



**Energy Institute WP 336**

**The Economics of Electricity Reliability**

Severin Borenstein, James Bushnell, and Erin Mansur

March 2023

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# The Economics of Electricity Reliability

By SEVERIN BORENSTEIN, JAMES BUSHNELL AND ERIN MANSUR\*

*The physics of an electrical grid requires that the supply injected into the grid is always in balance with the quantity consumed. If that balance is not maintained, cascading outages are likely to disrupt supply to all consumers on the grid. In the past, vertically integrated monopoly utilities have ensured that supply is adequate to meet demand and maintain grid stability, but with deregulation of generation, assuring adequate supply has become much more complex. The unique characteristics of electricity distribution means that there are immense potential externalities among market participants from supply shortfalls. In this paper, we discuss the institutions that US electricity markets have developed to avoid destabilizing supply shortfalls when there are multiple generators and retailers in the market. Though many of the markets rely on standardized requirements for supplier reserves, we conclude that recent technological progress may steer future evolution towards a system that relies to a greater extent on economic incentives.*

*On August 14, 2003, a midsized power plant owned by an Ohio electric utility (FirstEnergy) suffered an unplanned shutdown. Shortly thereafter several poorly-maintained large transmission lines failed. By late afternoon, voltage in its service territory had dropped to dangerous levels. The only way to restore stability would have been to interrupt service to a large portion of the Cleveland area, but no such service interruption was implemented. By 4:00 PM, uncontrolled outages began quickly cascading outward from Ohio, first to Detroit and Toronto, and then to Pennsylvania and New York. The outages eventually reached parts of nine US states and most of Ontario, which suffered intermittent blackouts for more than a week. All told, more than 50 million people were affected. Estimates of total costs were \$4-\$10 billion in the US and 0.7% of monthly GDP in Canada (U.S.-Canada Power System Outage Task Force, 2004).*

Typically, when the term “reliability” is used in the context of a consumer product, it refers to the product’s quality or longevity rather than to the ability to acquire the product at all.<sup>1</sup> In developed economies, electricity is one of the few consumer products for which the term reliability has always been applied to product availability.

Electricity resembles a service much more than a good. It is very costly to store for even seconds, so it must be produced largely at the same time that it

\* Borenstein: Haas School of Business, UC Berkeley, severinborenstein@berkeley.edu; Bushnell: Department of Economics, UC Davis, jbbushnell@ucdavis.edu; Mansur: Tuck School of Business, Dartmouth, erin.mansur@dartmouth.edu

<sup>1</sup>Only with the global pandemic and follow-on disruptions throughout the global supply chain has the availability of many products no longer been taken for granted.

is consumed. Demand varies minute to minute, so the barriers to storage mean that suppliers must be responsive to the fluctuations in demand. Unlike most services, however, electricity can be transported over relatively long distances at near zero cost up to transmission capacity, so production and consumption of the product need not be physically proximate. Still, transmission has capacity constraints, so large areas can be part of the same market most of the time, but sub-areas can become isolated quite rapidly.<sup>2</sup>

In most markets, a temporary supply shortage leads to high prices, isolated stockouts, or other non-market rationing schemes. The physics of an electrical grid, however, means that a supply-demand imbalance can cause two critical characteristics of electricity—voltage and frequency—to deviate from their required levels, which can damage both appliances using the electricity and generation units producing it. To mitigate that risk, generators have protective devices that disconnect them from the grid when such deviations occur. Those protective disconnections, however, worsen the voltage or frequency deviations on the grid, potentially causing more disconnections and, ultimately, triggering a cascade. Thus, electricity is almost unique among commodities in the way that a local supply-demand imbalance can cascade into widespread service disruptions, potentially affecting millions of customers located far away from the original market imbalance, as happened in 2003.

Despite this possibility of serious negative spillovers from a local imbalance, electricity grids typically cover very large areas due to the value of supply diversification in maintaining supply-demand balance. Even with conventional generation resources, assuring adequate supply is challenging, due to the risk of generator outages and the uncertainty of peak demand levels. Because outages and demand are imperfectly correlated across regions, connecting them into a common grid reduces the cost of capacity needed to reduce the probability of a supply shortfall below any given level. In the continental US, there are three main grids – roughly covering west of the Rocky Mountains, east of the Rockies, and Texas – each of which connects many different utility service areas.

Due to the unique physics of electricity, maintaining on-demand availability to millions of customers requires a precise juggling of real-time delivery systems. Furthermore, the complexity of electricity flow on a grid with millions of connected sources and sinks means that it is not practical in real time to establish which entities are responsible for a supply shortfall or surplus.<sup>3</sup> Because this interdependence stretches across areas served by different electric utilities,

<sup>2</sup>Beyond transmission capacity constraints on individual lines, movement of electricity around the grid is also constrained by Kirchhoff's Law, which dictates that electricity flows among multiple paths on a grid in inverse proportion to the resistance of each path. Unlike natural gas or water, there are no cheap valves that can be used to direct electricity to the most valuable location. As a result, the capacity to move electricity between locations is a very complex physics relationship that depends on the demands and supplies at each node of the grid.

<sup>3</sup>In fact, grid operators keep the system in balance not directly by measuring output from generation and consumption from customers in real time, but indirectly by measuring voltage, frequency, and other attributes that reflect aggregate supply-demand balance at various locations on the grid.

extensive rules have been developed over the decades to manage reserves and operational standards in real time.

Standards for operations and reserves help reduce local imbalances and generally prevent them from cascading to neighboring areas. Most economists who study electricity markets agree that relying purely on market forces to provide these types of real-time services would not be efficient, because of imperfect information and the fluctuating, and potentially massive, externalities from a local supply-demand imbalance. However, for long-run investments in electricity generation capacity to maintain grid reliability there is less agreement on the role of markets versus regulation.

In this paper, we review the historical and current landscape of regulations and markets created to assure reliability of this unusual, and critical, product. Unlike very short-run electricity imbalances, shortfalls in planning and investment can be assigned to specific actors as they occur. Thus, while real-time operations to assure reliability are generally carried out by a central grid operator—called a Regional Transmission Organization (RTO) or Independent System Operator (ISO) in the US<sup>4</sup>—advanced procurement of adequate supply is typically less centralized. Furthermore, the market design and mechanisms for rewarding investments in supply capacity vary greatly, from “energy-only” wholesale markets—where all compensation comes from selling electricity—to various forms of remuneration for capacity availability, whether or not that capacity produces electricity at the time.<sup>5</sup> Regardless of the design, these markets are facing new challenges as they use less “dispatchable” generation (*e.g.*, natural gas, coal, or nuclear) and more “intermittent” sources that fluctuate exogenously, like wind and solar.

In one sense, the problem faced in electricity supply is similar to any industry in which a complex web of vertically-related firms must coordinate on production and remuneration to deliver a product to consumers. Electricity, however, is possibly the most challenging situation due to the physics of grid stability, the high cost of storage, the shared network of transmission, the mix of for-profit companies with non-profit or heavily regulated firms, and the critical role this product plays in the functioning of an economy.

## I. A Short Primer on Electricity Regulation and Deregulation

The electricity industry has four main segments: generation, transmission, distribution, and retailing/billing. The first three involve physical hardware to produce and distribute electricity, while the fourth is a procurement and accounting function. Historically, all these segments were vertically integrated within

<sup>4</sup>We are not aware of any systematic difference between organizations that call themselves RTOs and those that call themselves ISOs. Throughout this paper we will refer to RTOs to represent either type of organization.

<sup>5</sup>The term energy-only is a bit of a misnomer in the sense that these markets do also procure and price ancillary services as well as electricity. Nonetheless, the term highlights the absence of any additional long-run compensation for capacity.

regional utility companies operating with monopoly franchises for serving customers within each of their territories (Joskow, 1997). There was also some trading among regional utilities, and there were some utilities—primarily municipal or cooperative distribution utilities—that purchased all of their power from other utilities and engaged only in distribution and retailing/billing.<sup>6</sup>

While some vertically-integrated utilities were owned by local governments or associations of governments, the majority of electricity in the US was and still is sold through investor-owned utilities under regulation by state agencies. Decades of such regulation under cost-of-service principles raised concerns about the incentives provided to regulated utilities and their resulting efficiency (Borenstein and Bushnell, 2000).

Starting in the late 1990s, several US states began restructuring their power sectors. Electricity generators began to earn market prices, and independent power producers could enter into this market. Furthermore, in many regions, the incumbents (the vertically-integrated, investor-owned utilities) were required to sell off their generation or operate it in a separate entity under market prices. Decisions about the type and amount of investment in new generation capacity shifted from a regulatory forum to a decentralized, market-based process. Power transactions, rather than being internal to a firm or between neighboring utilities, were to be made through a centralized wholesale power market.

Those centralized markets are operated by RTOs, which run the auctions that clear the wholesale energy markets as well as order minute by minute adjustments in output from generators in order to constantly balance supply and demand at each location. To do this, the RTOs also run markets for “ancillary services,” which are short term commitments by some generators to make capacity available that can increase or decrease output at the request of the RTO. RTOs also ensure reliable and non-discriminatory access to transmission systems. High-voltage power lines (*i.e.*, transmission) and low-voltage ones (*i.e.*, distribution) continue to operate as natural monopolies. As such, they remain under economic regulation at either the state or federal level. As in the decades before, investments in transmission and distribution (T&D) assets are reviewed by federal and state governing bodies and costs recovered under cost-of-service regulation principles.

Around the same time that many states moved to deregulate electricity generation, a smaller number adopted various forms of “retail competition.” The phrase means that customers can purchase their electricity from retailers other than the utility that provides local physical distribution of the electricity. Such competitive retailers need not be in the physical side of the electricity business, and most are not. Instead, they procure electricity from generators under longer-term contracts, or out of the wholesale spot market, and sell electricity to re-

<sup>6</sup>The industry also includes Federal Power Marketing Administrations, such as Bonneville Power Administration and Tennessee Valley Authority, which focus on the generation and transmission segments, and have little or no presence in distribution or retailing/billing.

tail customers. In most states with retail competition—including Texas, Ohio, Massachusetts—the retailers are for-profit companies, but in other states—such as California and Illinois—retail competitors can also, or only, be local government agencies. By the nature of such retail competition, neighboring customers need not be buying power from the same retail provider. All retailers, whether competitive for-profit, competitive non-profit, regulated investor-owned utility, or government entity, are collectively known as load-serving entities (LSEs).

Many states with retail competition retain a regulated “default provider” option for customers who choose not to actively switch to another provider. To date, retail competition has proven more popular with larger commercial and industrial customers. The majority of residential customers remain with their default provider, with the exception of Texas which does not have a regulated default retail provider (Borenstein and Bushnell, 2015).

Importantly, even in deregulated states, the reliability of a household’s electric supply is decoupled from its choice of retail service provider. The regulated utility distribution company delivers power to all retail customers to meet their real-time demand, regardless of which retailer is procuring power for the customer. Retailers are then responsible for covering the wholesale cost of all electricity delivered to their customers. When there is a supply shortfall, stability of the system is maintained through “load shedding,” demand reductions achieved by cutting all power to some customers. Typically, that is applied randomly by neighborhood with no consideration of which retail provider has procured insufficient supply.

As of 2021, about 69% of all electricity delivered in the US is in regions that are part of RTOs and about 44% is procured in markets with significant retail competition.<sup>7</sup>

## II. Reliability in Electricity Systems

As the experience from the 2003 blackout illustrates, electricity reliability is a function of much more than just adequate investment in generation capacity. In fact, by far the most common cause of electricity service interruptions (*i.e.*, blackouts) is a localized failure in the distribution system, such as might be caused by a tree branch falling on a power line. Electricity service interruptions can be categorized as localized distribution outages, larger-area transmission outages, or supply shortfalls, any of which, if not properly managed, can lead to cascading system outages.

When shortages of supply have occurred—with recent examples in California

<sup>7</sup>EIA form 861 provides data on electricity sales in Megawatt-hours (MWh). We define customers as being in an RTO if their retail provider is in a balancing authority (BA) that is one of the seven RTOs shown in Figure 4. Retail competition is state policy. Thus, we define retail competition as having electricity sales in a given ‘market’ (a BA-state pair) that are from non-utility retail providers (their service type in the EIA-861 sales data is not ‘Bundled’). A market is considered to have significant retail competition if non-utility retailers account for at least 10% of sales.

(2020), Texas (2021), Tennessee (2022) and North Carolina (2022)—shortfalls are generally anticipated far enough in advance to manage the shortage without disrupting supply to the vast majority of customers. Even during the Texas energy crisis in February 2021—the largest and most costly service interruption since the 2003 Northeast blackout—over 25% of projected consumption was curtailed, but the remaining 75% was delivered by the still-operating regional grid (UT Austin Committee, 2022). As serious as the Texas crisis was, it did not create cascading outages and far more drastic disruptions, though it came extremely close (Blunt and Gold, February 24, 2021).

Cascading outages—the most severe and rare type of outage by far—arise when there is a localized shortfall, usually due to the failure of a generation or transmission resource, that is not contained quickly enough by interrupting local customers. This is the distinctive feature of electricity systems: a local supply-demand imbalance effectively can disrupt the grid on a very large scale if not dealt with quickly and properly. In this way a *small* supply shortfall, which in markets for other goods and services would result in rationing supply to a small number of customers, in electricity can result in interrupting service to all demand, not just the amount that is in excess of available supply.

#### A. *Causes and Magnitudes of Outages in the US*

Many outages are unplanned, last-minute responses to weather or issues with the grid as discussed above. However, there are also planned outages that are usually for purpose of maintenance on distribution lines. Recently, planned outages have also been used in California due to the risk of wildfires and the resulting need to de-energize some transmission or distribution lines in order to prevent them from sparking fires (known as “Public Safety Power Shutoffs”). The data below do not make a distinction of whether the outage was planned or not.

Distribution utilities report information on the frequency and duration of outages.<sup>8</sup> For some utilities, we observe whether an outage was initiated at the distribution system (low voltage) or the transmission network (high voltage). The high-voltage outages might be caused by insufficient generation resources or by problems with the transmission wires. The System Average Interruption Duration Index (SAIDI) measures how many minutes the average customer served by a distribution utility experienced outages for a given year. Another index, SAIFI, measures the frequency of outage events: how many times a year did the average customer at a utility experience an outage.

From 2015 to 2020, customers experienced an average of 1.34 outages a year with an average cumulative duration of 5.67 hours annually. Distribution system outages account for the vast majority (87%) of customers’ outage minutes, with

<sup>8</sup>See the Annual Electric Power Industry Report (EIA form 861).

the balance being due to transmission or system supply shortfalls.<sup>9</sup>

These outages are not distributed evenly throughout the country. Figure 1 shows the distribution of the number of hours per year of outages across utilities, weighted by the number of customers, truncated at the 95<sup>th</sup> percentile. While most customers just experience a couple hours of outages annually, the distribution has a long right tail with some averaging over 15 hours a year. Entergy (a large utility in Louisiana) averages over 38 hours a year and some small cooperatives are over 100 hours. Figures 2 and 3 show spatial distribution of the average number of annual outages and minutes without power by county for the contiguous US. We see that customers in some states (namely, Louisiana, Maine, Oklahoma, West Virginia, and Connecticut) experience more than twice as much time with outages than the national average. In addition to these states, outages are also more common in Alaska and Vermont.

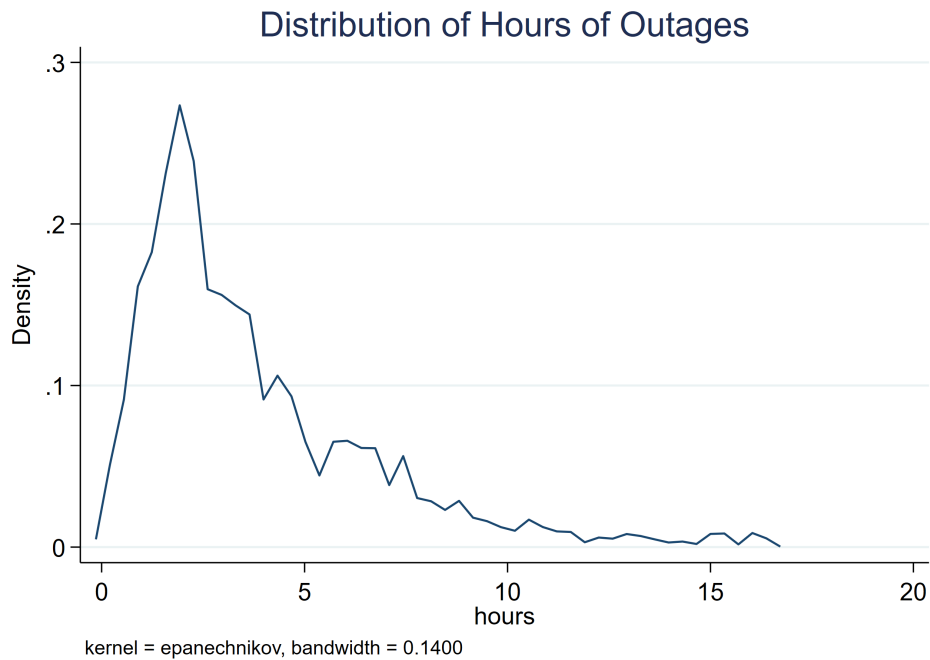


Figure 1. : Density of annual hours of outages across Utilities

<sup>9</sup>Distribution system outages are the 'System Average Interruption Duration Index with Major Event Days Minus Loss of Supply'. This index follows the Institute of Electrical and Electronics Engineers (IEEE) standards for measuring an outage duration (SAIDI). We use the measure that includes all outages (a major event day is an "interruption or group of interruptions caused by conditions that exceed the design and operational limits of a system" (see [https://www.eia.gov/electricity/annual/html/epa\\_11\\_01.html](https://www.eia.gov/electricity/annual/html/epa_11_01.html)). From this, the utilities remove 'loss of supply', which is an outage that was initiated from the high-voltage system.



### Outage Frequency (events/yr)

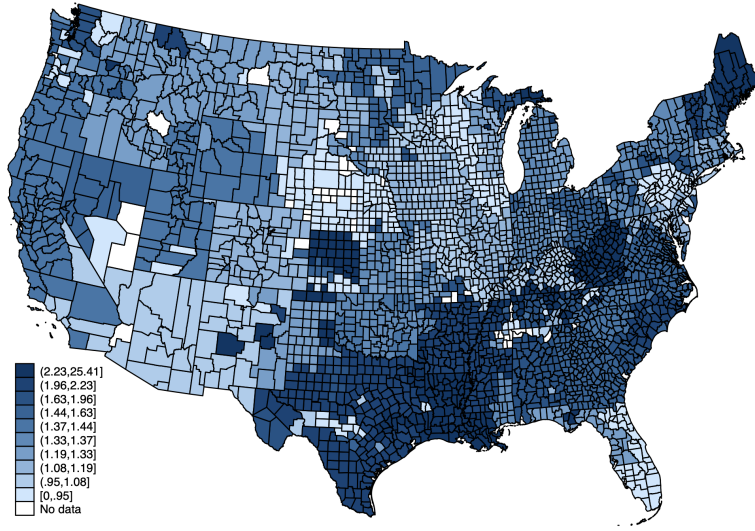


Figure 2. : Annual Number of Outages by County

### Outage Duration (hours/yr)

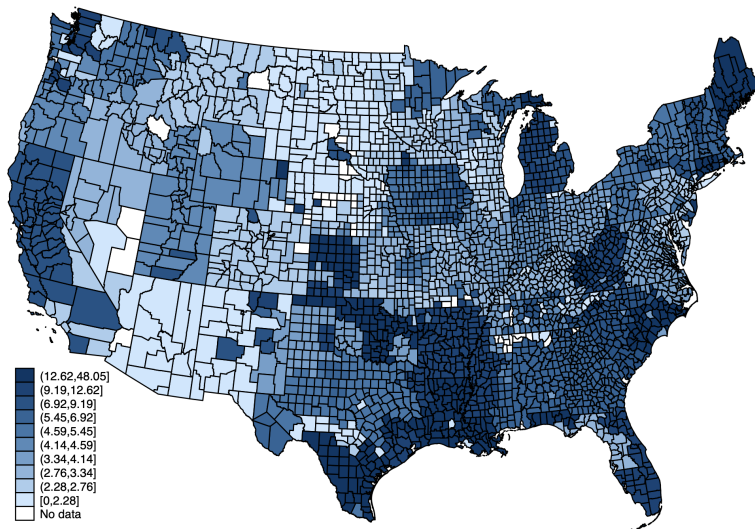


Figure 3. : Annual Minutes of Outages by County

The Electric Emergency Incident and Disturbance Report (Form DOE-417) lists specific large outages and other major events like the 2021 Texas energy crisis.<sup>10</sup> Table 1 pools reports over the past 20 years. While the 2003 Northeast blackout and the 2021 Texas crisis are notable, there are large events in most years. In fact, despite the Texas electricity crisis in 2021, that year overall had a similar total number of customers affected and energy losses from outages as other years. Table 1 shows the largest events (reported in millions of customers affected and power losses) from 2002 to 2021 by region and event type. Most are weather related.

### *B. The Economic Cost of Unreliable Electric Supply*

While it is clear that power outages are costly to customers, it is much less clear exactly how costly. Within the electricity industry, the cost of an outage is characterized by the “Value of Lost Load” (VOLL), a concept used for planning and investment decisions. Somewhat surprisingly to economists, policy discussions typically are about a single VOLL per kWh number, rather than a demand curve for electricity services with some end-uses producing much greater value than others. Gorman (2022) presents an intellectual history of VOLL and discusses the ways in which it overlaps with standard economic consumer theory, and the ways in which it departs. A single VOLL is somewhat consistent with an approach in which retail price is unresponsive to supply/demand balance and rationing is unrelated to the value derived from a particular use by a particular customer. In that case, the aggregate lost gross consumer surplus from a quantity shortfall would, in expectation, be equal to the size of the shortfall multiplied by the average gross consumer surplus across uses, which the VOLL is intended to reflect.<sup>11</sup> Even in that case, however, VOLL fails to account for critical characteristics of outages that would cause the lost consumer surplus to vary, such as weather and other environmental factors at the time of the outage, the extent of warning customers are given prior to the outage, as well as the size and length of the outage. The 2021 Texas energy crisis, for instance, illustrates that an outage during extreme cold that lasts for multiple days, and in some cases covers large areas so critical electricity services are not available nearby, is likely to be particularly costly per lost MWh.

There is an extensive literature on the economic effects of the availability and reliability of electricity in developing countries. This literature has not reached consistent findings. Some papers have found relatively modest economic effects in the short run (Dinkelman, 2011; Lee et al., 2020; Burlig and Preonas, forthcoming). However, others have found larger effects when the economy more fully adjusts over time (Lipscomb et al., 2013; Fried and Lagakos, forthcoming).

<sup>10</sup>Note that not all of these events are outages as it lists all major disturbances and unusual occurrences.

<sup>11</sup>Thus, the use of VOLL bears some resemblance to the use of the “value of a statistical life” numbers that are often used in policy analysis, except there is a potentially more straightforward market source for deriving VOLL.

Table 1—: Major Outages by Event Type, State and Year

Event Type	Region	Year	Customers Affected (millions)	Power Loss (Gigawatts)
Cascading Blackout	Northeast US	2003	7.37	78.64
Winter Storm Uri	Texas	2021	2.12	16.41
Hurricane Florence	North Carolina	2018	1.78	15.00
North American derecho	Atlantic/Midwest	2012	8.60	13.61
Hurricane Wilma	Florida	2005	3.24	10.00
Severe Weather	Washington state	2018	4.20	10.00
Transmission	Nevada	2021	1.30	9.00
Severe Weather	Nevada	2020	1.40	8.18
Hurricane Ike	Texas	2008	4.65	8.09
System Operations	Nevada	2021	1.30	8.00
System Operations	AZ/CA	2011	2.00	7.00
Hurricane Isabel	NC/VA	2003	1.80	6.51
Tropical Storm Isaias	New York Area	2020	2.94	6.22
Hurricane Frances	Florida	2004	2.78	6.00
Hurricane Matthew	Florida	2016	1.20	5.60
Hurricane Katrina	Louisiana	2005	2.08	5.54
Hurricane Irma	Florida	2017	3.92	4.50
Generation Inadequacy	Texas	2011	1.07	4.00
Wild Fires	California	2014	1.40	3.90
Weather/Transmission	California	2019	0.97	3.19
System Operations	Puerto Rico	2016	1.48	2.75
Cable accidentally cut	California	2005	0.90	2.58
Hurricane Rita	Lower Miss. Valley	2005	1.61	2.30
Severe Weather	Puerto Rico	2011	0.93	2.20
Equipment Trip/Failure	Puerto Rico	2012	0.90	1.80
Severe Weather	Missouri/Illinois	2006	2.50	1.50
Hurricane Charley	Florida	2004	1.20	1.40
Hurricane Jeanne	Puerto Rico	2004	1.42	1.24
Severe Weather	Maryland	2011	0.87	1.11
Hurricane Ivan	Southeast US	2004	0.92	0.92

Blackouts in developing countries have been shown to have economic costs on manufacturers, by altering inputs (Fisher-Vanden et al., 2015) and changing their scale of operations (Allcott et al., 2016). Blackouts are transitory shocks that reduce workers' earnings and lead to lower birth weights (Burlando, 2014).<sup>12</sup>

<sup>12</sup>Additional papers examine another reliability issue not common in industrialized countries, namely, unstable voltage or frequency (Trimble et al., 2016; Zhang, 2018; Carranza and Meeks, 2021; Berkouwer et al.,

There is, however, very little work on the effects of electricity reliability in the US or other advanced economies. In part, this is likely because levels of reliability are so high that it is difficult to tease out the longer run impacts of variation in reliability among US states or between countries with developed economies. There are a few studies of specific blackout events, including the Northeast blackout of 2003 and Texas in 2021, but even those extreme events raise substantial estimation challenges. Gorman (2022) discusses some attempts to infer the economic cost of unreliable supply from assumed elasticities of demand, but points out that this omits all of the factors that cause the economic loss to vary across events and customers. Some of the challenges are fairly specific to electricity, such as fixed prices and random rationing, but others are present in a wide range of issues associated with supply shortfalls, such as the correlation of demand with supply shocks and the impact of the shortfall's time span and prior warning of it.

### III. Economics of Supply-Demand Balancing in Electricity Spot Markets

As discussed above, periodically grid operators ration electricity through load shedding in order to keep localized shortfalls from expanding into regional blackouts. It is natural for an economist to ask why rationing is required at all, and why prices are not able to clear market imbalances. After all, even with relatively inelastic demand and strict capacity constraints, at some price the market would be expected to clear. Under standard assumptions, a perfectly competitive market charging the market clearing price in each period maximizes welfare in the short run. Furthermore, as shown by Steiner (1957) and Boiteux (1960), the scarcity rents created when demand strains generation capacity incentivize efficient generation investment—both quantity and technology type—in the long run.

In this section, we describe the combination of factors that have historically made this mainstream economic view of market clearing a fringe idea in electricity (Joskow and Tirole, 2007). Our focus is primarily on electricity systems that have deregulated wholesale electricity generation markets, as is the case in most of the US and most developed economies, though we also discuss how the issues manifest in more traditional vertically-integrated service areas.

The changing regulation of electricity generation in many developed economies during the 1990s and 2000s decentralized responsibility for investments in generation capacity. State and regional organizations continued to produce forecasts of demand and of generation resources, but no single entity was tasked with the responsibility of investing in the generation capacity necessary to meet the demand forecasts. While some economists expected that electricity prices would

n.d.). For example, Meeks et al. (2021) note that voltage fluctuation is a major issue in the Kyrgyz Republic. The authors use a randomized control trial to examine how installing smart meters affects service quality and find that treatment results in less voltage fluctuation and more electricity sales.

provide sufficient information and incentive to support investment, others argued for procurement mandates that are applied to all LSEs or a centralized market for procurement of generation capacity availability, as distinct from the sale of electricity itself. A number of electricity market factors are highlighted by those who see a need for greater regulation or coordination of capacity procurement.

#### *A. Little demand-side price response*

Due to fluctuating and inelastic demand and supply functions, along with very costly storage, the wholesale price of electricity can vary drastically even within a day. On high-demand days, the wholesale price during the minutes or hour with the tightest supply/demand balance can be 10 times or more the price during lower demand times of the same day. In almost no cases, however, do retail customers see any reflection of those prices. Instead, customers generally face prices that are set months or longer in advance—either a constant price at all times, or higher pre-set prices during some hours than others. Even such “time-of-use” (TOU) prices, however, reflect very little of the variation in wholesale prices, because peak demands and fluctuating supply constraints are typically weather driven and unpredictable months in advance.<sup>13</sup> Retail suppliers, however, are typically required to serve whatever quantity a customer demands at these pre-set prices, what is known as a “requirements contract.”

As a result, the derived demand for electricity in the wholesale market becomes extremely inelastic at a given point in time, regardless of how much consumers would actually respond if they faced retail prices that moved more dynamically with wholesale prices. This absence of real-time price signals to consumers also exacerbates market power concerns, as the inelastic derived demand makes the exercise of market power more profitable in the wholesale market.

#### *B. Price caps in wholesale markets*

Producers typically face price caps in the spot market for generating energy. While firms generally hedge risk with long-term contracts and trade most of the energy in advance, the prices for those trades are determined knowing that the final spot price is limited. In some cases, price caps may limit the ability of producers to exercise market power. However, they could also result in excess demand if they are set below the competitive level. For example, this could occur if short-run demand is even slightly elastic and fuel prices spike or other factors cause short run marginal cost to rise above the price cap.

One common argument for capping the price of electricity and wholesale markets is based on the fact that electricity is physically supplied in real time, but

<sup>13</sup>See Borenstein (2005). However, Schittekatte et al. (2022) provides an analysis suggesting that TOU pricing may become more reflective of costs under high levels of shiftable loads that may result with electrification of vehicles and buildings.

financial settlements take place weeks later. So a buyer might be unaware that they are consuming at an astronomical spot price, and be on the hook much later for that payment. Wholesale buyers, however, submit demand quantities that are a function of price, so they could impose their own price ceiling on their wholesale purchases.

### *C. Correlated risks in generation availability*

Supply-demand imbalances increase in likelihood if power plant outages may result from common shocks. For example, a natural gas pipeline accident or extreme cold could limit fuel supply for all gas-fired plants in a region, as happened in Texas in 2021. Similarly, a lull in regional wind associated with extreme heat would limit production from all wind turbines. For conventional technologies, most unplanned outages are primarily due to uncorrelated shocks, such as equipment failures. However, as electricity systems decarbonize by increasing generation from intermittent renewable resources—wind and solar—availability will become more correlated across power generation sources either due to known variation like the sun setting or stochastic events like cloud cover or wind lulls.

### *D. Random rationing makes supply shortfalls a public bad*

The likelihood of supply-demand imbalances due to the combination of price caps, highly inelastic demand, and correlated risks is heightened when the expected peak demand is nearly as great as the entire aggregate capacity in the system (*i.e.*, when the reserve margin is tight). Because such imbalances are addressed by shutting off power by distribution circuit—without regard to willingness to pay to avoid being blacked out or to who helped contribute to the shortage by not investing in, or contracting for, capacity—power shortages are turned into a “public bad” where individual retailers can free ride on one another.

These challenges in wholesale markets imply that there are extraordinary consequences of insufficient capacity investment. Like many capital-intensive industries where firms face uncertain demand in making irreversible investments, power generation can exhibit boom-bust cycles. While other such industries—such as resource extraction and semiconductors—have seen periods of high prices followed by excess entry and a price crash, we do not see many calls for coordinated firm investments in those industries. In fact, where such entities exist, such as OPEC, the negative impacts of their collusive activities are typically highlighted. Nonetheless, because of the notable economic challenges discussed here, some argue that there is need for coordinated capacity investment in electricity.

#### IV. Current Approaches to Long-Run Supply Adequacy

Currently in the US, there are three general approaches to supporting long-run capacity investment that is sufficient to meet expected demand, a process called “resource adequacy” (RA) within the industry. The first approach is the traditional electricity industry structure in which a monopoly utility makes investment under either the close regulation or direct ownership of the government. The second approach is a deregulated wholesale “energy-only” structure, similar to the process that drives investment in most other commodity markets. Firms make decentralized and independent investment decisions based largely upon expectations of future electricity prices. The third approach applies a hybrid of deregulation and centralized planning by imposing capacity procurement requirements on electricity retail service providers operating in deregulated markets. Figure 4 shows the seven US RTOs, of which only ERCOT has an energy-only structure. The others markets follow the third approach and have RA requirements (*e.g.*, capacity markets).<sup>14</sup> The areas in white remain under traditional vertical integration and manage resource adequacy primarily through the state regulatory oversight process. We discuss the benefits and risks associated with each approach below.<sup>15</sup>

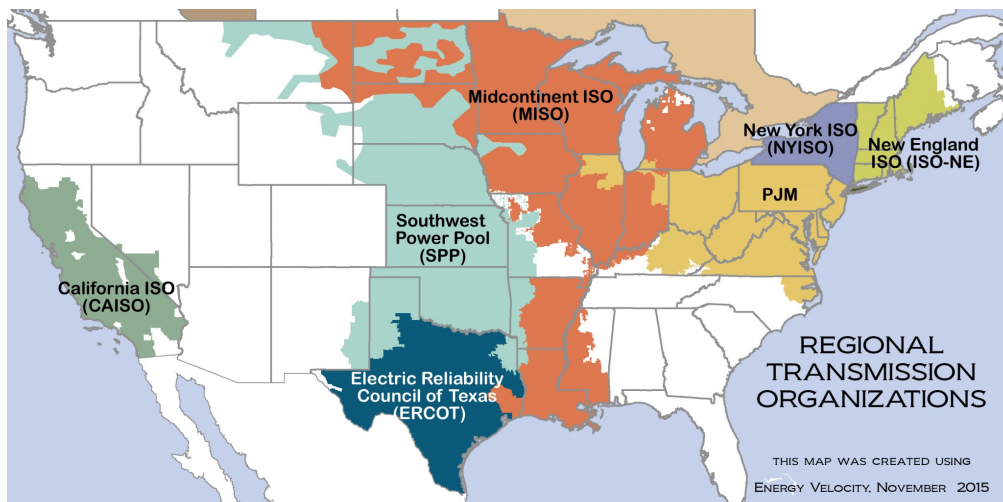


Figure 4. : Regional Transmission Organizations

<sup>14</sup>Source is <https://www.ferc.gov/sites/default/files/2020-05/elec-ovr-rto-map.pdf>.

<sup>15</sup>Some of the utilities in the white area of the map, while vertically integrated, participate in wholesale markets that have some resource adequacy requirements, so the determination of capacity needs is a hybrid of state regulatory oversight and the requirements of the wholesale markets in which they participate. Some utilities within some of the RTOs remain vertically integrated, in that they still own significant generation that is subject to state regulation, but by virtue of being part of the RTO, they are required to be part of the RTO's RA program.

It is important to recognize that significant new capacity has been built under all three approaches. Figure 5 shows the cumulative percent of existing capacity (namely those still operating as of 2021) by the year that the capacity was added to the grid.<sup>16</sup> This is not a measure of total capacity in each year as plants that have retired over this time are not included.

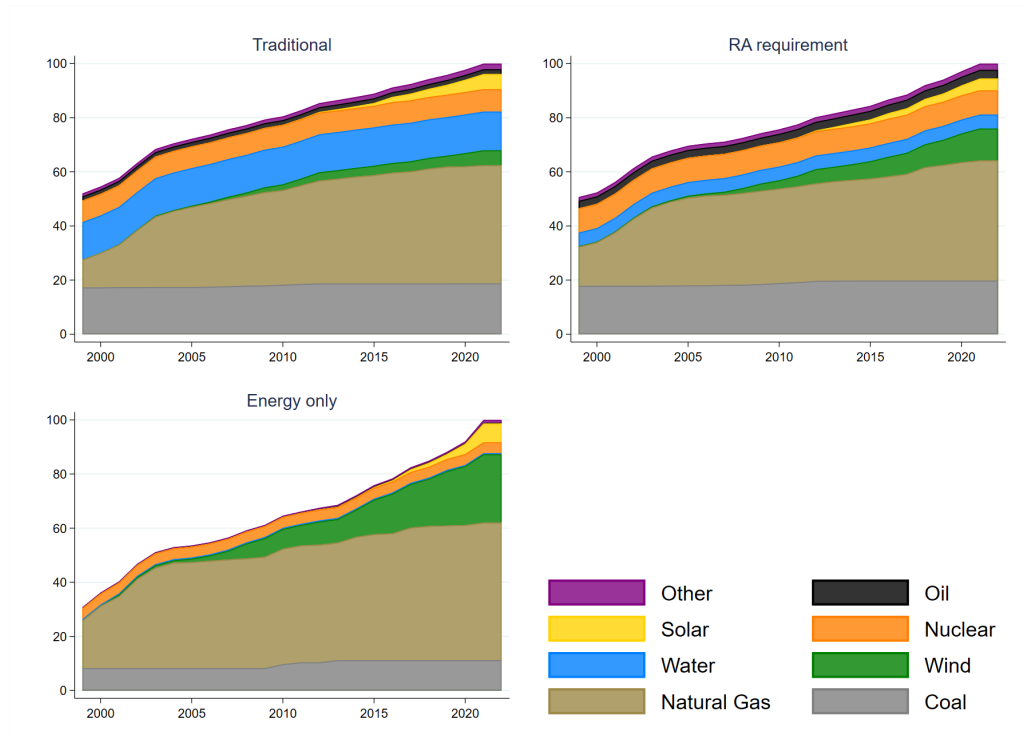


Figure 5. : Percent of Existing Capacity Reported Cumulatively by Initial Year

#### A. Traditional Vertical Integration and Regulation

Among the vertically integrated electric utilities, which still serve about one-third of the US demand, the typical RA process involves joint planning between the utility and its regulators to forecast future demand and establish “needs” for new investment. Specific generation quantities and types, as well as alternatives such as new transmission or demand reduction programs, are negotiated between utility and regulator. Investment in new capacity is then either made directly by the utility or purchased via a competitive solicitation overseen by

<sup>16</sup>Data are from EIA form 860. All plants that began operating before 2000 are grouped in 1999.



regulators. Once the need for new capacity is established, the recovery of investment costs is largely guaranteed by the regulator, except in the case of extreme cost overruns or gross negligence. The coordination of investment and retirement decisions for both generation and transmission is centralized within a single decision-making process.

At first glance, the combination of regulatory oversight, vertical integration, and monopoly franchise would seem to greatly simplify the process of resource planning. The incentive to free ride on the supply of another retailer is substantially reduced, though it can still arise to some extent between utility service areas that are part of the same grid, known in the industry as “leaning.”<sup>17</sup>

However, the traditional system lacks incentives for efficient investment given the near-guaranteed recovery of investment costs.<sup>18</sup> The system can create a theoretical bias toward capital (Averch and Johnson, 1962), although the specific implementation of regulation matters (Joskow, 1974). In general, the process can create incentives to inefficiently overbuild, thereby enhancing system reliability but at a potentially inflated cost (Joskow, 1997). Indeed, most of the impetus for restructuring the industry inside the US arose in states with high rates that could be traced to either excessive or inefficient investments in capacity (Borenstein and Bushnell, 2000).

#### *B. Deregulated wholesale markets without resource adequacy requirements*

As described in Section I, the deregulation of generation meant the decentralization of investment decisions in that sector. Regulatory reviews of investment decisions had largely been motivated by a need to justify and approve expenditures that would be added to the capital rate base of a regulated monopoly. With deregulation, the capital invested in generation was no longer guaranteed a regulated rate of return, and the dynamic therefore shifted from a concern over *excess* investment to one of potential inadequacy.

As with markets for most commodities, many deregulated electricity markets around the world rely upon expectations of future prices to provide the signal and incentive for investment in generation capacity. Indeed, wholesale electricity prices are quite sensitive to capacity margins. While prices typically range from \$10-\$80 per MWh, negative prices and prices exceeding \$1000 occur commonly (Table 2).

These markets depend on energy prices to signal the need for investment and thus tend to feature high price caps and exhibit more volatile spot-market prices. Figure 6 shows the highest hourly price in a given month for the ERCOT (Texas)

<sup>17</sup>The North American Electric Reliability Corporation (NERC), an industry association, has for decades coordinated standards to prevent leaning between utility control areas. Shortly after the 2003 Northeast blackout, the Federal Energy Regulatory Commission gave NERC authority to impose mandatory standards and to enforce penalties for failure to meet them (Nevius, 2020).

<sup>18</sup>Investments are evaluated by state regulators based on a ‘used and useful’ criterion. Rarely are costs excluded from the rate base, which are then passed on to customers.

Table 2—: Summary Statistics of Spot Prices in Wholesale Electricity Markets

	Mean	SD	Min	P10	Median	P90	Max
CAISO	33.87	39.85	-186.32	13.43	29.14	48.93	985.76
ERCOT	27.51	44.14	-24.18	14.54	21.99	38.94	5001.00
ISONE	40.24	45.39	-157.85	14.77	28.52	71.17	2454.57
MISO	28.19	19.41	-29.94	17.45	24.36	40.80	1805.60
NYISO	27.24	26.86	-223.93	10.57	23.01	41.38	927.48
PJM	32.17	31.37	-229.98	17.12	26.21	48.11	1839.28
SPP	23.82	26.62	-57.42	11.46	19.75	35.53	1592.68

Notes: In most markets, hourly spot prices (in \$ per MWh) are FERC 714 system lambdas that correspond to average real-time prices in markets from January 2013 to December 2020. CAISO prices are from [www.energyonline.com](http://www.energyonline.com).

energy-only market as well as for the two RTOs with the most mature capacity markets. Of all of the RTOs, ERCOT has experienced the largest, most frequent, and longest price spikes. While this mirrors the investment process in most other industries, electricity markets face the challenges discussed earlier that exacerbate the size and potential disruption from supply-demand imbalances. Because these imbalances are so costly, grid operators in energy-only markets typically attempt to provide guidance on future demand and other information intended to enable producers to plan more effectively.

Futures markets help enable capacity investment for production of a commodity when prices are unstable by aggregating information and beliefs about the future price, and by lowering the cost of making trades to hedge future prices. Unfortunately, due to the properties of electricity, futures markets have had very limited success. Since a futures contract specifies exact characteristics for delivery of a product—most importantly, in this case, the location and timing of delivery—the contracts will be most valuable if prices at the specified time and place of delivery are highly correlated with prices for delivery at other locations or times, or for closely related products. This minimizes “basis risk,” the volatility of the price differential between the contracted commodity and the commodity price for which one or both sides of the market is trying to hedge risk. Electricity prices, however, exhibit extreme basis risk, with high storage cost allowing temporally nearby prices to differ drastically and the potential for transmission constraints allowing locationally nearby prices to differ drastically. As a result, forward contracts for output from generation, while still fairly standardized in form, do not trade in a liquid or transparent market.

Finally, many energy-only wholesale markets are in areas with substantial retail competition. The higher and more volatile energy prices heighten price risk for retailers in energy-only markets. This price risk can provide a stronger incentive for retailers to procure - or hedge - their energy in forward markets. Some retailers physically hedge this risk by vertically integrating between generation

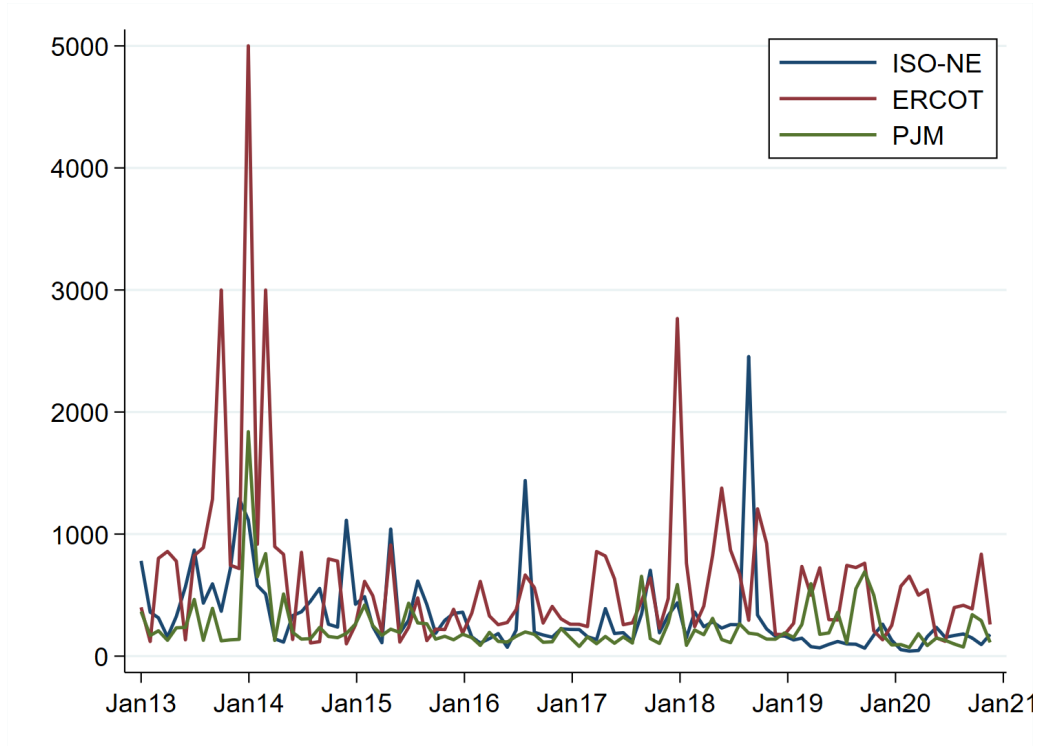


Figure 6. : Maximum Hourly Real-time Prices by Month and Market

and retailing functions. Some, however, benefit from bankruptcy laws by offering a fixed retail price and not hedging: if the wholesale spot price ends up low, they make money; if the wholesale price ends up high, they exit. When retailers fail to hedge, however, that reduces the quantity of power purchased through long-term contracts. Such contracts may be key to supporting investment in a capital-intensive industry with irreversible investments.

In Texas, the massive reliability problems triggered by winter storm Uri in February 2021 put the energy-only paradigm under greater scrutiny. It is not clear, however, that the typical capacity markets would have coped much better with that disruption. A critical element of winter storm Uri was the inability of much of the installed generation capacity to operate reliably, in some cases due to direct mechanical failures, but in more instances resulting from the lack of available natural gas supply. As discussed below, many markets with capacity requirements feature relatively weak incentives to ensure reliable performance from the capacity that is procured, and the performance requirements in markets that do feature them are arguably weaker than the \$9000/MWh energy price that was available for any generator that was able to produce during Uri.

### C. Deregulated wholesale markets with capacity payments

Many restructured power markets have adopted mechanisms that compensate generators for maintaining adequate capacity in addition to payments for the electricity produced from that capacity (Joskow, 2008). These regions combine concepts from traditional regulation, where ratepayers paid for the construction and operating costs of power plants, and energy-only markets where customers pay market prices for electricity. These deregulated wholesale markets have preserved a layer of regulatory planning by creating a distinction between “capacity” and the goods (*e.g.*, electrical energy) produced by that capacity. In general, capacity is procured through a coordinated planning process while energy is purchased in a more decentralized way. As we will discuss below, the distinction between capacity and energy has always been somewhat blurry, and is becoming more so with the advent of new supply technologies.

All markets with capacity payments follow a similar process with important distinctions as to how each step in the process is implemented. At a high level, this process entails the following steps.

- 1) **A forecast of resource capacity need** is determined at either a system or individual load-serving entity level. These forecasts range from months to several years into the future.
- 2) **Capacity is procured** in quantities that are certified to meet forecast needs. The procurement is implemented in some regions by a central entity (such as an RTO) and in others by a mandate applied to individual LSEs.
- 3) **Capacity either does or does not perform** during periods of tight resource needs. The performance requirements and incentives placed upon the capacity that is procured has varied greatly across regions and over time.

A series of extremely contentious regulatory hearings have focused on the process, the amount, and price of capacity that is procured. In the eastern US, grid operators centrally procure capacity for all LSEs, running reverse auctions where producers offer to have capacity available during a specific time period. In California, and much of the Great Plains, LSEs (including utilities) are obligated to procure or self-supply an amount of capacity based on the peak demand they serve, similar to an insurance mandate. Somewhat surprisingly, only recently has attention begun to focus on the performance and reliability benefits actually provided by the capacity that is procured.

Part of the argument for capacity payments is the presence of price caps in the associated energy markets, which are in turn justified by concerns over excessive market power in the energy markets. Price caps in electricity energy markets are believed to deny suppliers legitimate scarcity rents at times, creating a so-called “missing money problem” that constrains investment in capacity (Joskow, 2006; ?). Capacity payments are intended to replace those missing scarcity rents

(Bushnell, 2005). While the justification for capacity payments can be traced to market power concerns, it is important to note that the supply of capacity can also be vulnerable to market power.

When suppliers are overly concentrated, a mandate to purchase capacity from those suppliers can bestow market power upon them, at least in the short run. This market power can be exacerbated when capacity procurement is divided into localized markets with few sellers (Bowring, 2013). Conversely, state governments and regulators have been accused of depressing capacity prices in an anti-competitive manner by subsidising local generation through regulatory procurement, tax credits, and other incentives.<sup>19</sup>

The forecasting process entails projecting peak electricity demand needs at either a systemwide or LSE level. Projections of systemwide demand are more reliable as they do not require forecasts of the market shares of individual LSEs. Partly for this reason, regions that have adopted longer-term capacity requirements—more than a year in advance—tend to do centralized capacity procurement by the RTO based on systemwide demand forecasts.

The capacity planning approach has generally relied upon an explicit or implicit assumption that if systems are capable of meeting the hour of highest system demand, they will also be able to operate reliably in all other hours of the planning horizon. In other words, this approach assumes that if a system has enough capacity to meet its peak demand, it will have excess capacity in all other hours. This assumption has always been tenuous when applied to resources for which nameplate capacity may not reflect their ability to produce in a particular hour. This is true not only of renewable electricity, but also “energy-limited” resources such as hydroelectric power and storage. As these resources have come to comprise a growing share of the mix, the standard planning paradigms have become more stressed.

The supply shortages experienced in California during a heat wave in August 2020 provide an illustration of this issue. While California had a capacity requirement in place, it was focused on meeting hours of peak demand, usually in the late summer afternoon. However, the rapid expansion of solar power in California over the last decade left the state with ample supply during peak hours, but a critical need in the early evening as the sun set, which became known as the net demand peak (net of generation from intermittent renewables). On August 14, 2020, California was forced to implement blackouts around 6:30 PM, more than an hour after demand had peaked, when output was rapidly declining from solar farms, which had been credited with over 3000 MW of capacity towards meeting resource adequacy needs for that month (California ISO, 2021).<sup>20</sup>

Renewable and hydroelectric resources are not the only ones for which name-

<sup>19</sup>Several RTOs have deployed Minimum Offer Price Rules (MOPR), essentially bid floors on supply offers into capacity markets, in an attempt to offset these subsidies. These rules have been controversial in recent years as they have raised the cost of procuring nuclear and renewable resources (Aargaard et al., 2022).

<sup>20</sup>Solar was generating 3460 MW at 6:30 PM, but dropped by more than half by 7 PM and was down to 195 MW by 7:30 PM.

plate capacity has at times proven to be a poor measure of reliability contributions. Older fossil power plants have experienced periods of frequent outages, and historic approaches for penalizing such outages have been criticized as too weak. In addition, fuel supply, particularly that of natural gas, has proven to be a significant contributor to reliability problems in several regions, the most notable being the experience of Texas during winter storm Uri in 2021.

Faced with resources whose availability was viewed as unreliable, some regions have adopted more aggressive performance incentives for resources that sell capacity. The main policy question concerns what types of availability problems should be the financial responsibility of the resource and what problems should be considered a *force majeure*. Traditionally, for example, a capacity resource would not be considered responsible for a shortage of natural gas or low levels of wind. Furthermore, penalties have been relatively modest even for outages that were deemed the responsibility of the resource (Bushnell et al., 2017). More recently, some RTOs, such as PJM and New England, have moved to shift more liability for non-performance onto the sellers of capacity and have applied steep penalties, on the order of \$1000s per MWh to resources that are unavailable during a period of regional scarcity. By sharply increasing the per-MWh cost of unavailability, such penalties create performance incentives for resources that approach similar levels experienced in energy-only markets.<sup>21</sup>

## V. Going forward: Decarbonization and Technological Change

Electricity policy faces the challenge of reducing GHG emissions while ensuring reliable and affordable power. Costs have drastically declined for generation from wind and solar—the two technologies most associated with decarbonization—but output volatility from these sources would make supply less reliable if not combined with other resources. Luckily, progress in complementary technologies continues, from energy storage and automated demand response to “firm” carbon-free generation, such as new technologies for nuclear power and geothermal.

The shift to these alternative technologies affects power markets in three important ways: its impact on average wholesale energy prices; its impact on capacity market prices; and the extent to which intermittency of wind and solar, and energy limitations of batteries, create new reliability concerns that are not satisfactorily addressed by conventional RA crediting. Each of these concerns have been observed in restructured electricity markets. In California, for example, the penetration of utility-scale solar has helped drive low, or even negative, energy prices during the middle of the day (Bushnell and Novan, 2021). In addi-

<sup>21</sup>These so-called “performance capacity” policies have not been universally supported. Some critics fear that these policies shift too much risk to supply resources and could as a result lead to either under-investment or higher capacity prices. Others have pointed to the fact that penalties have rarely been applied. Natural gas shortfalls at some plants in New England during recent cold-weather conditions caused ISO-NE and PJM to trigger performance penalties for only the second time in over five years Barndollar (2023)

tion to influencing energy prices, renewable generation has earned an increasing share of capacity payments.

One key policy question, therefore, is whether alternative resources, such as renewable generation or battery storage, can and should provide a comparable form of “capacity” as conventional resources. Such questions get to the heart of what has been a central issue with RA policy from the start: what exactly constitutes “capacity” under such policies?

RTOs have struggled even to define the attributes that constitute the boundaries between conventional and alternative resources. Lithium-ion batteries provide a useful illustration. Battery chemistries continue to evolve and with them, their performance characteristics: charging and discharging speeds, round-trip energy loss, and capacity degradation and failure probabilities from different sorts of usage profiles. As an electricity *storage* technology, batteries must also be charged at some point, so their reliability value depends on the ability to adequately charge as well as discharge when they are called upon. And the incremental value of storage depends on the dispatchability of the electricity *generating* technologies on the grid. A system with high levels of dispatchable carbon-free generation will derive less value from storage technologies than one more dependent on intermittent renewables.

Among the key questions that have been debated and periodically revised are the following:

- Should capacity qualifying to provide RA be limited to resources that can be made available on demand, or evaluated based upon a probabilistic expectation of performance?
- How location specific should capacity procurement be?
- What performance obligations should be required?
- What are the penalties for non-performance?

These questions highlight the distinction between an energy-only setting and those with compensation for capacity. Performance in an energy-only setting is simply the sale of energy (or ancillary services) in a daily or hourly market. If a unit is operating and selling into the market, it earns revenue. If it is not, then it earns no revenue. Under a capacity payment paradigm, qualified units earn revenue in advance and can keep those earnings, in most cases even if the unit is not available under a long set of possible exemptions. When RA resources were of similar technologies and operated by firms with similar incentives, common assumptions about availability did not distort procurement very much. However, with more diverse resources, RTOs are again revisiting their assumptions about performance and the incentives provided to resources committed through RA markets.

Resource mix and resource adequacy paradigms also have implications for energy markets. Increasing generation shares from intermittent resources without

substantial cost reductions in storage or other complementary technologies will lead to growing wholesale prices volatility. More and more hours will have zero or negative prices, and a small number of hours will generate the vast majority of producer rents from the wholesale market. Years could go by with constant excess supply and low prices, and at other times there could be long periods of very high prices, as occurred recently in the Australian energy-only market. While in theory both sides of the market can insure against such scenarios through either long-term contracting with one another or third-party insurance, in practice such volatility may undermine confidence in wholesale markets. Furthermore, such volatility creates its own opportunities for unproductive strategic behavior, including LSEs using bankruptcy as an option when wholesale prices climb and they are inadequately hedged, as well as generators using tight wholesale markets to exercise market power. These possibilities may suggest a continued role for at least some sort of government-mandated level of insurance.

#### A. *Incentives and Mandates for Performance*

A capacity market would have no value if resources were not expected to be able to produce energy when the market was tight. Here we examine how capacity markets are being modified to consider incentives and mandates to achieve performance. In their review of the NYISO capacity market, Harvey et al. (2013) note the following:

*The larger the total revenues collected through the capacity market rather than the energy or ancillary service market, the greater the concern with the many inherent approximations that appear in the necessary simplifications of the complex problem of constructing forward estimates of resource requirements and defining administrative requirements to provide appropriate performance and investment incentives for capacity suppliers.*

When the types of capacity being procured were relatively similar, the simplifications and assumptions created less bias among resource types in procurement. These stresses have become more significant with the increased use of alternative resources to meet capacity needs. This has left the designers of RA policies with two choices: (1) further refine and categorize, ex ante, the types of capacity to be required; or (2) increase reliance on performance incentives to provide signals about the characteristics and performance abilities of new capacity.

RTOs are taking a diverse approach to this choice. Harvey et al. (2013) strongly support an emphasis on performance incentives, arguing that “attempting to use capacity market rules to elicit capacity resources with the optimal mix of characteristics to meet load over the operating day has the potential to become more and more difficult as the diversity of the resource mix increases and has the potential to end badly, resulting in both lower reliability and higher consumer cost.” In New England, ISO-NE has also shown a preference for strong



performance incentives that would be uniformly applied to all resources selling capacity. ISO-NE argues that performance incentives are the key to inducing flexible resources necessary to complement intermittent supply: “Changes to the [forward capacity market] that improve incentives for resource flexibility and availability will provide better incentives for investment in resources that can balance intermittent power supply” (Independent System Operator New England, 2016).

Conversely, in California the CAISO, in conjunction with California state agencies, has been incrementally working towards a setting with multiple, nested, capacity requirements. In addition to a standard RA requirement that is applied to all participating LSEs, the California Public Utilities Commission adopted a “flexible” (or fast responding) Capacity Procurement requirement in 2014. The requirement for the first time explicitly distinguishes types of capacity by operational characteristics. Other RA requirements and capacity markets differentiate resources by location, and reduces their qualifying capacity through availability metrics, but do not place explicit limitations based upon an ability to respond on demand to operational orders.

The California proceeding highlights many of the difficulties inherent in specifying not just a quantity of capacity, but also a range of operational requirements in an RA context. If fast ramping capability is a key need, must such capability be available for a full hour or smaller intervals? Must resources be available all the time, during peak needs, or during “shoulder ramping periods” (early mornings and late evenings when market demand changes substantially)? The difficulties have been magnified by the need to compare dramatically different resource types, including energy-limited storage, intermittent renewables, conventional generation, and demand flexibility.

The emergence of new resources and technologies is also causing a re-assessment of appropriate levels of energy price caps. In the past, prices in the \$1000/MWh range could be safely thought to be well above the marginal cost of any generation resource. Debates over price caps therefore centered on the long-run implications of denying suppliers sufficient scarcity rents. However, the growing prominence of batteries and other technologies, along with the potential for more active participation by demand alters this logic. Opportunity costs and willingness-to-pay could easily rise above \$1000/MWh. Therefore higher price caps may be necessary for efficient market clearing in the short run. Such an outcome would dilute one of the main justifications for capacity payments - that price caps deny suppliers necessary scarcity rents.

### *B. Technology and Reliability*

A bedrock, though typically unstated, assumption behind RA standards and policies is that customer preferences for supply reliability are uniform and that they are very high. Preferences, however, are not identical and many customers likely would have a willingness to pay for RA well below the level imposed

upon them by these structures. For instance, Cramton and Stoft (2006) maps the ubiquitous “one outage in 10 years” standard to an implied Value of Loss Load. Using \$80,000 per MW-yr as the cost of capacity, they translate the one-in-ten standard to a VOLL of \$267/kWh, which is over 1000 times greater than the average retail price and equivalent to paying more than \$1000 per hour to run a home central air conditioner. While there may be some uses that have such a high value, there are clearly many uses that customers would avoid if faced with such a high price.<sup>22</sup>

As described above, the basis for such standards, similar to the basis for RA policy, is to prevent negative spillovers, or the “free-riding” of one LSE on the resources of others (Spees et al., 2013). This is predicated upon the notion that it is impossible to identify and implement the reliability preferences of individuals or communities.

The advancement of technology provides an opportunity to revisit these assumptions. The American Recovery and Reinvestment Act of 2009 provided \$4.5 billion for “smart grid” technologies (Joskow, 2012) and the 2022 Infrastructure Investment and Jobs Act includes provisions for \$13 billion to modernize the electric grid. Even with these investments, grid operators are likely still many years from being able to identify supply and demand at the LSE level in real time. Nonetheless, smart meters and other monitoring technologies allow forensic analysis to identify ex post when an LSE was short and levy penalties that could help deter such behavior.<sup>23</sup>

These developments imply that it may be possible to retreat from the axiomatic belief that reliability is a public good. Certainly within short operational time frames, shared responsibility for operating reserves will be necessary for the foreseeable future. However, over longer planning horizons it may be possible to identify control areas or individual LSEs that have failed to provide adequate resources and impose substantial penalties for their impact on the reliability of other customers. Ultimately it may become possible to interrupt only the customers of the inadequate service providers, although this would require being able to identify culpability for supply shortfalls in near real-time.

Thus, with emerging technologies and creative market design, it may be possible to allow individual LSEs to approach their resource acquisition according to their individual choices and beliefs about the market, rather than through a standardized set of metrics and rules. Disagreements between local regulators and RTOs about the likely effect of energy efficiency programs, intermittent supply, demand response or even conventional generation can be put to the test by

<sup>22</sup>This is well in excess of most estimates of VOLL, though allowing for the risk of cascading outages may complicate this translation.

<sup>23</sup>Ironically, most of the country operated their interconnected control areas in such a fashion before the onset of regional RTOs. Each individual utility was responsible for balancing its load through internal resources and voluntary exchanges with neighboring regions. The temptation to free-ride on a neighbor’s supply, always technically possible for interconnected control areas, was tempered by NERC oversight and the prospect of serious ex-post penalties for “leaning” on a neighbor’s system.

allowing local LSEs to make their choices, but also live with the consequences.

At the same time, technological change is making the standard capacity paradigms less and less tenable. With greater resource heterogeneity, it is becoming more difficult to know what combination of resources optimally balances cost minimization and reliability maximization. Relying upon capacity obligations or capacity markets to cost-effectively provide grid stability depends critically on accurately crediting the contribution of different technologies towards resource adequacy. That is challenging even in a technologically static setting, because the value of any one resource depends on the overall mix of resources. It is even more challenging when technologies are changing and operators are learning how best to use them.

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