of a storage facility to the system creates transmission interconnection costs. Storage providers should also be permitted to participate in markets for capacity and ancillary services, recognizing, as discussed below, that the capacity value of specific storage facilities will vary with the maximum duration of the energy these facilities are capable of storing (see Chapter 1).

Recommendation 8.3: The Federal Energy Regulatory Commission (FERC), state regulators, and ISOs should reform and align market rules to enable efficient participation—in wholesale energy and ancillary service markets, as well as in capacity markets—by providers of both grid-based storage and distribution-level generation and storage (including from facilities located on customer premises). These rule reforms should accommodate the participation of aggregators in wholesale markets.

Because of the disaggregated industry structures that exist in many parts of the United States, allowing customer-based and distribution-level resources to participate in wholesale markets raises complex market design issues. Nonetheless, the growing importance of such distributed assets and the potential system-level benefits they can provide make this an important issue to address. Minimizing total system costs will require that providers of customer-premises and distribution-level generation and storage be allowed to buy and sell at the wholesale energy price, adjusted for transmission and distribution losses (and be allowed to participate in ancillary services and capacity markets, as discussed below)—at least through aggregators, as FERC Order 2222 requires. Efficient operations may also require that system operators be able to track the capacities, resource status (e.g., state-of-charge for storage facilities), and operations of behind-the-meter generation and storage facilities.

As noted above, various designs for capacity markets and other capacity compensation mechanisms have been deployed to encourage investments in generation by supplementing revenues earned from energy and ancillary service markets. These efforts have had mixed results and have necessitated frequent market design changes. Existing capacity market mechanisms were originally designed for systems with fully dispatchable, utility-scale generation. In such systems, installed capacity (sometimes derated by a few percentage points to reflect typical forced outage rates) is a good measure of the ability to provide power in times of system stress—typically during demand peaks on hot summer afternoons or, less commonly, on very cold winter days.

Computing the expected ability of VRE generators and storage resources to provide both capacity and energy in times of system stress is more complicated.[28] Essentially, it requires an examination of (1) the full probability distribution of supply, both at the bulk power level and from behind-the-meter providers, and (2) the full probability distribution of demand. Analyzing the latter requires properly accounting for correlations between expected production from different types of VRE generators (e.g., output from wind generators in the same area will be much more highly correlated than output from dispatchable generators today) and for correlations between VRE supply and energy demand, both of which will be much more sensitive to variations in weather conditions. A high-VRE system could be stressed in the late evening of a hot day, for example, when demand is below the system peak but there is no solar generation and (potentially) very little wind generation. Widespread electrification of space heating as part of an economy-wide decarbonization strategy is also likely to increase the relative importance of winter demand peaks for capacity planning. In addition, the expected capacity contribution of a VRE generator of any particular type will depend on the structure of the generation fleet. The higher the share of solar generation, for instance, the more likely it is that system stress occurs in the late afternoon or early evening (after system demand peaks), when solar output is declining or zero. In California, for example, the involuntary load shedding that occurred in August 2020 took place after the peak demand hour but at a time of "net peak demand" later in the evening, as the sun went down.[29]

Although existing capacity mechanisms are being adapted to account for the "effective load carrying capability" (ELCC) of VRE generation, fully adapting these mechanisms for systems that include significant storage resources will pose new market design challenges. Unlike VRE

[28] The problems discussed in this paragraph and the next also arise as planning problems for vertically integrated systems, but, in the absence of markets, they do not raise market design issues.
[29] "Net peak demand" is defined as the total demand on a bulk power system less the supplies from intermittent wind and solar generators. On the August 2020 load shedding event in California, see CAISO (2021, Figure 4.3).

generators, the power that a fully or partially charged storage facility can supply is not likely to vary much over time. However, the length of time over which a storage facility can supply this power (and thus "carry load") is limited both by the facility's design duration and, in the short run, by its state of charge. And state of charge at any given instant in time will be determined by prior operating decisions. Since periods of system stress are typically characterized by high energy prices, storage operators will have incentives to have their facilities fully charged just before such periods. System stress, however, cannot be forecast perfectly, and there is essentially no experience with the operating decisions that owners of storage facilities are likely to make when participating in systems with significant VRE and storage resources. Moreover, as more storage resources with a particular design duration (e.g., four hours) are added to the system, their ELCC will start to decline. Market rules will need to be developed to address these challenges and to correctly determine the capacity value that storage resources can provide to meet reliability standards.

Recommendation 8.4: ISOs should either (1) redesign existing capacity mechanisms as they apply to VRE generation and storage, taking into account the stochastic properties of VRE generation and demand and the fact that storage is energy-limited, or (2) replace those capacity mechanisms with an increased reliance on integrated resource planning that properly accounts for these factors.

Power system planners and operators face a fundamental problem: it is not clear how resource adequacy standards should be set for systems with high levels of VRE and storage. There would seem to be a complex tradeoff between energy-limited and non-energy-limited capacity, depending on the nature and duration of expected stress events. We believe this issue has not yet received adequate study.

Rather than hoping that well-intentioned modifications to current market designs will produce acceptable results, it may be better in the short run to implement well-structured integrated resource planning processes, similar to the planning processes that could be (but are not always) employed by vertically integrated utilities to set targets for various levels of VRE and storage capacities. Even recognizing that integrated resource planning has not always worked well in the past, in part because of a tendency among planners to minimize uncertainty, some vertically integrated utilities in the United States may have already made the most progress on this front. These utilities could have a structural advantage in managing the transition to a decarbonized system by virtue of their ability to capture all related value streams internally. In contrast, mandates and requirements by individual states, which have become increasingly common, will lead to inefficient outcomes and higher costs if they are uncoupled from rigorous integrated resource planning.

Finally, as discussed in Chapter 7, the ability of storage to delay or displace investments in transmission and distribution can be quite valuable in systems with rapidly growing demand. The efficient use of storage requires that providers of storage resources be compensated for such benefits. Accordingly, storage must be (1) fully integrated into ISO-managed transmission planning processes; (2) allowed to compete with traditional transmission and distribution expansion options; and (3) compensated for providing reliability, market efficiency, and/or public policy services as wires-based options would be, pursuant to FERC Order 1000 (FERC 2011). Efficiently integrating storage resources also requires that storage assets that provide wires-related services be allowed to participate in wholesale power markets (at least where that is possible while still providing the wires-related services). Making this happen will require significant regulatory efforts at both the state and federal levels.

Recommendation 8.5: FERC should move to integrate storage into transmission planning processes while state regulators should require the integration of storage in distribution system planning—and storage devices should be allowed to provide wholesale power market services where physically possible.

This recommendation, which also applies to market structures that rely on vertically integrated utilities, focuses on developing regulatory frameworks and market designs that recognize the full set of value streams that storage assets can provide (with respect to wholesale power, transmission, distribution, and customer-side services) without overstating their combined value. In this context, simplifications that do not allow storage to capture all available value streams—such as the concept of "storage as a transmission-only asset"—should be avoided.[30]

[30] FERC has recently allowed the Midcontinent ISO to employ this concept (MISO 2021).

8.6 Retail Rates and Economy-Wide Decarbonization

Currently, retail electricity rates for most residential and small commercial and industrial customers in the United States do not vary over time or in response to system conditions at the bulk power level as reflected in spot wholesale prices. These rates, which are dominated by volumetric (per-kWh) charges, do not encourage or even enable demand response to changes in the marginal value of electricity, and they do not encourage efficient patterns of electricity consumption or efficient investments in energy storage and generation capabilities on customer premises. They are thus inconsistent with allocative efficiency. The benefits of introducing more efficient rate designs will rise sharply as VRE generation and storage play a greater role and as the spot price of electricity (or, in the case of vertically integrated utilities, the system marginal cost) at the bulk power level becomes more variable.

In addition, large commercial and industrial customers frequently pay significant charges based on their demand during the system's peak demand hours ("coincident peak charges") that incentivize them to invest in on-site energy storage that can be used to reduce their coincident peak (CP) demand and thus reduce their electricity bills. Often, these investments constitute a form of "uneconomic bypass," as they reduce storage investors' bills without providing commensurate benefits system-wide, thereby shifting the burden of cost recovery to other customers. In high-VRE systems the effect may be to shift demand to periods of "net peak demand" rather than away from these periods and thus to further stress the system.

Near-term reform of CP demand charges for large customers seems both feasible and increasingly important. As the cost of storage continues to fall, profitable opportunities for large customers to avoid CP-based demand charges will grow. Failure to address this issue would enable large customers to greatly reduce the revenues collected via demand charges, substantially shifting the burden of covering utility costs to other customer classes. This would have adverse impacts in terms of both total system costs and equity. Avoiding these impacts will require a redesign of retail rates to recover system fixed costs through charges that are less easily gamed—such as customer charges or different types of demand charges.

Recommendation 8.7: State regulators should replace coincident peak (CP) demand charges for large customers with measures of impact on system supply costs that are less easily gamed.

The best approach to ideal, efficient, and equitable retail rate design is not obvious at this point, and significant additional research efforts are called for. While rate design issues are being explored in many forums,[31] efforts to continue current research are critical—including efforts to analyze retail rate mechanisms that closely link the marginal component of retail prices to variations in wholesale prices, as well as voluntary contracting options that allow retail suppliers (in either competitive or monopoly structures) to adjust customers' electricity demand in response to wholesale prices in return for discounts of one sort or another. Programs for cycling air conditioning and water heating loads, which fit this mold, have been around for many years and are popular with consumers. These options likely need to be extended to include other sources of load, such as for EV charging and customer-owned energy storage. In addition, insurance-like designs that limit the impacts of high wholesale prices on residential and small commercial and industrial customers in return for fixed payments deserve further study.

Recommendation 8.6: The U.S. Department of Energy (DOE), in cooperation with state regulators, should increase support for independent research, including support for well-designed randomized controlled experiments,C aimed at (1) devising efficient and equitable retail rate designs for high-VRE systems with storage and (2) encouraging their widespread adoption.[32]

Arguably, responsibility for all the research recommendations in this chapter and Chapter 6 should be given to DOE, along with levels of funding that fully reflect the high importance and complexity of the topics involved.

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[31] For further discussion of how retail rate structures need to be reformed to enhance overall efficiency in a more distributed, decarbonized grid see: NARUC, https://pubs.naruc.org/pub/19FDF48B-AA57-5160-DBA1-BE2E9C2F7EA0;
Alliance to Save Energy, forging-a-path-to-the-modern-grid.pdf (ase.org), Electricity rates for the zero marginal cost grid (packetizedenergy.com); Regulatory Assistance Project (2015) https://www.raponline.org/knowledge-center/smart-rate-design-for-a-smart-future/; Sergeci (2018), Rate Design in a High DER Environment, http://files.brattle.com/files/14504_sergici_slides_for_sepa_workshop_on_alternative_rate_design_20180920_sent.pdf; Hledik, Zahneiser-Word, Cohen (2018) Storage-oriented rate design: Stacked benefits or the next death spiral?, The Electricity Journal; Faruqui, Bourbonais (2020), The Tariffs of Tomorrow, IEEE Power & Energy Magazine (May–June, 2020).

[32] The U.S. government provided support at the federal level for a number of innovative retail rate experiments in the 1970s. (See, e.g., Kohler and Mitchell (1984).) It would be worthwhile to draw on that experience to structure more advanced randomized controlled trials of alternative rate structures.

Two important but competing principles should guide continued research on retail rate design. First, efficient electrification and efficient investment in customer-based generation and storage require that *marginal* retail rates be allowed to vary with wholesale spot prices that include the cost of carbon constraints. As we show in Chapter 6, decarbonization will increase average power costs compared to a policy with no carbon constraint. In this context, achieving efficient and rapid electrification means that small customers must be able to adjust their demand to avoid high-cost periods (or have a supplier make such adjustments for them) and to take advantage of the significant periods when spot prices (and thus marginal system costs) are low—particularly to charge electric vehicles. On the other hand, as some customers in Texas recently learned (Blumsack 2021), tying the entire generation component of retail rates directly to wholesale spot prices for electricity would expose small customers to potentially enormous financial risks. It is possible, however, to mitigate that risk while maintaining efficient marginal rates through various types of forward contracting with insurance features and/or "load control" arrangements (e.g., contracts to manage air conditioning or water heating cycles)[33] between utilities or competitive retail suppliers and customers. Such contracts or arrangements can take advantage of smart metering, communications, and behind-the-meter "smart" appliance control technologies to mitigate consumers' risks while linking a portion of retail rates to wholesale prices. Potential retail rate designs will need to be explored in more detail to evaluate both the allocative efficiency properties of alternative pricing and contracting mechanisms and their income distribution properties.[34]

A second competing principle follows from the fact that most of the costs in a high-VRE system with energy storage will be fixed in the short run, and overall efficiency requires that such fixed costs be recovered through charges that are also fixed in the short run (as with mobile phone subscriptions). Moreover, given the extreme spot price volatility to be expected in future energy-only systems based on the modeling in Chapter 6, and the near ubiquity of capacity mechanisms (and price caps well below VoLL) in the less volatile systems of today, it seems

[33] See for example https://www.comed.com/WaysToSave/ForYourHome/Pages/CentralACCycling.aspx and https://concordma.gov/494/Controlled-Water-Heating.

[34] Many "first-generation" decarbonization policies, such as net metering for rooftop solar generation and subsidies for electric vehicles, have favored wealthier consumers. Devising decarbonization policies that are both equitable and efficient is well beyond the scope of this study but is profoundly important.

inevitable that price caps and capacity mechanisms will become even more important in high-VRE systems. Revenues from these capacity mechanisms will also need to cover much of the costs of VRE generators and, likely, storage facilities. Recovering those costs through volumetric (per-kWh) retail charges will discourage electrification at the margin. At the same time, high, uniform fixed charges levied on all customers are plainly inequitable. Thus, further research is required to identify alternative regimes that provide efficient price signals to retail consumers and in which an appreciable fraction of consumers' bills is independent of current consumption. Potentially useful rate designs must also generally be perceived as fair by the public and policymakers.[35]

Even if there is consensus in the research community about the best retail rate designs, it will be largely up to state regulators to implement the necessary retail pricing reforms. Not all state regulators are likely to embrace those reforms with great enthusiasm, of course, and even where they do, cooperative and municipal utilities often are not subject to state retail rate regulation, and competitive retailers must have some freedom to design their own rate structures. Some customers will benefit from retail rate design changes while others will see higher costs. These distributional effects will lead to controversies in the regulatory process and potentially undermine efficient changes to retail rate designs. Efficient mechanisms to reduce any adverse distributional impacts should be given more consideration.

Large industrial customers are already more likely to face retail prices that vary with actual or expected system conditions, in part because they are generally considered more able to manage price risk than small customers. In states with retail competition, large customers typically negotiate the terms and conditions of their individual contracts with competing retail suppliers. In states without retail competition, state regulators are already likelier to allow utilities to offer alternative pricing options to large customers that are more closely tied to movements in wholesale prices.

[35] For some interesting preliminary explorations of this issue, see Burger (2019). In Spain and elsewhere, retail customers can enter medium-term contracts for maximum kW levels of power consumption. Since maximum power consumption is generally correlated with income, one might think this would be a reasonably equitable way to structure fixed charges. We were told, however, that in Southern California, many low-income people live in hot areas away from the coast to reduce their housing costs. As a consequence, they use more electricity for air conditioning than wealthier households that can afford to live nearer the ocean.

8.7 Conclusion and Key Takeaways

This chapter considers how alternative organizational, regulatory, and policy arrangements can enable energy storage to contribute to the broader goal of decarbonizing the entire economy at the lowest possible total cost. The decarbonized electricity systems of the future, because of their far greater dependence on variable renewable energy (VRE) generation and energy storage, will pose novel operational and financing challenges, as well as complex challenges in regulation and market design. The recommendations included in this chapter, and in the summary of key takeaways that follows, are designed to address these challenges.

- With high shares of zero-carbon, intermittent renewable energy generating technologies, electricity systems circa 2050 will need to cope with unprecedented supply fluctuations. Energy storage will play a much larger role in these systems, which will also have to contend with the mixed supply and demand impacts of a large number of newly electrified end-uses.

- Two features of the efficient, decarbonized systems modeled in Chapter 6 have particularly important implications for the design of markets and governance institutions. The first is a very different distribution of wholesale spot prices with many hours of very low prices, along with a few hours of very high prices. The second is that storage, both grid-scale and at customer premises, is a potential substitute for, or complement to, essentially all other elements of the power system.
- State and federal regulatory agencies need increased staffing and budgets to enhance their capabilities to design and implement regulatory mechanisms that can guide the transition to efficient high-VRE systems with storage.
- State regulators should develop rules that allow owners of storage (and generation) assets installed on customer premises to sell services to the vertically integrated utilities within whose geographic footprint they are located under appropriate terms and

conditions that facilitate efficient investment in and use of “behind-the-meter” generation and storage.

- Devising state and federal rules that are both efficient and aligned will not be simple, but it will be essential for the high-VRE systems of the future. The Federal Energy Regulatory Commission (FERC), state regulators, and ISOs should reform and align market rules to enable efficient participation—in wholesale energy and ancillary service markets, as well as in capacity markets—by providers of both grid-based storage and distribution-level generation and storage (including from facilities located on customer premises). These reformed rules should accommodate the participation of aggregators in wholesale markets.

- Market rules will need to be developed to adapt capacity mechanisms for the “effective load carrying capability” of VRE generation and to correctly determine the capacity value that storage resources can provide to meet reliability standards. ISOs should either (1) redesign existing capacity mechanisms as they apply to VRE generation and storage, taking into account the joint stochastic properties of VRE generation and demand and the fact that storage is energy-limited, or (2) replace those capacity mechanisms with an increased reliance on integrated resource planning that properly accounts for these factors.

- Storage can provide benefits for transmission and distribution systems that can be particularly important in rapidly growing systems, such as those discussed in Chapter 7. To efficiently realize these benefits, federal regulators should integrate storage into transmission planning processes, while state regulators should require the integration of storage in distribution system planning. In addition, storage devices should be allowed to provide wholesale power market services where physically possible.

- The best approach to ideal, efficient, and equitable retail rate design is not obvious at this point, though it is clear that overall reliance on uniform volumetric (per-kWh) charges must be reduced, and it is likely that a larger fraction of revenues must be raised by charges that do not vary with current consumption. Significant additional research is called for. The U.S. Department of Energy (DOE), in cooperation with state regulators, should increase support for independent work aimed at (1) devising efficient and equitable retail rate designs for high-VRE systems with storage and (2) encouraging their widespread adoption.

- Even if there is consensus in the research community about the best retail rate designs, it will be largely up to state regulators to implement the necessary reforms. Some customers will benefit from retail rate design changes while others will see higher costs. Retail competition in some states adds a further layer of regulatory complexity. Efficient mechanisms to reduce any adverse distributional impacts should be given more consideration.

References

American Public Power Association (2021), *2021 Statistical Report* and *Electricity Generation Fact Sheet*, available at https://www.publicpower.org/system/files/documents/2021-Public-power-Statistical-Report.pdf and https://www.publicpower.org/policy/electricity-generation, visited July 28, 2021.

Astrape Consulting (2013). "The Economic Ramifications of Resource Adequacy," available at https://pubs.naruc.org/pub.cfm?id=536DBE4A-2354-D714-5153-70FEAB9E1A87, visited February 21, 2022.

Blumsack, Seth (2021). "What's Behind $15,000 Electricity Bills in Texas?" *The Conversation*, February 24, available at https://theconversation.com/whats-behind-15-000-electricity-bills-in-texas-155822, visited July 27, 2021.

Burger, Scott (2019). "Rate Design for the 21st Century: Improving Economic Efficiency and Distributional Equity in Electricity Rates," unpublished dissertation, MIT Institute for Data, Systems, and Society, available at https://dspace.mit.edu/handle/1721.1/123564.

CAISO (California Independent System Operator) (2019). "Energy Storage: Perspectives from California and Europe," Discussion Paper, October, available at http://www.caiso.com/Documents/EnergyStorage-PerspectivesFromCalifornia-Europe.pdf, visited July 27, 2021.

CAISO (2021). "Final Root Cause Analysis: Mid-August Extreme Heat Wave," January 13, available at http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf, visited February 21, 2022.

Cleary, Kathryn and Karen Palmer (2020). "Electricity Markets 101." Resources for the Future, March 3, available at https://www.rff.org/publications/explainers/us-electricity-markets-101/?gclid=EAIaIQobChMIj5_JiOWO9gIVNW1vBB3D1wVIEAAYAiAAEgJIIfD_BwE, visited February 20, 2022.

CPUC (California Public Utilities Commission) (2018). *Decision on Multiple-Use Application Issues,* Rulemaking 15-03-011, January 11, available at https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M206/K462/206462341.PDF, visited July 27, 2021.

Edison Electric Institute (2021). *Sources of Electric Generation*, available at https://www.eei.org/resourcesandmedia/Documents/Sources%20of%20Electric%20Generation.pdf, visited July 28, 2021.

FERC (Federal Energy Regulatory Commission) (2011). *Order 1000: Transmission Planning and Cost Allocation by Transmission Owning and Operating Public Utilities*, July 21, available at https://www.ferc.gov/sites/default/files/2020-06/Order-1000.pdf, visited February 21, 2022.

__________ (2018). *Order 841: Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators*, February 15, available at https://www.ferc.gov/media/order-no-841, visited July 28, 2021.

__________ (2020). *Order 2222: Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators*, September 17, available at https://www.ferc.gov/sites/default/files/2020-09/E-1_0.pdf, visited July 28, 2021.

Hafstead, Marc (2019). "Carbon Pricing 101," Resources for the Future, June 6, available at https://www.rff.org/publications/explainers/carbon-pricing-101/, visited July 27, 2021.

International Energy Agency (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050.

Joskow, Paul L. and Jean Tirole (2007). "Reliability and Competitive Electricity Markets." *Rand Journal of Economics*, 38(1): 60-84.

Kohler, David F. and Bridger M. Mitchell (1984). "Response to Residential Time-of-Use Electricity Rates: How Transferable are the Findings?" **Journal of Econometrics**, 26:1-2, 141-177.

MISO (Mid-Continent Independent System Operator)(2021). "Storage as Transmission-Only Asset (SATOA) PAC004," June 30, available at https://www.misoenergy.org/stakeholder-engagement/issue-tracking/storage-as-transmission-only-asset/, visited July 28, 2021.

National Renewable Energy Laboratory (2016). "Competitive Electricity Market Regulation in the United States: a Primer," Technical Report NREL/TP-6A20-67106, December, available at https://www.nrel.gov/docs/fy17osti/67106.pdf, visited July 28, 2021.

Roques, Fabien (2021). "Hybrid Electricity Markets: Key Principles and Possible Approaches," (presentation), June 21, 2021. http://www.ceem-dauphine.org/assets/dropbox/17h45_2-2_Fabien.pdf. accessed July 27, 2021.

Weber, Michael E. (2021). "The Texas Power Crisis Didn't Have to Happen," American Society of Mechanical Engineers, June 15, available at https://www.asme.org/topics-resources/content/the-texas-power-crisis-didn-t-have-to-happen, visited July 27, 2021.

World Bank, The (2021). *Carbon Pricing Dashboard*, available at https://carbonpricingdashboard.worldbank.org/, visited July 27, 2021.

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