Market Rules in Transition: Energy Storage Value and the U.S. Electric Grid

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Abbreviations and Acronyms

MW, MWh	megawatt (1MW = 1,000 kW), megawatt-hour
kW, kWh	kilowatt, kilowatt-hour
MISO	Midcontinent Independent System Operator
FERC	Federal Energy Regulatory Commission
CAISO	California Independent System Operator
PJM	Pennsylvania New Jersey Maryland Interconnection
ISO-NE	Independent System Operator - New England
NYISO	New York Independent System Operator
SPP	Southwest Power Pool
EIA	U.S. Energy Information Administration
DOE	U.S. Department of Energy
R&D	Research and development
ARRA	American Recovery and Reinvestment Act
IPP	Independent Power Producer
IOU	Investor-Owned Utility
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
ESA	Energy Storage Association
RTO	Regional Transmission Organization
ISO	Independent System Operator
ERCOT	Electric Reliability Council of Texas
EIM	Energy Imbalance Market
NGR	Non-generator resources
NOPR	Notice of Proposed Rulemaking
LMP	Locational Marginal Price
G&T	Generation and Transmission
JAA	Joint Action Agency
DER	Distributed Energy Resource
NGR	Non-Generator Resource
ESR	Energy/Electric Storage Resource
RMI	Rocky Mountain Institute
EPRI	Electric Power Research Institute
IREC	Interstate Renewable Energy Council
GHG	Greenhouse Gas
CPUC	California Public Utilities Commission
SOC	State of Charge
BTM	Behind the Meter

I. Introduction

In the United States, energy storage systems have played an important role on the electric grid for decades, primarily in the form of pumped hydroelectric systems constructed in the 1970s. However, the last ten years have seen a surge in a new storage technology: battery storage, largely driven by the falling costs of lithium-ion battery technology. Since 2011, U.S. installed battery capacity has almost doubled every two years (U.S. EIA, 2018b). Installed battery storage capacity exceeded 1000 megawatts (MW) by the end of 2018, and the upward trend is expected to continue – the Midcontinent Independent System Operator (MISO) interconnection queue alone has almost 600 MW of planned battery storage capacity. ("MISO Generation Interconnection Queue") (Spector, 2019; U.S. EIA, 2018a). As increasing numbers of battery storage systems are deployed, grid operators are starting to grapple with the complexities of a technology that does not fit neatly into existing market rules and structures. Although most energy markets have participation rules for pumped hydroelectric storage systems, battery storage systems operate quite differently and require new participation models. Battery energy storage can operate as generation, load, or even transmission, and can offer multiple ancillary services of value to the grid. The services an energy storage installation is willing and able to offer to the grid varies widely based on system configuration and installation location. The term value stacking is commonly used in conversations about energy storage and refers to the ability of storage to provide multiple valuable services to the grid forming a "stack" of potential value to capitalize on.

The multi-purpose nature of storage makes it difficult for projects to participate in U.S. energy markets in a profitable way. Current market rules do not allow storage projects to capture multiple value streams within the stack, which creates a misalignment between private and social incentives and leaves value on the table. Because private actors do not internalize the full benefits of their potential actions, they underinvest in storage. The lack of appropriate market rules and participation models for storage has unquestionably been a barrier to battery storage deployment in the United States in recent years. To lessen the barriers to market participation, the Federal Energy Regulatory Commission (FERC) released Order 841 in February of 2018 which requires all grid operators to amend existing market rules (formalized in filed tariffs) to ensure storage resources can participate fully in energy, capacity, and ancillary services markets (Federal Energy Regulatory Commission, 2018). The Brattle Group estimates that Order 841's full implementation will unlock 7000 MW of new battery storage power capacity in the United States (St. John, 2018). Preliminary proposal filings from regional transmission organizations and independent system operators (RTOs/ISOs) were submitted in December of 2018, and full implementation is expected by December of 2019.

In light of changing market rules, the timing is ideal to consider questions of energy storage value and how various market changes will enable storage to participate in the energy, capacity, and ancillary services markets most effectively to maximize private value to project owners and social value to the grid. Section II offers background on current and historical trends in deployment, technology and cost. Section III will explore concepts of storage value, including value stacking and private and social value. Section

IV moves to market rules and policy as they currently stand, including prior FERC orders on energy storage and a discussion of storage projects operating outside of existing markets. Section V provides an overview of FERC Order 841 and a comparative analysis of the proposals filed by each of the six federally regulated RTO/ISOs: MISO, California Independent System Operator (CAISO), Pennsylvania New Jersey Maryland Interconnection (PJM), Independent System Operator - New England (ISO-NE), New York Independent System Operator (NYISO), and Southwest Power Pool (SPP).

Section VI applies economic theory to look beyond Order 841 and illustrate the lingering deadweight loss between private value and social value for energy storage. Although Order 841 resolves many market inefficiencies, disagreement remains over the optimal strategy to manage state of charge, quantify avoided cost, set minimum run times, and support social decarbonization goals. State of charge management is examined as a case study to explore lingering deadweight loss that prevents the capture of maximal private and social value. Private and social value relationships, complicated by risk mitigation and the dynamics surrounding resource control, continue to impact and potentially limit energy storage deployment even beyond Order 841. As an industry, more discussion is needed about the value stack of private and social value, not just the stack of revenue available for individual project owners.

Section VII will end the paper with a discussion of institutional barriers to optimal market design for energy storage, and policy options for deploying and utilizing storage resources to support grid decarbonization goals.

II. Background

A. Resource Types

Energy storage for the electric grid is far from a new concept. Pumped hydroelectric (pumped hydro) storage systems first appeared in the United States and Europe in the 1920s, and are designed to both store electricity at the gigawatt scale and provide ancillary services to the transmission system ("Pumped Hydroelectric Storage," 2019). These facilities operate by pumping water between two reservoirs at different elevations, as illustrated in Figure 1 below.

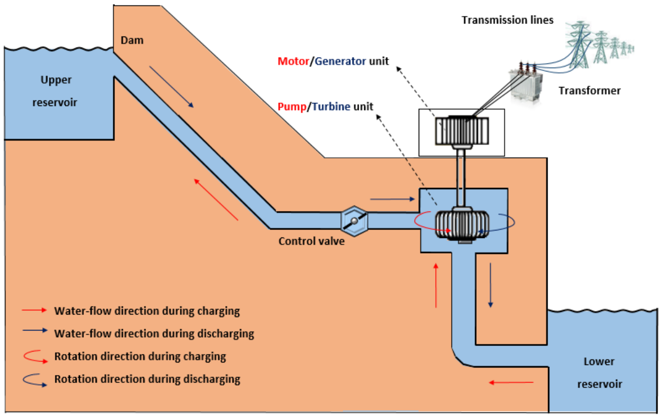

Figure 1. Pumped Hydro Diagram (Nikolaidis, Pavlos & Poullikkas, Andreas, 2017)

As recently as 2011 pumped hydro storage accounted for 98% of global installed energy storage capacity (B. Roberts & Harrison, 2011). In the United States alone, 40 pumped hydro facilities are in operation today and provide approximately 20 GW of storage capacity to the electric grid ("Pumped Hydroelectric Storage," 2019). These facilities are important grid resources, but they face limitations. They require specific geography to be constructed and a large amount of upfront capital to construct. Compared to newer storage technologies, they are also relatively inflexible and require longer timelines to transition from acting as load to acting as generation.

Recognizing the shortcomings of pumped hydro as an energy storage solution, the U.S. Department of Energy (DOE) ramped up its energy storage research and development (R&D) program in 2009, investing $185 million through the American Recovery and Reinvestment Act (ARRA) in the form of matching funds for energy storage projects (B. Roberts & Harrison, 2011). This successfully catalyzed a period of research and innovation for grid-scale storage lasting from 2009 until approximately 2014. During this five-year period, 124 projects were installed utilizing an impressively diverse set of battery storage technologies (Hart & Sarkissian, 2016). The DOE Global Energy Storage Database shows that projects installed during this catalyzation period listed 27 different 'use cases' in their project validation, referring to applications and services pursued to capture value ("DOE Global Energy Storage Database," n.d.). In 2012, a 5 MW/1.25 Megawatt-hour (MWh) battery was commissioned for Portland General Electric through a smart grid pilot funded by the DOE (John Vernacchia, 2017). This project was the first large-scale grid battery installed in the U.S. to use a lithium-ion chemistry (John Vernacchia, 2017). By 2015, lithium-ion batteries had emerged as the most common battery chemistry for project installation (Hart & Sarkissian, 2016). This is attributed to both the DOE funding available through ARRA and the huge cost reductions lithium-ion batteries saw during this period due to spillover innovation from related industries. Cell phone and electric vehicle manufacturing, for example, both rely primarily on batteries with a lithium-ion chemistry, and R&D investments in these sectors also helped drive cost reductions for lithium-ion battery production and installation (Lambert, 2017).

Lithium-ion batteries, based on an increase in private investment and sheer MW installed, appear to be a competitive option for many energy storage use cases; notably, frequency regulation (Hart & Sarkissian, 2016). But it is unclear if lithium-ion will be the best storage technology and chemistry for all energy storage applications. In a 2016 report prepared for the Office of Energy Policy and Systems Analysis researchers quote IHS estimates that "the total U.S. energy market opportunity for storage systems that would participate in frequency regulation markets to be only 3% of a total potential U.S. grid-scale battery market over 100GW in 2030…Major applications in the future include transmission and distribution services that reduce the need for other capital investments, renewables integration, and peak shaving/demand management" (Hart & Sarkissian, 2016).

Several other promising grid-scale storage technologies are under development, and can be sorted into three broad categories: kinetic energy technologies, electrochemical technologies, and thermal storage (Hart, Bonvillian, & Austin, 2018). Thermal storage refers to technologies that can store energy as heat or cold but cannot inject electricity back on to the grid. Therefore, thermal storage solutions are usually considered separately from other grid-scale storage resources and will not be considered in the scope of this work. Table 1 lists the key technology solutions in use and in development within the kinetic and electrochemical categories. Intuitively, kinetic energy storage focuses on capturing electrical energy in a mechanism from which it can be released as kinetic energy (energy of motion). Pumped hydro relies on gravity to move water back down to the lower reservoir when stored energy needs to be released. Flywheels, similarly in motion, rely on the turning of a wheel. Electrochemical energy storage relies on the conversion of electrical energy to chemical energy within a battery for storage.

Table 1 Grid-scale energy storage technologies by type. Developed from ("ESA," 2019; Hart et al., 2018)

Category	Key Technologies
Kinetic	Pumped hydroelectric Compressed air energy storage (CAES) Flywheels
Electrochemical	Lithium-Ion Batteries Lead Acid Batteries Nickel-based Batteries Flow Batteries

These technology types offer different combinations of two key storage parameters: power capacity and duration. Power capacity refers the to the system's maximum possible electrical output, expressed in watts. Duration refers to the length of time over which a system can maintain its electrical output, generally expressed in hours. The diagram in Figure 2, produced by the Interstate Renewable Energy Council, shows the loose relationships between power and duration for different technology types.

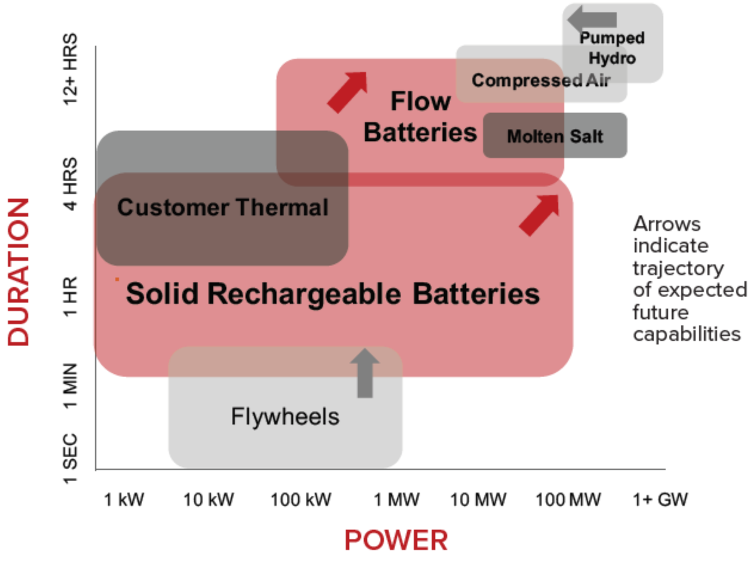

Figure 2. Performance Characteristics of Energy Storage (Stanfield, Petta, & Baldwin Auck, 2017)

When multiplied together, power capacity and duration give a system's energy capacity, expressed in watt-hours.

B. Terminology and Scope

Going forward in this document, pumped hydro will be considered in a separate category from other energy storage resources. This is done for two reasons: first, pumped hydro's historical trends and use cases are quite different from the other energy storage technologies that have taken off in the last ten years, and require a different frame of reference to understand; second, pumped hydro facilities are sizable in comparison to most other storage resources (gigawatt project sizes versus kilowatt or megawatt project sizes), and the newly installed energy storage resources look negligible when held up against these mammoth projects. Pumped hydro storage remains an important resource for the U.S. electric grid, but the purpose of this analysis is primarily to examine more recent energy storage trends and market rules that affect the likelihood that these new resource types will reach gigawatt-scale deployment. For clarity, the following three terms will be used throughout the document:

1) *Energy storage and pumped hydro*: Inclusive of all technologies in Table 1
2) *Energy storage*: Excludes pumped hydro, includes all other Table 1 technologies
3) *Battery storage*: Refers only to the technologies listed as "Electrochemical"

Only energy storage resources that can both receive and inject electricity onto the grid will be considered in scope. Therefore, all forms of thermal storage and natural gas storage will not be discussed in this work. This analysis is also focused on projects that are in front of the meter, meaning they are distribution or transmission grid connected and do not sit at a customer site behind the utility meter. All forms for energy storage in all locations (in front of and behind the utility meter) are important to study and understand but limiting the scope to projects of the type and size addressed by FERC Order 841 was necessary for this work. Discussion in Section VI and VII will address these "excluded" resources in terms of next steps for future research and relevant FERC efforts that remain in development.

C. U.S. Market Trends & Storage Use Cases

Since 2015, battery storage deployment has ramped up and costs have declined across a variety of technology types. However, lithium-ion battery chemistries continue to dominate – by the end of 2017, 80% of installed US battery storage capacity used a lithium-ion chemistry (U.S. EIA, 2018a). At the end of 2017, the United States had 708 MW of installed battery storage power capacity (867 MWh energy capacity) spread across the country. 2018 saw an additional 311 MW come online, for a total of 1,019 MW battery power capacity installed (Spector, 2019; U.S. EIA, 2018a). The two most dominant battery storage markets through 2017 are PJM, with 40% of existing battery power capacity installed (30% of energy capacity) and CAISO, with 18% of installed battery power capacity (44% of energy capacity) (U.S. EIA, 2018a). These markets have dominated battery storage installations due to favorable market rules and policy incentives (to be explored more fully in Section III) – namely, a robust frequency regulation[1] market in PJM and a state-wide policy in California requiring utilities to procure storage resources. Often, due to technical design constraints, storage systems

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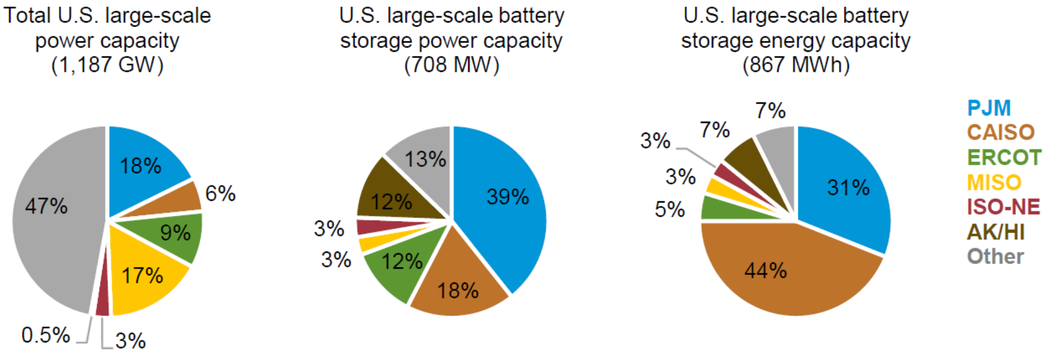
[1] Frequency regulation is defined in Table 2 and Table 3 and refers to a service that helps the grid maintain a consistent frequency of 60 Hz by making minute generation adjustments up or down every millisecond

excel at providing energy capacity or power capacity. To do both effectively is less common, and installations will skew towards energy or power capacity depending on what the regional market values (Deloitte, 2015). Figure 2, below, from the EIA Battery Storage Market Trend Report, provides a visual illustration of these trends by region, including the graph at left showing total large-scale power capacity trends for comparison[2].



Notes: Energy capacity data for large-scale battery storage installed in 2017 are based on preliminary estimates.
Sources: U.S. Energy Information Administration, Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*; U.S. Energy Information Administration, Form EIA-860, *Annual Electric Generator Report.*

Figure 3. "Figure 1: Large-Scale U.S. Power and Energy Capacity by Region (2017)" (U.S. EIA, 2018a)

Different market rules in the CAISO and PJM markets explain the difference in the percentage of energy capacity and power capacity in each market in Figure 3. In the CAISO market, generation resources must provide at least 4 hours of output to contribute reliability reserves in the market. This requires storage resources in the CAISO market to have larger energy capacities in order to meet the 4-hour output requirement (U.S. EIA, 2018a). In contrast, the PJM market is dominated by installations providing frequency regulation services which can be compensated in the market for their fast, short response and therefore do not require extensive output durations.

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[2] For this illustration, large-scale is defined as installations greater than 1 MW power capacity.

As of 2016, energy storage power capacity ownership was largely split between ownership by independent power producers (IPPs) – more common in the PJM market – and ownership by Investor-Owned Utilities (IOUs) – more common in the CAISO market (U.S. EIA, 2018a). More recent data from the DOE's Global Energy Storage Database shows that as of February 2019, energy storage ownership is now fairly evenly divided between utilities, customers, and third party actors ("DOE Global Energy Storage Database," n.d.). Within the category of utility-owned storage projects, over 70% are owned by IOUs ("DOE Global Energy Storage Database," n.d.).

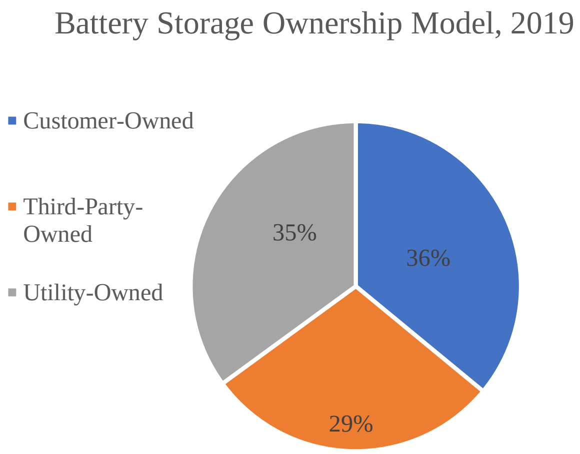

Figure 4. Battery Storage Ownership Trends ("DOE Global Energy Storage Database," n.d.)[3]

Across U.S. battery storage installations, project sizes range from 0.1 MW to 36 MW power capacity, and from 0.03 MWh to 250 MWh energy capacity ("DOE Global Energy Storage Database," n.d.). The average project size for battery technology projects is 3.8 MW (7.1 MWh) with a median of 1 MW (1 MWh) ("DOE Global Energy Storage Database," n.d.). Flywheel projects in the database are sized similarly, but the pumped hydro and CAES projects trend meaningfully larger ("DOE Global Energy Storage Database," n.d.). Most projects are projected to operate for 10 to 20 years.

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[3] Using 214 projects listed as operational in the U.S.

U.S. energy storage project owners list a variety of key applications and services[4] provided by their storage installation. More than twenty different use cases were listed in the database, the most relevant of which are captured in Table 2 below. Many of these services will be revisited in Section III and IV as they pertain to market rules, but a brief description of each use case is provided below for reference.

Table 2. Use Cases for battery storage projects greater than 100kW power capacity ("DOE Global Energy Storage Database," n.d.; Stanfield et al., 2017; U.S. EIA, 2018b)

Use Case	**Description**
Black Start	Help the grid restart after an outage
Demand Response	Act as load that can be called upon by the utility to increase or decrease usage to help balance supply and demand
Electric Bill Management	Implies an application that uses the storage resource for energy arbitrage: charging when prices are low, discharging when prices are high
Renewable Energy Time Shift	Pair with a resource (such as solar) and use storage to shift hours when the owner is selling energy to the grid
Electric Supply Capacity	Participate in the capacity market as a generating capacity resource
Reserve Capacity (Spinning/Non-Spinning)	Provide the grid with additional generating reserves that can come online quickly
Frequency Regulation	Help the grid maintain a consistent frequency of 60 Hz by making minute generation adjustments up or down every millisecond
Microgrid Capability	Support a microgrid that can island itself from the grid and operate independently
On-Site Power	Provide power to a residential, commercial, or industrial facility
Ramping/Load Following	Operate the storage resource flexibly and "follow" system load as it increases or decreases in real time
Transmission/Distribution Upgrade Deferral	Act as a transmission or distribution resource
Peak Demand Management	Provide peak demand reduction/load modulation to ensure supply and demand are matched cost-effectively
Renewables Capacity Firming	Make renewable resources more dispatchable by absorbing or releasing micro-variations in

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[4] Collectively referred to as "use cases"

	system output to match market commitments more closely

Figure 4 shows the top ten most commonly listed use cases, including their ranking as the first to fourth service being provided (indicating primary use case, secondary use case, etc.) for each of the energy storage projects listed as operational in the United States. Frequency regulation, energy time shift, electric bill management, and reserve capacity dominate the list of primary services provided.

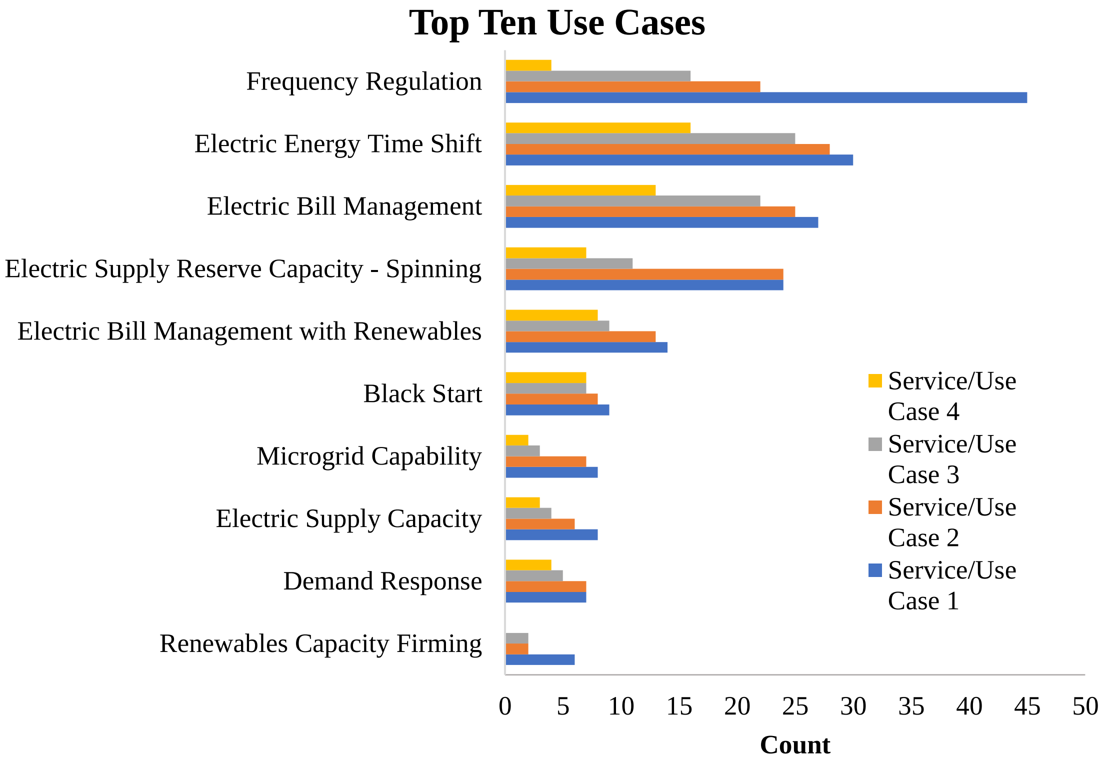

Figure 5. Most commonly listed use cases, Feb 2019. Data from (“DOE Global Energy Storage Database,” n.d.)

D. *Storage Resource Costs*

During the ARRA investment period (from 2009-2014) battery storage technology experienced a wave of cost declines and installation rates began to pick up across the globe (Hart & Sarkissian, 2016). Between 2012 and 2018 alone, the levelized cost of energy (LCOE) for lithium-ion batteries with a four hour duration fell 74% (St. John, 2019). A 2018 report from GTM Research (now Wood Mackenzie) predicts that energy storage system cost reductions will continue at a rate of 8% per year from 2018 to 2022, a slight decline from previous years ("Wood Mackenzie," 2018).

Lazard's Levelized Cost of Storage (LCOS) analysis, most recently updated in November 2018, analyzed the observed costs and revenue streams available across a variety of storage technologies. Several key findings from this analysis are worth noting (Lazard, 2018):

- Cost declines for lithium-ion battery technologies were greater than predicted in the most recent year-long period
- Cobalt and lithium carbonate prices are expected to rise, which will reduce or eliminate future declines in lithium-ion battery technology costs
- Factory utilization is high, which may delay battery availability
- Storage resources with a duration of 4 hours or less are the most cost-effective storage option
- Project economics continue to improve, but thanks to shrinking costs not rising revenues

Lazard includes a number of LCOS comparisons in the report, including subsidized and unsubsidized costs for both power capacity and energy capacity values. Below is the unsubsidized LCOS in $/MWh for varied storage technologies at varied locations. Overall, the options in front of the meter at the wholesale and utility level show the lowest LCOS values (Lazard, 2018). Applications for storage paired with photovoltaic (PV) also fair particularly well at both the utility and commercial level.

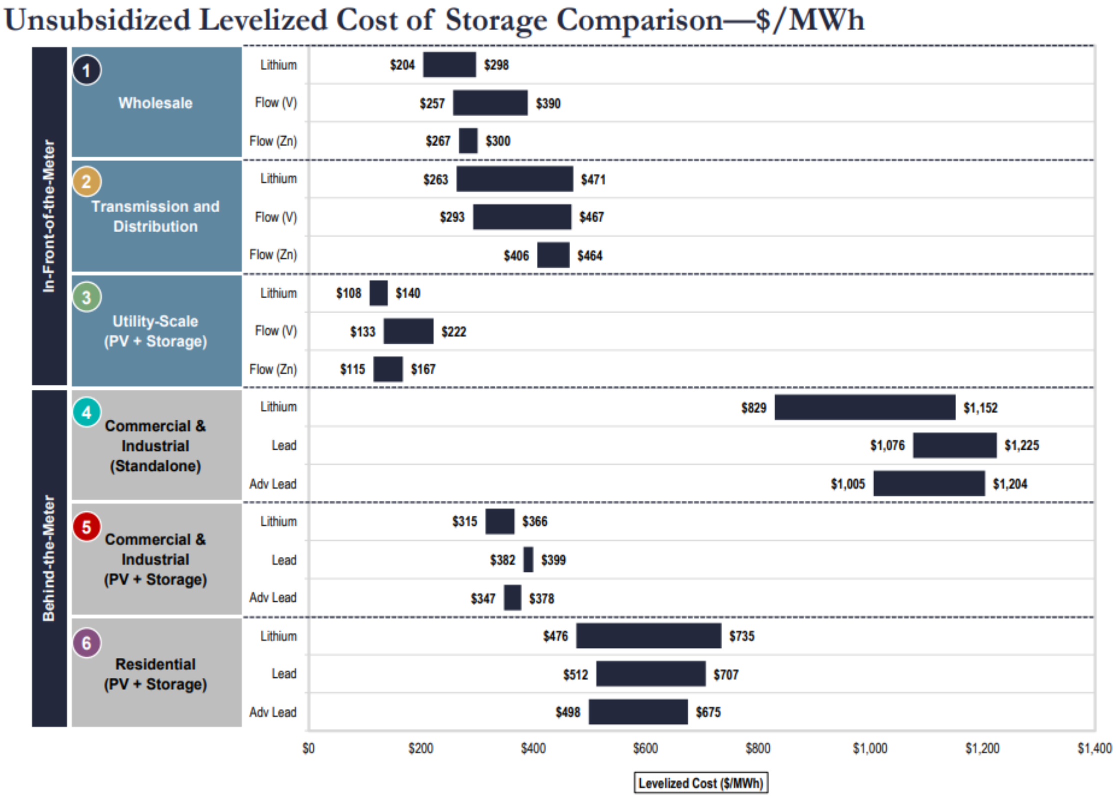

Figure 6. Lazard's LCOS v4.0 - Unsubsidized LCOS $/MWh (Lazard, 2018)

Overall, project cost continues to be a barrier to energy storage project deployment. Financers are unsure if financial projections for projects can be trusted, and ongoing uncertainty in capital costs and regulatory changes make storage projects risky to pursue. The term “bankability” refers to “how credible a storage project’s overall economic viability is considered by traditional lenders” (Robson & Bonomi, 2018). Improving the bankability of storage projects will be crucial to continued storage deployment, in the United States and globally. Academics and financial experts alike are researching strategies to improve bankability in addition to reductions in capital costs – some necessary steps include improving warranties, setting international codes and standards, and improving revenue stream modeling tools (Robson & Bonomi, 2018).

III. Storage Policy & Market Rules

A. State and Federal Policy

From a policy perspective, there are a number of relevant pieces of state and federal legislation that were designed to incentivize energy storage deployment. At the federal level, the Business Energy Investment Tax Credit (ITC) allows project developers to request a tax rebate of 30% on any investment in eligible renewable energy technology (US DOE, 2017). Although storage resources are not eligible for this tax rebate on their own, they are eligible when paired with an eligible solar or wind resources (US DOE, 2017). Analysts from ICF saw the impact of the ITC when comparing standalone battery projects with solar plus storage projects. Often, the standalone projects were simply not cost effective, but the combination of solar with storage could improve the project return on investment by 10-20% (Gerhardt & Bartels, 2018). Industry stakeholders, led by the Energy Storage Association (ESA), are pushing hard for a stand-alone energy storage ITC, but their efforts have not received strong support from other renewable energy associations thus far.

Most policymaking for energy storage at the federal level occurs through the Federal Energy Regulatory Commission (FERC). FERC is an independent federal agency situated within the Department of Energy tasked with regulating the transmission and wholesale sale of electricity, natural gas, and oil in interstate commerce ("What FERC Does," 2018). FERC regulates the regional transmission organizations and independent system operators pictured in the map below[5].

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[5] The Electric Reliability Council of Texas (ERCOT) and the two pictured Canadian ISOs (Alberta Electric System Operator and Electric System Operator) are not subject to FERC regulation.

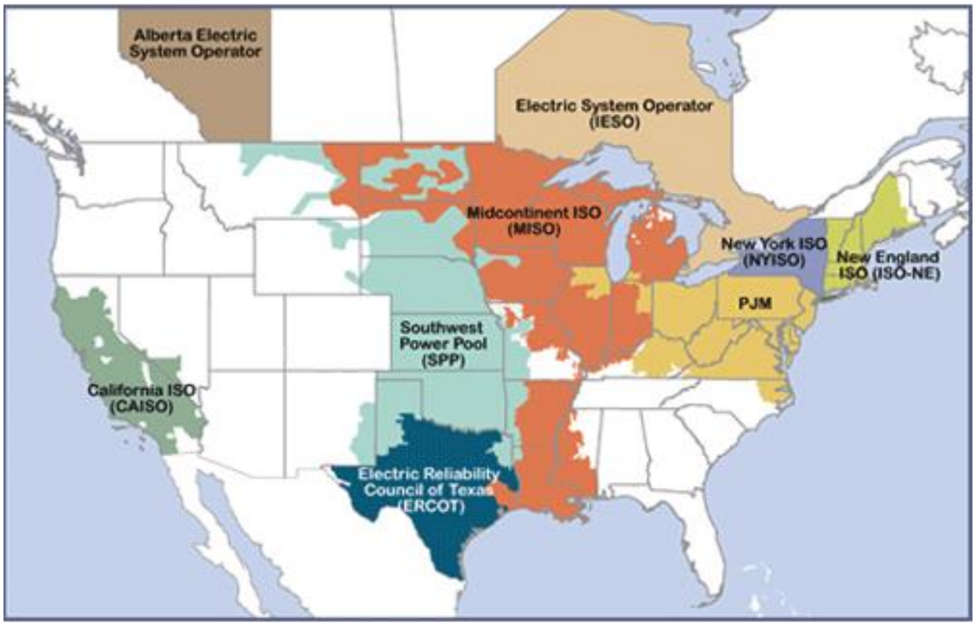

Figure 7. Map of FERC's RTO/ISO participants ("RTO/ISO," 2018)

Although it looks like most of the Western United States does not participate in an organized RTO or ISO, since 2014 CAISO has operated the Western Energy Imbalance Market (EIM), a "real-time bulk power trading market" ("About: Western EIM," 2019). The EIM includes utilities like PacifiCorp, Idaho Power, NV Energy, and Arizona Public Service. Currently, the EIM offers real-time energy trading and is advertised as an opportunity for the western United States to more effectively utilize renewable resources, and to economically optimize the grid over a wider footprint in order to save participants money ("About: Western EIM," 2019). CAISO has plans to expand market participation opportunities for EIM members to include day-ahead energy, capacity, and ancillary services trading to increase economic optimization across the EIM footprint (California ISO, 2018).

In order to create new federal energy rules, FERC will first issue a Notice of Proposed Rulemaking (NOPR) to solicit stakeholder comments on a proposed rule or policy change. After incorporating stakeholder comments where appropriate, FERC will issue an order describing the rule change and a timeline for compliance. Compliance generally requires RTO/ISOs to file a response explaining their compliance strategy, and to update filed tariffs and market operation processes to reflect the new rule. Over the last fifteen years, a number of FERC orders have had direct or indirect implications for energy storage. An overview of the relevant FERC orders for energy storage will be provided in section B below.

At the state level, a handful of states have energy storage mandates and initiatives in place, and more than a dozen others have active proceedings relating to energy storage. Table 4 lists current energy storage mandates and incentives in the United States. Four states have energy storage mandates in place: California, Oregon, Massachusetts, and New York (Telaretti & Dusonchet, 2017). Notably, California had a storage procurement mandate in place five years earlier than any other state (The Brattle Group, 2018). The energy market in Texas, ERCOT, is not subject to FERC regulation. Therefore, Texas state legislation serves as a stand-in for the federal rule making process. Texas Senate Bill 943, passed in 2011, contained language and requirements similar to FERC Order 841 and started the process within Texas of increasing market participation opportunities for energy storage.

Table 3. Current State-Level Energy Storage Mandates (Sakti, Botterud, & O'Sullivan, 2018; Telaretti & Dusonchet, 2017; The Brattle Group, 2018)

State	Year Enacted	Description
California	2010	AB 2514 mandates 1325 MW installed by 2024
Texas	2011	SB 943 says energy storage can participate in the wholesale market (ERCOT).
Oregon	2015	House Bill 2193 mandates 5 MWh installed by 2020
Massachusetts	2016	HB/SB 4568 mandates 200 MWh by 2020
Arizona	2017	PUC must investigate storage target; $4 million residential energy storage program
Maryland	2019	Investment Tax Credit for energy storage

New York	2017	Mandate of 1.5 GW by 2025

Beyond these states, close to a dozen others have active legislative proceedings related to energy storage. These states include Minnesota, Vermont, New Hampshire, Colorado, New Mexico, and Washington D.C., to name a few (Stanfield et al., 2017; The Brattle Group, 2018). Many states are considering storage as part of a broader Grid Modernization bill or docket, not as a stand-alone procurement mandate. Other state storage strategies – some of which are reflected in the table above – include allowing storage to count towards the state RPS targets, offering financial or tax incentives for storage installations, or requiring utilities to include storage in their integrated resource plan (U.S. EIA, 2018a).

B. FERC and Energy Storage

The Federal Energy Regulatory Commission has addressed energy storage both directly and indirectly on a number of occasions. The most notable of these orders are Order 890, 719, 745, 755, and 784, which all address energy storage indirectly. Most recently, Order 841 built off of these initial orders to directly address market participation rules for energy storage. Figure 8 shows the timeline of release for the six most storage-relevant FERC Orders.

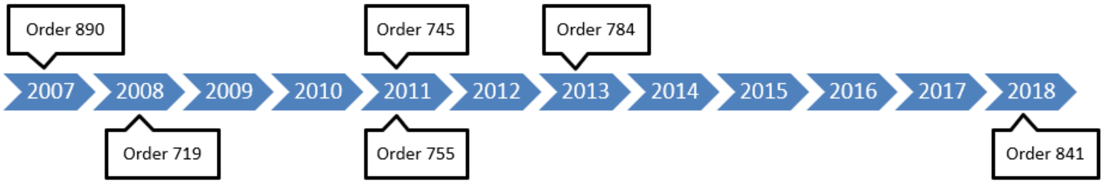

Figure 8. Timeline of storage-relevant FERC orders

FERC Order 890, released in 2007, was primarily written to address “undue discrimination and preference in transmission service,” but also included the first requirement that non-generating resources be considered on equal footing with traditional generating resources for ancillary services and reliability (Federal Energy Regulatory Commission, n.d.). Improved opportunities for demand response was the example used frequently within the order. In 2007, and still today, many storage resources participate as demand response in energy markets. Order 719 followed soon after in 2008, and further improved wholesale market participation opportunities for demand response resources by requiring all RTO/ISOs to recalculate market prices for energy and ancillary services every five minutes (Federal Energy Regulatory Commission, 2008). This rule change allowed fast-responding resources – such as demand response and energy storage – to be compensated more appropriately for services provided to the grid (Bhatnagar, Currier, Hernandez, Ma, & Kirby, 2013; Sakti et al., 2018)

2011 saw the release of two related FERC Orders: 745 and 755. First, Order 745 specifically allowed demand response to participate in wholesale markets when cost competitive with other resources. Order 745 also required that participating demand response be compensated for reduced consumption at the appropriate locational marginal price (LMP) – essentially, at the rate that grid operators would have had to pay a generator to meet demand at that time (Walton, 2016). Order 755 followed shortly after and improved compensation for ancillary services such as frequency regulation. 755 separated payment for ancillary services into two streams: one for capacity, and one for performance (Kumaraswamy & Cotrone, 2013). This separation greatly improved compensation streams for fast responding resources such as energy storage and led to a storage market explosion in PJM – the first market to implement these changes.

FERC Order 784, released in 2013, expanded the scope of Order 755 by applying the requirements in 755 to all public utilities, not just RTO/ISO participants (Kumaraswamy & Cotrone, 2013). In addition, Order 784 revised accounting and reporting requirements for energy storage to place additional emphasis on speed and accuracy of resource response (Todd Olinsky-Paul, 2015). Overall, the intention of Order 784 was to "promote transparency, address discrimination, and promote competition in ancillary services markets" (Bhatnagar et al., 2013). As seen in this listing, until FERC Order 841 was released in early 2018, many FERC activities addressed energy storage tangentially, but very little focused attention was given to energy storage participation. The release of 841 is likely tied to shifting resource economics and the increasing deployment of storage resources over the last decade. Section V provides a deep-dive into the requirements in FERC Order 841 and the proposals filed for compliance by regulated RTO/ISOs in the United States.

C. Current Market Participation

Energy storage resources provide a variety of services to the grid, as explored in the use cases in Table 2. The most notable of these services can be sorted into three categories: energy, capacity, and ancillary services. Existing and developing market rules tend to address storage market participation within these three categories. Table 3, below, defines each category and the key services/use cases included in each category.

Table 4. Energy storage services. Adapted from (Forrester, Zaman, Mathieu, & Johnson, 2017)

Service	**Description**
Ancillary Services	Services that support the reliable operation of the bulk transmission system. These services are often split into two categories: 1) Balancing: services that help the grid remain stable through small imbalances of supply and demand. Examples include frequency regulation and load following. 2) Contingency: services that are available to respond in the event of an unexpected grid event or failure. Examples include both spinning and non-spinning reserves.
Energy Services	Storage resources can participate in energy arbitrage to operate profitably in existing energy markets: resources charge when energy prices are low and discharge when energy prices are high. This encapsulates a variety of the services listed in Table 2 including electric bill management, electric/renewable energy time shift
Capacity Services	In existing capacity markets (not available in all markets), storage resources can participate in forward capacity markets much like a standard generator.

Current market rules provide some, but not all of these market participation opportunities for energy storage resources. The figure below –prepared by Sakti et al – shows a comparison of market participation opportunities in all FERC regulated RTO/ISOs as of May 2018. The table serves as an ideal reference for market opportunities and barriers for energy storage prior to FERC Order 841.

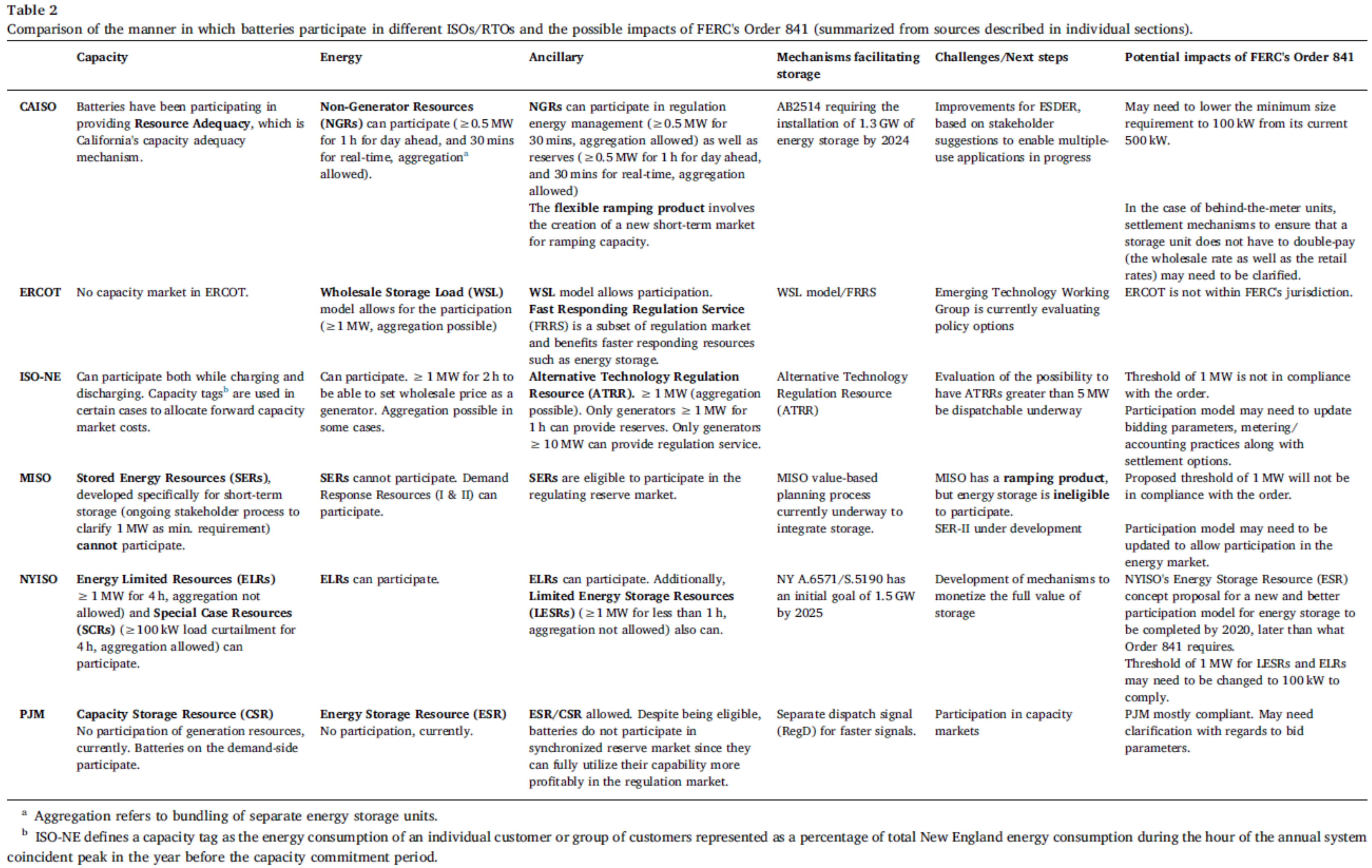

Table 2

Comparison of the manner in which batteries participate in different ISOs/RTOs and the possible impacts of FERC's Order 841 (summarized from sources described in individual sections).

	Capacity	Energy	Ancillary	Mechanisms facilitating storage	Challenges/Next steps	Potential impacts of FERC's Order 841
CAISO	Batteries have been participating in providing **Resource Adequacy**, which is California's capacity adequacy mechanism.	**Non-Generator Resources (NGRs)** can participate (≥ 0.5 MW for 1 h for day ahead, and 30 mins for real-time, aggregation[a] allowed).	**NGRs** can participate in regulation energy management (≥ 0.5 MW for 30 mins, aggregation allowed) as well as reserves (≥ 0.5 MW for 1 h for day ahead, and 30 mins for real-time, aggregation allowed) The **flexible ramping product** involves the creation of a new short-term market for ramping capacity.	AB2514 requiring the installation of 1.3 GW of energy storage by 2024	Improvements for ESDER, based on stakeholder suggestions to enable multiple-use applications in progress	May need to lower the minimum size requirement to 100 kW from its current 500 kW. In the case of behind-the-meter units, settlement mechanisms to ensure that a storage unit does not have to double-pay (the wholesale rate as well as the retail rates) may need to be clarified.
ERCOT	No capacity market in ERCOT.	**Wholesale Storage Load (WSL)** model allows for the participation (≥ 1 MW, aggregation possible)	**WSL** model allows participation. **Fast Responding Regulation Service** (FRRS) is a subset of regulation market and benefits faster responding resources such as energy storage.	WSL model/FRRS	Emerging Technology Working Group is currently evaluating policy options	ERCOT is not within FERC's jurisdiction.
ISO-NE	Can participate both while charging and discharging. Capacity tags[b] are used in certain cases to allocate forward capacity market costs.	Can participate. ≥ 1 MW for 2 h to be able to set wholesale price as a generator. Aggregation possible in some cases.	**Alternative Technology Regulation Resource (ATRR).** ≥ 1 MW (aggregation possible). Only generators ≥ 1 MW for 1 h can provide reserves. Only generators ≥ 10 MW can provide regulation service.	Alternative Technology Regulation Resource (ATRR)	Evaluation of the possibility to have ATRRs greater than 5 MW be dispatchable underway	Threshold of 1 MW is not in compliance with the order. Participation model may need to update bidding parameters, metering/accounting practices along with settlement options.
MISO	**Stored Energy Resources (SERs)**, developed specifically for short-term storage (ongoing stakeholder process to clarify 1 MW as min. requirement) **cannot** participate.	**SERs** cannot participate. Demand Response Resources (I & II) can participate.	**SERs** are eligible to participate in the regulating reserve market.	MISO value-based planning process currently underway to integrate storage.	MISO has a **ramping product**, but energy storage is **ineligible** to participate. SER-II under development	Proposed threshold of 1 MW will not be in compliance with the order. Participation model may need to be updated to allow participation in the energy market.
NYISO	**Energy Limited Resources (ELRs)** ≥ 1 MW for 4 h, aggregation not allowed) and **Special Case Resources (SCRs)** (≥ 100 kW load curtailment for 4 h, aggregation allowed) can participate.	**ELRs** can participate.	**ELRs** can participate. Additionally, **Limited Energy Storage Resources (LESRs)** (≥ 1 MW for less than 1 h, aggregation not allowed) also can.	NY A.6571/S.5190 has an initial goal of 1.5 GW by 2025	Development of mechanisms to monetize the full value of storage	NYISO's Energy Storage Resource (ESR) concept proposal for a new and better participation model for energy storage to be completed by 2020, later than what Order 841 requires. Threshold of 1 MW for LESRs and ELRs may need to be changed to 100 kW to comply.
PJM	**Capacity Storage Resource (CSR)** No participation of generation resources, currently. Batteries on the demand-side participate.	**Energy Storage Resource (ESR)** No participation, currently.	**ESR/CSR** allowed. Despite being eligible, batteries do not participate in synchronized reserve market since they can fully utilize their capability more profitably in the regulation market.	Separate dispatch signal (RegD) for faster signals.	Participation in capacity markets	PJM mostly compliant. May need clarification with regards to bid parameters.

[a] Aggregation refers to bundling of separate energy storage units.

[b] ISO-NE defines a capacity tag as the energy consumption of an individual customer or group of customers represented as a percentage of total New England energy consumption during the hour of the annual system coincident peak in the year before the capacity commitment period.

Figure 9. Storage Market Participation Opportunities & Barriers, May 2018 (Sakti et al., 2018)

As mentioned in Section II, CAISO and PJM have seen the most robust battery storage market participation to date. Through an ongoing stakeholder process, CAISO developed an energy storage participation model for non-generator resources (NGR) that was first introduced in 2010. Thoughtfully developed market rules in combination with a state policy mandate for storage procurement accelerated the CAISO storage market several years ahead of other markets (Sakti et al., 2018). As Section IV will show, CAISO has largely complied with the requirements of FERC Order 841 for several years.

PJM has also been an interesting market for energy storage in the last five years. In 2011, PJM modified its compensation practices for frequency regulation services to comply with FERC Order 755, creating two separate compensation streams – one for opportunity cost, and one for performance – in order to better compensate fast-responding resources (Forrester et al., 2017). This change in market rules led to an explosion of battery installations in the PJM footprint. However, further market rule changes in 2015 and again in 2017 led many developers to physically remove their storage resources from the PJM footprint. They claimed the market rule changes triggered operational parameter changes that the newly installed resources were not designed to accommodate (Forrester et al., 2017). Energy storage market participation opportunities across other markets have been sporadic, which triggered FERC's release of Order 841 to create more consistency across markets and more participation opportunities across the board.

D. External Projects

The focus of this work is on changing market rules triggered by FERC Order 841. However, many existing (and future) battery storage projects will be completely indifferent to these regulatory changes. Many currently installed projects do not operate within an area that FERC has jurisdiction over. The Electric Reliability Council of Texas (ERCOT) is not under FERC jurisdiction and is instead governed by the state of Texas. In addition to Texas, thirteen other U.S. states do not participate in an organized wholesale market, and eight additional states only have partial participation (Stanfield et al., 2017). Those regions will not see any change in market participation opportunities due to FERC Order 841. However, as CAISO’s EIM continues to expand, much of the western United States may benefit from Order 841’s objectives.

Energy storage projects installed by distribution utilities may also find themselves isolated from these changing market participation opportunities. Small distribution utilities are often removed from the price signals coming from an organized market even if they are technically a participant – those signals are felt and seen primarily by their generation and transmission (G&T) utility or joint action agency (JAA). For example, a recent battery storage project completed by Minnesota cooperative utility Connexus Energy operates primarily as a demand response asset to avoid high demand charges from their G&T, Great River Energy. Connexus installed a co-located 10 MW solar plus 15 MW (30 MWh) storage system in late 2018 (Burandt, 2018). In order to maximize the lifetime of the storage system and ensure the project economics are favorable, Connexus’s storage can only be “called” 75 times a year and will only operate as a demand response resource when requested by Great River Energy. This allows Connexus to minimize the demand charges they see from Great River Energy and save enough money to cover the cost of the installed system.

United Power, a large cooperative utility in the greater Denver area, installed a similar battery storage system early this year (Best, 2019). Much like Connexus, United Power is isolated from RTO/ISO market signals and instead uses their storage system to minimize charges from their G&T, Tri-State. Both Great River Energy and Tri-State have expressed frustration with these projects, and Tri-State issued a policy in response to United Power's project to cap the amount of storage their distribution utility members are allowed to install (Best, 2019).

All this to say: FERC Order 841 does not affect every stakeholder in the U.S. energy storage market. Some projects will remain isolated from its impacts, while others will see their project economics change drastically. FERC's authority is limited to regulating transmission and wholesale energy transactions in interstate commerce. State-level regulators and policymakers will continue to play a critical role in increasing market opportunities for energy storage, by building off Order 841 and providing additional opportunities that are beyond the scope of FERC's interests and authority.

IV. Value Concepts and Market Theory

As market rules, policy, and project economics for battery storage shift, it is imperative to turn next to a discussion of value. This multifaceted concept comes up frequently in the national conversation about battery energy storage. This section will briefly introduce the market inefficiencies and "missed value" opportunities in today's storage industry, introduce the concept of value stacking for private value, and explore the social value of storage for decarbonization.

A. Value and Market Efficiency

It is particularly challenging to create efficient market structures in the U.S. energy landscape because the energy industry is heavily regulated at both the state and federal level. This regulation is primarily intended to promote market efficiency and mitigate the power held by monopoly utilities in noncompetitive market environments, but the layers of regulation often lead to inefficiencies and disagreements over who has the authority to regulate whom. In addition, not all regulation is intended to promote efficiency – market regulators may have other pressing goals like low-income protections, reliability, or rural electrification.

Some states have restructured the energy industry, meaning there are additional opportunities for competition at the distribution level and utilities do not own generation (are not vertically integrated). Other states remain traditionally regulated, with vertically integrated utilities given monopoly service territories. Most RTO/ISO energy markets include states with both regulated and deregulated energy systems, adding complexity to the development of market rules that will promote efficiency for all participating actors and maximize net value at all levels.

Traditional economic theory says that that markets operate efficiently when the following conditions are met (Keohane & Olmstead, 2016):

1) The market is competitive – all actors are aiming to maximize value
2) All market actors have full and complete information
3) All relevant costs and benefits are included in market transactions

For energy storage participation in RTO/ISO markets prior to Order 841, these conditions are not consistently met across all RTO/ISOs, creating opportunities to optimize market efficiency and increase value for actors at all scales. In particular, condition #3 is far from met for energy storage under current market conditions because numerous monetizable revenue streams for services are not available at the private level even though those services may provide huge social benefit. For example, a recent storage cost-benefit analysis completed by the state of Massachusetts set out to determine the public benefits of deploying 600 MW of storage power capacity in the state (*State of Charge: Massachusetts Energy Storage Initiative*, 2016). The assessment showed that a much higher amount of storage would be optimal for the Massachusetts grid – up to 1766 MW – producing $2.3 billion in benefits to ratepayers in the form of reduced electricity prices, reduced peak demand, deferred grid updates, and reduced greenhouse gas (GHG) emissions, among others (*State of Charge: Massachusetts Energy Storage Initiative,* 2016). The authors specifically note that although the public benefits of energy storage deployment far outweigh the costs, existing private revenue mechanisms are inadequate for the benefits to outweigh the costs for a private developer (*State of Charge: Massachusetts Energy Storage Initiative*, 2016). For many markets, this disconnect between monetizable private value and deliverable social value leads storage deployment levels to stay far below the ideal level. In Massachusetts, only 2 MW of storage power capacity is operational even though 1766 MW is considered optimal – that equates to 0.1% of the optimal amount of storage power capacity on the Massachusetts grid!

The results of the Massachusetts study, where public benefits are huge but private benefits are virtually non-existent, indicate a lack of policy and market rules to align private and societal interests. This is a key example of the existence of a positive externality in the storage market due to the exclusion of relevant benefits from the market. Figure 10, below, shows a supply and demand curve experiencing a positive externality. Marginal private benefits ($MB_{private}$) are far below the optimal marginal social benefit (MB_{social}) level, resulting in a dead weight loss (DWL) of value for all market actors – both individuals and society at large.

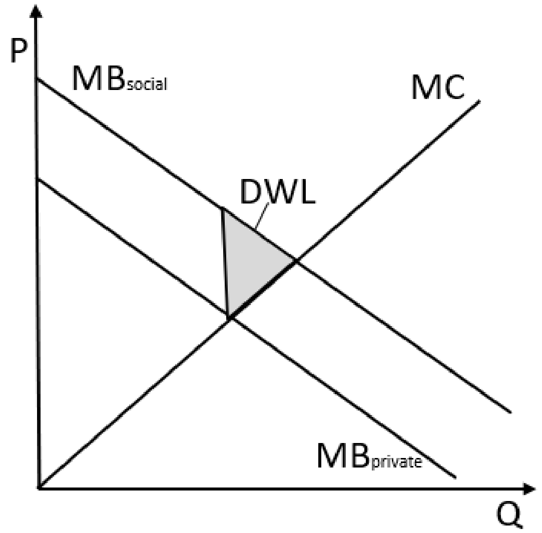

Figure 10. Private and Social Value Relationships

When large public benefits are available, but the market is not mature enough to appropriately compensate private actors for the value being provided, a disconnect exists between private and social value. The disconnect or tension between private and social value for energy storage differs by location of interconnection: behind the customer meter, distribution connected, and transmission connected. If the project is located behind the customer meter, private value is assessed for an individual customer-owner, likely engaged in simple revenue opportunities like energy arbitrage, electric bill management, or renewable energy time shift for a paired home solar system. If the project is located on the distribution or transmission grid, private value may be accrued by an IPP and the project is more likely to be pursuing wholesale market value opportunities in the energy, capacity, or ancillary services markets. Depending on the market these resources are located in, the most profitable private value opportunities may not align at all with the highest value opportunities for the grid. For example, in a market with highly restricted ancillary services participation opportunities for storage, a distribution-level storage resource may default to providing only demand response to the grid, even though the resource is capable of delivering much more value through services like frequency regulation or spinning reserves.

In other words, private and social value may not be at odds, but incentives are simply not appropriately aligned. Individual resources owners then chase their own self-interest (profitability, through available revenue streams), but an inefficient market design means they may select services that do not have the highest social value or may chose not to construct the project at all. For energy storage, both private and social value streams can be increased through market optimization to shrink or eliminate the dead weight loss and match social benefits to private benefits.

FERC Order 841 is a first attempt to eliminate some dead weight loss from the market by monetizing value streams that private resource owners are already capable of providing, therefore creating additional social value that was not available before. Section VI will examine the areas in which Order 841 has successfully aligned and maximized private and social benefits, as well as identify where and why inefficiencies still exist.

B. Value Stacking and Private Value

Value stacking as a concept is not exclusive to energy storage, but it is discussed frequently within the storage industry in the context of private value available to individual actors. The basic principle behind project-level value stacking comes down to this: for a resource like storage, the system owner or operator may need or want to capture more than one value or revenue stream in order to make the investment profitable long-term. This requires providing multiple grid services to create a stack of value for the resource owner. Market rules allow specific grid services that storage provides to be monetized, creating multiple revenue streams. If captured, these revenue streams make projects more likely to be built. Market rules that do not allow all value streams to be monetized can lead to socially sub-optimal usage or deployment of storage resources. The concept of value stacking has been considered the “holy grail” for energy storage for the last several years but has proved difficult to actually implement. Often storage systems are providing multiple high-value services, but market structures are not sophisticated enough to compensate storage appropriately for all those services. As discussed above, these outdated market compensation structures motivated FERC to release Order 841 to reduce the deadweight loss in the market and increase the stack of values available for private capture.

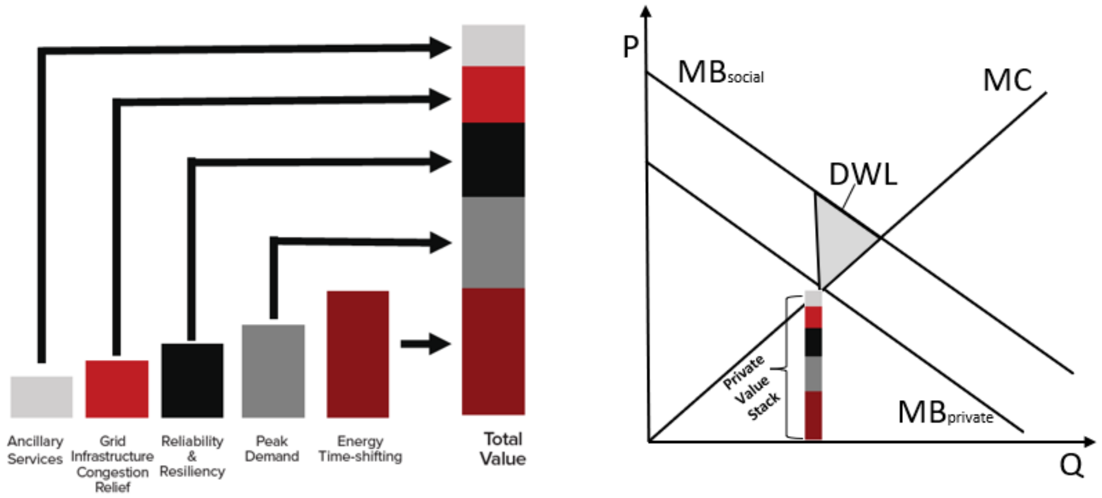

Figure 11. Left: Energy Storage Value Stack – Visual Illustration from IREC (Stanfield et al., 2017); Right: Private value stack positionality within storage market

In 2015, the Rocky Mountain Institute (RMI) completed a foundational report on energy storage value stacking that continues to be a key reference in the industry on this topic. In the report, RMI identified thirteen different services that battery storage can provide to the grid at different service levels: customer services, utility services, and RTO/ISO services (Fitzgerald, Mandel, Morris, & Touati, 2015). They analyzed six leading studies of the value of each service, in normalized $/kW, and found that the results varied dramatically between studies – by as much as 600% (Fitzgerald et al., 2015). RMI attributes this massive variation to the huge number of variables involved in estimating energy storage value, and the varied and changing market rules for storage. In fact, RMI's modeling efforts artificially removed all existing regulatory barriers in order to produce meaningful results, a sign of just how far existing market rules are from optimal for energy storage resources.

The key challenges identified in the report are: regulatory variation among states and regions, sensitivity of results to small technical system specification parameters, and primary dispatch constraints (Fitzgerald et al., 2015). Primary dispatch, perhaps the most interesting of the three, is worth further discussion as a barrier because it is a constraint to the value a storage system can capture. If the resource is assigned a primary dispatch service – for example, frequency regulation – it may not be available to optimally dispatch other services like real-time energy because it is required to always be available to provide the primary dispatch service[6].

Within any work considering the potential of a value stack, there is an acknowledgement of the tension between maximizing value by stacking services and ensuring longevity of the battery resource over a time window long enough to support the project economics. Most electrochemical batteries can only be discharged a finite number of times before they need to be replaced, which can lead operators to focus on just one or two high value services to ensure the battery is not "worn out" in just a few years. Therefore, the strategy to maximize value over a given day may look very different than the strategy to maximize value over a project's lifetime. Concerns over longevity also drive the desire from private actors to manage and control the resource state of charge, thereby managing the charge cycles occurring per day. By controlling state of charge, private actors can mitigate the risk of "wearing out" the battery before scheduled retirement. Issues of resource control and risk management continue to create tensions between private and social actors for storage resources: for grid operators, fully private management of state of charge can limit the efficiency of the market and leave value on

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[6] A key takeaway from the Rocky Mountain Institute report was that storage resources are able to maximize their value stack when situated behind a customer meter (Fitzgerald, Mandel, Morris, & Touati, 2015). This position allows the storage resource to (theoretically) provide all thirteen services and therefore offers the potential to capture the maximum amount of value. However, in reality behind the meter (BTM) resources cannot provide services to the utility or the RTO/ISO in any part of the U.S. right now with the exception of California.

the table, but most private actors gravitate towards a self-management approach as a necessary form of project risk mitigation.

Groups like the Electric Power Research Institute (EPRI) are developing tools to quantify available revenue streams and help developers determine if it is economical to build a project in a given market ("Storage Value Estimation Tool," 2016). Their publicly available Storage Valuation Estimation Tool (StorageVET) is useful for determining the shape and profitability of a potential value stack, but at present it only incorporates regulatory assumptions for the CAISO market. IREC's Charging Ahead report indicates that at present, there is no "silver bullet" modeling methodology for energy storage valuation (Stanfield et al., 2017). Available tools and methods vary widely based on the intended use of the results, and these tools will continue to evolve as the storage industry matures.

C. Social Value and Decarbonization

Storage resources are often touted as the ultimate tool for grid decarbonization and are assumed to offer a high social value to the grid for reducing carbon emissions when paired with renewable resources. In fact, decarbonization is often the stated or implicit goal of storage procurement mandates or incentives to accelerate storage deployment. In many ways this is an accurate assumption, but storage does not inherently support social decarbonization goals without appropriate market rules in place for private actors. As market rules shift at a time when the urgency of climate change is coming to the fore (both nationally and globally), it is important to focus on this particular form of social value to determine if market rules are enabling private actors to contribute to social decarbonization goals, or exacerbating misalignments between private and social value streams.

First, the value storage offers for grid decarbonization can vary widely based on the duration of the storage resource in consideration. Research for the California Public Utilities Commission (CPUC) from 2014 found that using storage to avoid renewable curtailment on the CAISO system provides significant system value, but to avoid curtailment longer duration storage was much more effective (Energy+Environmental Economics, 2014). In this 2014 analysis, long duration is defined as at least four hours of run time, and study authors hypothesize that increasing long duration storage on the CAISO system would also minimize GHG emissions by reducing the number of times fossil fuel “peaker” plants are needed in a given year (Energy+Environmental Economics, 2014). Although this result is not verified analytically in the report, the 2014 CAISO system often required 4-5 hours of fossil fuel run time to meet the evening peak which a shorter duration (less than 4 hours runtime) storage resource could not easily replace.

More recent collaborative research from MIT and the Argonne National Laboratory came to similar conclusions. Modeling efforts by De Sisternes and Jenkins showed that shorter duration storage resources (2 hours or less) only made sense when very stringent GHG emissions reductions were required by the model (de Sisternes, Jenkins, & Botterud, 2016). Barring huge reductions in cost, these shorter duration systems did not warrant massive deployment. Longer duration storage (defined here as at least 10 hours of runtime), however, more consistently delivered system value even in lower GHG emissions reduction scenarios (de Sisternes et al., 2016). Notably, neither short or long duration were essential for a decarbonized grid if nuclear energy was included as an option in the grid resource mix (de Sisternes et al., 2016).

Second, depending on the services provided and existing grid mix, adding energy storage can actually cause emissions to increase. Research from Carnegie Mellon University in 2015 drew meaningful attention when it found that adding energy storage to the current U.S. electric grid increased emissions in the short term (Hittinger & Azevedo, 2015). Importantly, the energy storage systems that Hittinger and Azevedo modeled were only assumed to provide one service: energy arbitrage. They found that most often, it was cheapest for the storage systems to charge from baseload resources like coal and natural gas plants, thereby causing baseload fossil fuel plants to run more often to accommodate their added demand (Hittinger & Azevedo, 2015). This accounted for the meaningful net increase in emissions. Their work is an important counternarrative to the notion that storage is inherently a clean or renewable energy option offering high value for grid decarbonization efforts. In reality, storage resources may even counter efforts to decarbonize the grid if they are not operated appropriately.

As the cost of renewable resources continues to fall faster than the cost of storage, some groups are starting to suggest that overbuilding wind and solar capacity and dispatching or curtailing as necessary may actually be a more cost-effective way to meet decarbonization goals than deploying meaningful storage capacity (Putnam & Perez, 2018). However, storage continues to play a role in the most aggressive decarbonization scenarios. Recent modeling of the Minnesota electric grid by Vibrant Clean Energy showed that by 2035, energy storage was selected for all decarbonization scenarios modeled (Vibrant Clean Energy, 2018). Although suggested deployment varied from as low as 2 GW (35 GWh) to as high as 9.5 GW (166 GWh), all scenarios showed that more storage on the system lowered both emissions and costs (Vibrant Clean Energy, 2018).

In many ways, storage and renewables go hand in hand – "the new power couple," ICF researchers joke (Gerhardt & Bartels, 2018). Although it is undeniably accurate that a storage resource can increase the value of an intermittent resource when paired with it directly, it is important to caveat any statements about the overall grid value of storage as a complement to renewables and thereby to decarbonization efforts. Storage can offer social value for grid decarbonization, but it must be deployed at the right locations, with adequate duration, and with appropriate market and policy mechanisms in place to realize its full decarbonization value. Section VI and VII will examine how effectively FERC Order 841 has improved the alignment between private and social value streams to encourage decarbonization, and will discuss additional policy and research that may be needed to further eliminate dead weight loss in the storage market and optimize the social value available from decarbonization.

V. Comparative Analysis

A. FERC Order 841

FERC Order 841 was released in February of 2018, with initial compliance filings due by December of 2018. The primary objective of Order 841 was to "require each RTO and ISO to revise its tariff to establish a participation model consisting of market rules that, recognizing the physical and operational characteristics of electric storage resources, facilitates their participation in the RTO/ISO markets" (Federal Energy Regulatory

Commission, 2018). The order clarifies that the revised participation models for storage must meet four key requirements:

1) Ensure storage resources can provide all energy, capacity, and ancillary services they are technically cable of providing.
2) Ensure storage resources can be dispatched and can set the market price as both a buyer and a seller.
3) Account for the “physical and operational” characteristics of storage resources.
4) Set the minimum size requirement for market participation at 100 kW.

Stated simply, the goal of Order 841 is to remove barriers to participation for storage, enhance market competition, and support the resiliency of the grid (Energy Storage Association, 2018). FERC considered including requirements for distributed energy resource (DER) aggregation in the order (which is highly applicable for behind the meter storage resources) but determined the scope was too large and removed DER aggregation to be addressed in a future order (Federal Energy Regulatory Commission, 2018).

The official order includes hundreds of pages of detail and all together 76 different directives that RTO/ISO markets must address (St. John, 2018). FERC was careful to define electric storage as “a resource capable of receiving electric energy from the grid and storing it for later injection of electric energy back to the grid,” thereby excluding thermal resources from falling under the jurisdiction of Order 841 (Energy Storage Association, 2018). In general FERC rulemaking proceeds cautiously to preserve the delicate balance of state and federal power when issuing a ruling. The scope of their jurisdiction is very carefully limited to transmission and wholesale sales of energy in interstate commerce, and any deviation from that scope will trigger litigation. Although

FERC offered fairly detailed guidelines on what must be addressed by each RTO/ISO, the "how" of implementation is mostly left up to the RTO/ISO. Among other requirements, Order 841 requires that RTO/ISO markets allow storage resources to de-rate capacity to meet minimum run time requirements, establish appropriate bidding parameters for storage, and allow storage resources to self-manage state of charge (The Brattle Group, 2018). RTO/ISO markets must also address how they will manage complexities such as:

- *Avoiding conflicting dispatch instructions:* how will the market ensure a storage resource is not asked to both charge and discharge in the same interval?
- *Provide storage make-whole payments:* how will the market re-pay storage resources for transmission access charges accrued when the grid operator requires the resource to charge?
- *Participation in ancillary services without offering energy services:* can a resource provide services such as frequency regulation without also submitting an energy schedule?
- *Minimum run time:* what will the market require as the minimum consecutive run time to offer forward capacity? Shorter runtime requirements are often easier for resources to meet, but longer runtimes are less complicated for the ISO/RTO to manage.

Although the filings submitted by each RTO and ISO market in December of 2018 contain many similarities, the strategy and methods developed by each market vary. Below, each filing's proposed participation model will be discussed, followed by a comparison matrix showing market compliance on each of the order's key required components. Some of the preliminary concerns expressed by stakeholder groups – most notably the Energy Storage Association – will be discussed here and in Section VI. In every response filing submitted, ESA notes that no market compliance plan has discussed how storage that is co-located with a generation resource (such as solar) will be treated, and if participation opportunities will be different for these resources (Kaplan, 2019e). Given that only co-located storage resources are eligible to take the federal ITC, it is critical to ensure that these resources are not limited in any way by the participation models proposed.

1. California Independent System Operator

CAISO's compliance filing for Order 841 was the sparsest of the filings. As alluded to in previous sections, CAISO was nearly in compliance with the requirements of Order 841 many years in advance. Driven by the state-wide storage procurement mandate passed in 2010, the CAISO embarked on a multi-year stakeholder process to develop three storage participation models. In fact, many of Order 841's recommendations refer to CAISO's storage participation model as the best-in-class standard that other markets should replicate. As a result, the CAISO filing is very short and is primarily spent describing all the ways in which their tariff already meets FERC's new requirements (Weaver, Collanton, & Mannheim, 2018). The only major change CAISO made to comply with the filing was to lower their minimum size threshold from 500 kW to 100 kW (Weaver et al., 2018).

CAISO's participation model relies on three distinct models for energy storage:

1) *Non-generator resources (NGR):* Resources that operate as either generation or load that can be dispatched to any operating level within their entire capacity range but are

also constrained by a MWh limit to (1) generate energy (2) curtail consumption for demand response or (3) consume energy (Weaver et al., 2018). The NGR model is the most commonly used option for energy storage resources and offers the most flexibility and participation opportunities of the three models. NGR resources must complete both a participating generator agreement and a participating load agreement (Weaver et al., 2018).

2) *Pumped hydro*: The CAISO market has a high number of pumped hydro units when compared to other markets. To accommodate these units CAISO has developed a separate participation model specifically for pumped hydro facilities. They can participate in two modes, Generating Unit or Participating Load, and can submit bids in both modes (Weaver et al., 2018).
3) *Demand response:* Storage systems in the CAISO market are welcome to participate solely as demand response. This option is particularly popular for behind the meter resources (Weaver et al., 2018).

Using these three models, storage resources can participate fully in the CAISO energy and ancillary services markets. CAISO does not have a forward capacity market, instead relying on a Resource Adequacy process to ensure an adequate supply is available to the market. Storage resources can participate as Resource Adequacy if they meet the requirements. The only concerns raised by stakeholder groups about the CAISO proposal was with regard to their treatment of Transmission Access Charges[7]. The Energy Storage Association, the largest and most vocal industry association for energy storage, does not believe CAISO has clarified if storage resource dispatched by the ISO will be subject to

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[7] Fee to transport energy via the transmission grid

these charges, and has requested additional follow up from FERC on this point (Kaplan, 2019a).

2. Midcontinent Independent System Operator

MISO’s filing clarifies their definition of an Electric Storage Resource (ESR) as “a resource capable of receiving energy from the transmission system and storing it for later injection of energy back to the transmission system” (Malabonga, 2018). Unlike CAISO, MISO includes all types of energy storage within this definition, including pumped hydro units. They also clarify that behind the meter storage resources are not included in the ESR definition (Malabonga, 2018). ESRs can participate in the MISO energy and operating reserves markets through eight potential commitment status modes: Charge, Discharge, Continuous, Available, Not Participating, Emergency Charge, Emergency Discharge, and Outage (Malabonga, 2018).

By selecting one or a set of the eight modes above, an ESR participates in the energy and operating reserves market in whatever way is appropriate for the given technology. For example, continuous mode implies that the resources can transition seamlessly between charging and discharging and would be the likely choice for a standard battery storage system. A pumped hydro unit, in contrast, may not be able to quickly transition from charge to discharge, and instead may choose to bid in Charge or Discharge mode across an entire day or for specific market intervals. Units can also select Not Participating mode in order to offer ancillary services without an energy schedule (meaning the unit will participate in the ancillary services market but not in the energy market).

MISO has indicated that they can only allow ESRs to start registering by the December 3, 2019 deadline, and will not be able to accommodate full participation until March 1, 2020 (Malabonga, 2018). Similar to the CAISO proposal, the Energy Storage Association remains unhappy with MISO's treatment of Transmission Access Charges for ESRs (Kaplan, 2019b).

3. Pennsylvania New Jersey Maryland Interconnection

The PJM filing uses the same acronym chosen by MISO to refer to energy storage resources, and overall reflects a similar market design strategy. ESRs in the PJM market can choose between three operation modes: Charge, Discharge, and Continuous (Glazer, Flynn, & Tribulski, 2018). As in the MISO participation model, Charge and Discharge mode are included for resources like pumped hydro that cannot quickly transition between charging and discharging. Most battery storage resources are expected to select Continuous mode.

The majority of the PJM filing was spent offering a defense of their selected minimum run time to offer forward capacity. PJM selected a minimum duration of ten hours to participate in the forward capacity market – a value significantly higher than other market proposals, which range from two to four hours of consecutive run time (Glazer et al., 2018). PJM stated that this run time was appropriate for all storage resources because it is the current requirement for pumped hydroelectric resources (Kaplan, 2019d). Although resources can de-rate capacity to meet the ten-hour run time, PJM is facing criticism from industry groups for this requirement (Maloney, 2018). This run time requirement may reflect PJM's preference for technology types like pumped hydro, compressed air energy storage, or flow batteries – resources that offer longer durations. It is interesting to note that market rules may not be designed to be technology neutral. Instead, they may reflect the preferences or perceived needs of the ISO.

PJM was also the only RTO/ISO to submit two separate filings and request two implementation dates. The first filing detailed accounting updates the PJM would make by February of 2019 in order to enable full implementation by FERC's deadline of December 3, 2019. The separation of these two filing was an interesting indication of the widely different impacts FERC's Order 841 requirements will have on RTO/ISO markets over the next year. For some markets, implementing 841 fully will require meaningful time and resource commitments. For others, the changes will almost go unnoticed.

4. New York Independent System Operator

NYISO's definition of Energy Storage Resources closely matches the FERC definition, with a few additional specifications. NYISO clarifies that ESRs must store energy from the grid and later inject it onto the grid at the same point, and that ESRs must be able to "inject at a rate of at least 0.1 MW for a period of at least one hour" (Campbell, 2018). ESRs can participate in the NYISO markets as "Withdrawal-Eligible Generators," meaning generators that are capable of withdrawing energy from the grid for the purpose of later injection back on the grid. NYISO proposes a "dispatch-only" participation model for ESRs, meaning participating ESRs are viewed as "always available" consistent with their bids (Campbell, 2018). NYISO can then dispatch freely between charge and discharge in line with their bidding parameters.

For resources that cannot operate in continuous dispatch mode as described above, they are still eligible to participate as an Energy Limited Resources (ELR) (Campbell, 2018). A pumped hydro resource participating in the NYISO market would likely participate as an Energy Limited Resources, but stakeholders are concerned that the ELR model is not adequate even just for pumped hydro participation (Maloney, 2018). In addition, NYISO's filing prohibits storage resources from participating in both the retail and wholesale energy markets (Kaplan, 2019c). For storage resources located behind the customer meter, this restriction could be particularly limiting and runs counter to the objectives of Order 841 to expand participation opportunities for storage.

5. Independent System Operator - New England

In line with FERC's recommendations, ISO-NE defines an energy storage resource as "a facility that is capable of receiving electricity from the grid and storing the energy for later injection of electricity back to the grid" (Wolfson, Lombardi, & Grover, 2018). In the ISO-NE market, ESRs will participate as "Electric Storage Facilities" which must register within two existing market constructs: a dispatchable Generator Asset – allows the resource to inject capacity, energy, and ancillary services onto the grid - and a Dispatchable Asset Related Demand – which allows the resource to consume energy and provide demand response (Wolfson et al., 2018). Resources within these market constructs then select one set of rules:

1) *Continuous Storage Facilities*: similar to other market designs, the continuous storage rules assume a resource can transition seamlessly from charge to discharge, and can do so at any MW level that falls within their operating range (Wolfson et al., 2018).
2) *Binary Storage Facilities*: designed primarily for pumped hydro units, these rules apply for resources that cannot transition seamlessly between charging and discharging (Wolfson et al., 2018).

To add even more complexity, ESRs that select the *Continuous Storage Facility Rules* must also opt to register as an Alternative Technology Regulation Resource (ATRR) in order to provide regulation services to the ISO-NE market (Wolfson et al., 2018). Because ISO-NE did not create a new market construct specifically for ESRs, but instead is requiring storage resources to register within existing market participation models, there are concerns that storage participation in ISO-NE may be more limited than in other markets (Maloney, 2018).

6. Southwest Power Pool

SPP adopted FERC's definition of electric storage, but added a clarification: resources are excluded from the electric storage categorization if they are physically incapable or contractually barred from injecting electric energy on to the transmission system (Wagner & Nolen, 2018). SPP's filing is careful to state that energy storage resources can register and participate in SPP's Integrated Marketplace as any existing resource type assuming they meet the requirements for participation. Storage can also participate specifically as a Market Storage Resource (MSR), a newly added resource type in the SPP market (Wagner & Nolen, 2018). In order to bid in to the energy market, MSRs must submit an Energy Offer Curve, which reflects the "Continuous" mode offered by a number of other market proposals. This Energy Offer Curve can include both positive and negative MW values, implying that the resource can transition between charging and discharging instantaneously.

Although SPP does not operate a capacity market, they do have a Resource Adequacy requirement for participating load serving entities much like the CAISO market. Storage resources are eligible to count as resource adequacy if they meet existing market requirements (McAllister & Ramadevanahalli, 2019). Comments for the ESA do point to this capacity participation model as acceptable, but subject to manipulation in SPP stakeholder processes that could make it very challenging for storage to qualify as resource adequacy (Kaplan, 2019e).

B. *Comparison Table*

Table 5. Comparison of CAISO, MISO, PJM, NYISO, ISO-NE, and SPP Compliance Filings for FERC Order 841; filed December 3, 2018 (Campbell, 2018; Glazer et al., 2018; Malabonga, 2018; Wagner & Nolen, 2018; Weaver et al., 2018; Wolfson et al., 2018) [8]

	CAISO	**MISO**	**PJM**	**NYISO**	**ISO-NE**	**SPP**
Energy market (DA, RT) market participation?	Yes					
Forward capacity market participation?	No → No forward capacity market exists in CAISO. Resources can participate as Resource Adequacy resources if they meet requirements	Yes → ESRs can participate if they are able to meet minimum run time requirements	Yes → PJM has a 3-year forward capacity market. “Capacity Storage Resource” redefined to include all ESRs able to meet run time requirements	Yes →ESRs can participate in the Installed Capacity market if they meet criteria for a Generator plus ESR specific requirements	Yes → Storage resources can participate in the Forward Capacity Market through Generator Asset participation function	No → No forward capacity market exists in SPP, but ESRs that meet continuous run time requirements can participate as Resources Adequacy resources
Ancillary services market participation?	Yes → Must meet specific eligibility requirements for Frequency Reg, Spinning and Non-Spinning Reserves	Yes → No energy schedule is required to provide Reg, Spinning, and Supplemental Reserves, or Up/Down Ramp Capability	Yes → ESRs have participated in the PJM ancillary services market since 2009. Can offer certain services without an energy	Yes → Reg Service and Operating Reserve (spinning, non-spinning, 30-min reserve) when also submitting an energy schedule	Yes → Can participate in the forward reserves market, regulation market, provide black start, reactive power, and primary	Yes → Reg Up & Down, and Spinning Reserves procured through the market. Other ancillary services require a separate,

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[8] DA = Day-Ahead; RT = Real-Time; ESRs = Energy Storage Resources; Reg = Regulation

			schedule		frequency response	non-market application
Market services that can be provided[9]	1) DA & RT Energy 2) DA & RT Frequency Reg (up/down ramping) 3) Spinning Reserves 4) Non-Spinning Reserves 5) Resources Adequacy	1) DA & RT Energy 2) DA & RT Frequency Reg (up/down ramping) 3) Forward Capacity 4) Regulation Reserves 5) Spinning Reserves 6) Supplemental Reserves 7) Blackstart Service 8) Reactive Supply and Voltage Control	1) DA & RT Energy 2) Forward Capacity 3) Synchronized Reserves 4) Non-synchronized Reserves 5) DA & RT Frequency Reg (up/down ramping) 6) Reactive services 7) Black start (min 16-hour duration)	1) DA & RT Energy 2) Forward Capacity 3) Frequency Regulation 4) Spinning reserves 5) Non-spinning reserves 6) 30-min reserves 7) Voltage support	1) DA & RT Energy 2) DA & RT Frequency Reg (up/down ramping) 3) Forward Capacity 4) Regulation Reserves 5) Spinning Reserves 6) Non-spinning Reserves 7) Blackstart Service 8) Reactive Supply and Voltage Control	1) DA & RT Energy 2) DA & RT Frequency Reg (up/down ramping) 3) Resource Adequacy 4) Regulation Reserves 5) Spinning Reserves 6) Non-spinning Reserves 7) Reactive Supply and Voltage Control
Minimum Size	100kW					
Minimum consecutive run time to offer forward capacity	N/A	4 hours across coincident peak	10 hours on a summer peak day	4 hours	2 hours	N/A
Ability to de-rate capacity?	Yes → All resources can de-rate to meet the minimum run times above, and a market monitor will watch for potential market manipulation via physical withholding					
Execute wholesale transactions at LMP?	Yes	Yes	Yes → But only for purchases of energy that are later resold to PJM	Yes → But only for purchases of energy that are later resold to NYISO	Yes	Yes
Ability to self-manage state of charge (SOC)?	Yes → Storage resources can self-manage or allow CAISO to manage SOC through	Yes → SOC can be communicated via commitment status in particular dispatch intervals.	Yes → ESRs are required to manage SOC through offers, modes and bid parameters. Market	Yes → resources can self-manage SOC or elect to have NYISO manage Energy Level given submitted	Maybe →Via bid parameters, but explanation was not very convincing as to if resources will really be	Yes → Must communicate SOC through bid parameters, SOC forecast, and in real time via

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[9] As listed in FERC Order 841 compliance filings. May not be comprehensive.

	market optimization		optimization available only for pumped hydro.	bid parameters. IMM will watch for withholding/ market manipulation	able to self-manage	telemetry. No market mechanism to manage SOC and no plans to add one
Participate as a buyer or seller?	Yes					
Prevent conflict dispatch	Yes → Resources submit a single bid curve in some version of “continuous” mode (with supply as negative generation) which prevents conflict dispatch				Maybe →Description is far less clear than other filings	Yes → Prevented through Energy Offer Curve
Storage make-whole payments	Eligible					
Implementation date requested	December 3, 2019	March 1, 2020	Feb 3, 2019: Accounting updates Dec 3, 2019: Fully implemented	May 1, 2020	December 3, 2019 for majority, January 1, 2024 for DARD participation as a Regulation Resource	December 1, 2019

VI. Results

A. Value and Market Efficiency

FERC Order 841 is shifting the relationship between private and social value for energy storage resources by creating newly available revenue streams. Private value in this realm refers to the revenue streams available to an individual actor or project owner, whereas social value refers to the benefits and services available to the grid at large (assessed here at the RTO/ISO level). Overall, the RTO/ISO market compliance filings for FERC Order 841 are similar. Most filings met the majority of requirements for items like market participation, minimum capacity size, and market participation as both a buyer and seller at wholesale LMP. There are many successes to be celebrated here; for example, in the PJM and MISO markets, storage was not eligible to participate in the energy market prior to Order 841. The introduction of a participation model for storage in these energy markets creates new value opportunities for private project owners and creates social value by increasing the diversity of resources available to provide energy. A more diverse resource mix offers a variety of grid benefits, including improved system resiliency.

Similarly, prior to Order 841 storage resources could participate either as a generator or as load (demand response) in SPP. Now, with the addition of SPP's Market Storage Resource, storage can participate in the energy market on a continuous spectrum from load to generation. This participation opportunity resolves a disconnect between private value and social value – project owners gain value by more thoughtfully switching between supply and demand to align with real-time LMP, and the SPP system gains social value through the added flexibility of a continuous resource.

Energy market participation in PJM and MISO, and multi-market participation in SPP are just two examples of the way Order 841 reduced dead weight loss and eliminated the misalignment between the value individual resources can provide (energy) and a social service the grid needs (diverse energy resources for reliability and resiliency). Therefore, based on the initial compliance filings it appears that Order 841 should be considered a success because it has eliminated arbitrary participation barriers for energy, capacity, and ancillary services and forced the development of adequate participation models for storage in these markets. In theory, meaningful dead weight loss created by the lack of these basic participation models has been eliminated and overall market efficiency has improved.

Looking beyond these immediate market efficiency successes, more nuanced differences between the RTO/ISO participation models emerge at the intersection of private and social value. Two requirements that stand out for diversity within the compliance filings are:

1) Minimum run time required to offer forward capacity
2) State of charge management

A quick review of the comparative analysis above reveals that not all markets chose the same minimum consecutive run time to offer forward capacity. ISO-NE selected a run time as low as two hours, while PJM requested 10 hours on a summer peak day. Capacity duration is closely tied to social value for decarbonization, but current project economics favor shorter duration resources. Although the Energy Storage Association is not happy with PJM's 10-hour capacity run time requirement, it may in fact be the most socially optimal of the filings thanks to the benefits of long duration storage for grid decarbonization. PJM has not required this onerous run time for its energy or ancillary services market, and therefore one could argue that from a value maximization perspective their selected run time may be more efficient than other market proposals if decarbonization value was fully quantified. The relationship between storage duration and value for decarbonization is still fuzzy at this point and warrants further research. But it is important to caution against a dismissal of lengthy run time requirements for capacity without additional research and analysis to quantify the relationship between duration and social decarbonization value.

Lingering tension between private and social value plays out most visibly in each market's treatment of state of charge, where the compliance filings show a surprising diversity of approaches. The relationship between private and social value for state of charge management will be analyzed further as a case study in section B from the lens of private or social value prioritization. Because state of charge is closely tied to project longevity, managing it over the course of a market day and project lifetime is risky for operators. Market rules to promote efficiency through state of charge management are complicated by concerns over resource ownership and control, both of which are tied to capturing enough revenue streams to justify financial investments in the project.

B. Case Study: State of Charge Management

State of charge (SOC) management is a critical and controversial topic for energy storage resources. FERC Order 841 specifically addresses state of charge management, stating that "in this Final Rule, we require each RTO/ISO to allow electric storage resources to self-manage their state of charge" (Federal Energy Regulatory Commission, 2018). State of charge refers to the level of stored energy available within the storage resource at a given moment in time. RTO/ISOs must allow project owners to manage this level as well as their upper and lower charge limits. Because Order 841 also allows storage resources to de-rate their capacity to meet minimum run time requirements, state of charge management also raises concerns about capacity withholding and potential market manipulation. Strategy and treatment of state of charge management is the area with the most complexity in the proposed tariff filing. In fact, a response filing from

FERC in early April of 2019 requested specifically that RTO/ISOs file additional follow up information related to state of charge management (Bade, 2019)[10].

The RTO/ISO approaches to SOC management vary across a spectrum of market efficiency. This section will look in more detail at the approach each RTO/ISO takes regarding SOC management and using economic theory of market efficiency will assess each market's balancing of private and social value. Generally, SOC is managed through a combination of bidding parameters, self-scheduled resource commitments, RTO/ISO dispatch decisions, and real-time market optimization software. In the day-ahead energy market, resources can submit a variety of bidding parameters to indicate how their state of charge should be managed – the table below shows an example set of bidding parameters from the SPP compliance filing.

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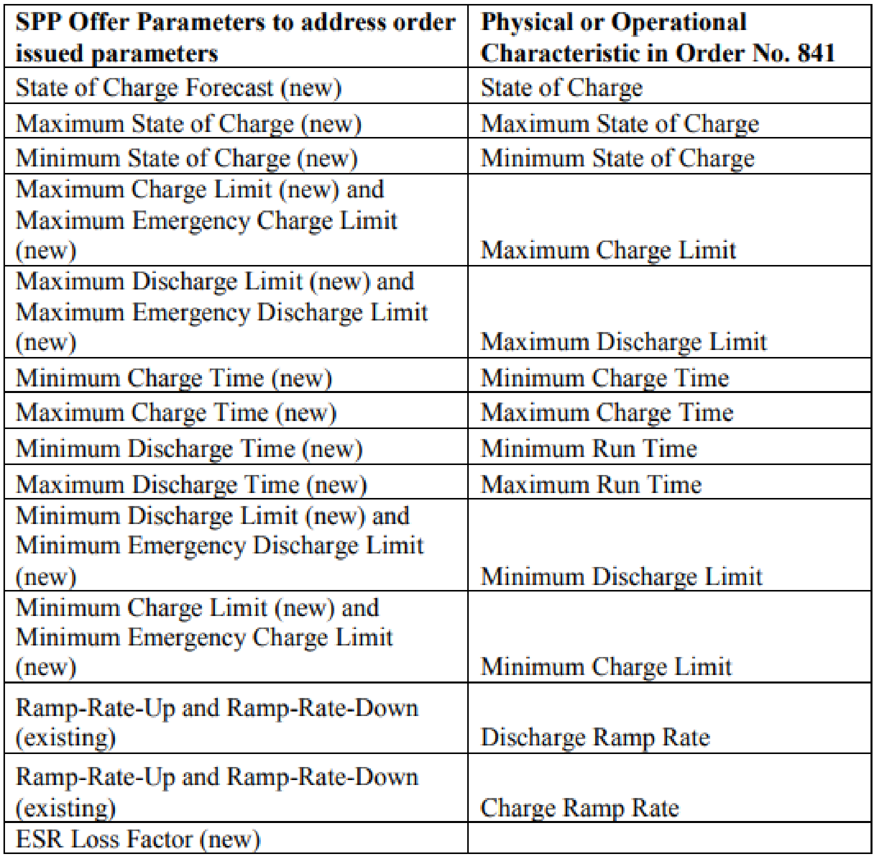
[10] The SOC management strategies are still, therefore, in development. Clarification from the RTO/ISOs in response to FERC's request may reveal that strategy has shifted or was misrepresented in the initial filings.

Table 6. SPP Offer Parameters (Wagner & Nolen, 2018)



SPP Offer Parameters to address order issued parameters	**Physical or Operational Characteristic in Order No. 841**
State of Charge Forecast (new)	State of Charge
Maximum State of Charge (new)	Maximum State of Charge
Minimum State of Charge (new)	Minimum State of Charge
Maximum Charge Limit (new) and Maximum Emergency Charge Limit (new)	Maximum Charge Limit
Maximum Discharge Limit (new) and Maximum Emergency Discharge Limit (new)	Maximum Discharge Limit
Minimum Charge Time (new)	Minimum Charge Time
Maximum Charge Time (new)	Maximum Charge Time
Minimum Discharge Time (new)	Minimum Run Time
Maximum Discharge Time (new)	Maximum Run Time
Minimum Discharge Limit (new) and Minimum Emergency Discharge Limit (new)	Minimum Discharge Limit
Minimum Charge Limit (new) and Minimum Emergency Charge Limit (new)	Minimum Charge Limit
Ramp-Rate-Up and Ramp-Rate-Down (existing)	Discharge Ramp Rate
Ramp-Rate-Up and Ramp-Rate-Down (existing)	Charge Ramp Rate
ESR Loss Factor (new)	

In combination with the bidding parameters, resources can submit an energy schedule (self-schedule) which indicates exactly how the resource should be dispatched throughout the day. This option offers the most individual control and the most aggressive risk management for the project owner. Beyond self-schedule, many markets offer to dispatch the resource economically in the real-time market, using bidding parameters as guide points to ensure the resource stays within its operational constraints. In this market dispatch scenario, resources do not submit a full energy schedule, and the real-time market solves for the least-cost solution every five minutes to drive dispatch decisions. Going one step further, some markets offer dispatch optimization in the real-time market which looks at predicted demand and pricing several hours ahead in the market before determining how to dispatch resources. These solutions for SOC management will be discussed in more detail within three categories below: Optimization of Social and Private Value, Prioritization of Private Value, and Prioritization of Social Value.

Optimization of Social and Private Value: CAISO, NYISO

CAISO's treatment of SOC comes the closest to market efficiency of any of the filings. According to the CAISO compliance filing: "The CAISO accounts for storage resources' state of charge and charging constraints. The CAISO offers storage resources the flexibility to manage their state of charge on their own (through bidding), or to have the CAISO market optimization process manage the resource's state of charge and charging limits (through bidding and master file parameters)" (Weaver et al., 2018). This means that although resources can fully self-manage SOC if desired (as required by Order 841), they can also opt in to a market optimization system that will dispatch the resources optimally over a 1 hour 45-minute time window in the real-time market. This optimization option in theory should maximize both social and private value and minimize deadweight loss in the market, because the optimization time window mitigates the social/market risk of dispatching a resource only minutes before it is more desperately needed to meet an anticipated increase in demand. This window of optimization should also maximize value for the storage resource because a dispatch decision made only in five-minute increments might discharge the resources at 10:00am, when in reality the need is much higher at 11:30am. Higher need for the grid is expressed in higher LMP prices, and therefore higher profit available for the private actor to capture.

CAISO’s SOC management strategy is still far from perfect, however. An issue paper released earlier this year describes some of the SOC optimization changes that CAISO is looking to make. The briefing explains, “The real-time market optimization horizon may impede scheduling coordinators from optimally managing their NGR over the day. The real-time market optimizes schedules over a 1 hour and 45-minute time horizon that does not consider conditions later in the day” (California ISO, 2019). CAISO does have a sophisticated market optimization system in place, but that optimization is limited to a window of less than two hours. A more efficient participation model would optimize state of charge across an even more extended time window such as four or eight hours. While CAISO has made strides towards optimal SOC management and resource dispatch, there is still net value to be captured (and positive externalities eliminated) if the optimization window can be expanded further across the market day.

NYISO’s state of charge management strategy includes many of the same bidding parameters as SPP, but also requires resources to choose between two participation options (Campbell, 2018):

1. *ISO-Managed Energy Level:* ESR’s energy level (SOC) constraints will be directly accounted for in the optimization.
2. *Self-Managed Energy Level:* indicates the ESR’s energy level (SOC) constraints will not be directly accounted for in the optimization, on the assumption that resources will self-manage their dispatch using available bidding parameters.

Energy storage resources can only select one of these modes for all hours in the day-ahead market but can switch between the two every hour in the real-time market. If resources select the ISO-Managed option, NYISO will select the least production cost solution (Campbell, 2018). The day-ahead market is optimized over a 24-hour window, but real-time market optimization only occurs across a 1-2.5 hour period (real-time commitments are optimized over 2.5-hour window, and real -time dispatch over a 1-hour window) (Campbell, 2018). Self-managed resources must manage their own state of charge across the day, and will be penalized for any mismanagement (Campbell, 2018). This market design for state of charge management closely matches the CAISO market design, with clear options between self-managed and market-managed SOC and similar real-time optimization time frames. Although market actors do not have complete information, dispatch decisions are being adjusted within a 1-hour window of market information. However, NYISO's filing indicated that they will not be able to implement the proposed tariff changes until May of 2020 instead of the requested deadline of December 2019. This indicates that NYISO may still be developing much of the market optimization software described, unlike CAISO where this sort of optimization software is already in use.

Prioritization of Private Value: MISO, PJM, SPP

MISO's compliance filings listed a number of bidding parameters resources must submit in order to participate in the energy market, including parameters like SOC, minimum and maximum SOC, and emergency minimum and maximum SOC (Malabonga, 2018). A resource's state of charge can be managed in a particular dispatch interval by using or adjusting commitment status, energy dispatch status, the energy offer curve, dispatch limits, or self-schedule volumes (Malabonga, 2018).

In the day ahead market offer, or in real-time through telemetry, resources communicate and therefore control SOC. MISO explicitly states that energy storage resources are required to manage their own state of charge, and no market optimization or market-managed SOC option is available (Vannoy, 2018). Kevin Vannoy, MISO's Director of Market Design, explains that although limited SOC management software is available for pumped hydro resources, it cannot be used for more flexible storage units because it assumes only one charge/discharge cycle per day and does not contain constraints for daily minimum or maximum charging energy (Vannoy, 2018) However, if storage resources offer flexibility to the market dispatch (communicated through bidding parameters) they will be charged and discharged economically throughout the day. Fully self-scheduled resources will be dispatched as scheduled instead of most economically across the day (Vannoy, 2018).

In the PJM market, energy storage resources are required to manage their own state of charge through offers and mode scheduling (continuous, charge, or discharge) (Glazer et al., 2018). Offers can be for a dispatched resource, or self-scheduled with a non-dispatchable range, similar to the process described in the MISO market. If continuous mode is scheduled, the resources can switch between charging and discharging but this mode is not economically optimized over time. Dispatch decisions are based solely on real-time LMP, and are not optimized across any window of time (Glazer et al., 2018). Similarly, the day-ahead market is not economically optimized.

SPP's compliance filing indicates that they explicitly will not manage state of charge for participating energy storage resources (Wagner & Nolen, 2018). The market participant is expected to self-manage all SOC variables through bidding parameters and an energy schedule submitted the day ahead. Much like the MISO and PJM market proposals, energy storage resources can submit a dispatchable range as part of their bidding parameters instead of a schedule, which allows for market economics to guide resource dispatch through the day. However, this methodology does not include any optimization of dispatch across the day.

From a market efficiency perspective, MISO, PJM and SPP are all prioritizing private control and private risk mitigation instead of aiming to maximize net benefits (both private and social) from storage participation. Although this is likely viewed by market participants as favorable for private value stream management, it may increase overall deadweight loss in the market and therefore reduce available value for both private and social actors. In other words, this strategy allows private actors to fully control what revenues end up in their private value stack, but it does not eliminate all positive externalities and may not capture all available value in the market.

Prioritization of Social Value: ISO-NE

ISO-NE has taken a notably different approach to state of charge management than other markets. ISO-NE has chosen not to represent SOC as a bidding parameter as most of the other markets have. Instead, SOC will be only a telemetry value, represented as Available Energy and Available Storage (Wolfson et al., 2018). However, because this approach is telemetered it is questionable whether market participants are really able to control SOC as required by Order 841. ISO-NE's filing explains:

> *"For Continuous Storage Facilities, Available Energy and Available Storage will also be telemetered to ISO-NE, but for these facilities, software will automatically update Maximum Consumption Limit and Economic Maximum Limit values in order to meet the same duration requirements. As noted above, the automation of*

> *this process for Continuous Storage Facilities eliminates the need for the participant to telephone the ISO-NE control room each time a Continuous Storage Facility updates its physical operating limits to align with its state of charge. The automation also helps ensure that the facility's operating limits are accurate and therefore that the desired dispatch points issued by ISO-NE are feasible and the facility has sufficient energy to follow them."* (Wolfson et al., 2018).

Industry groups have interpreted this opaque statement to mean that ISO-NE will automatically de-rate energy storage resources every few minutes to ensure adequate capacity is available to the market (Maloney, 2018). This approach prioritizes maximizing social value to the grid, but at the expense of private control. It is not clear at this point if the approach taken by ISO-NE is in compliance with FERC Order 841 or if it too strictly limits individual control. ISO-NE claims that SOC can still be adequately managed by the market participant through day-ahead or real-time Supply Offers or Demand Bids (Wolfson et al., 2018), but places more emphasis on value and control for the market at large.

Managing state of charge is a challenge unique to energy storage resources, and the strategies proposed above by each of the six markets are still very much in development. Some markets are aiming for full market optimization, which will minimize deadweight loss but may come at the expense of private control and risk management. Other markets are focused on preserving autonomy and control for individual participants, seemingly through a focus on maximizing private value by offering participants full control of their private value stack. However, the unintended result of this strategy may be an increase in deadweight loss in the market and missed private and social value opportunities. One market, ISO-NE, has pushed so far towards a prioritization of social value and control that they may not be in compliance with FERC Order 841 and may be required to revise their strategy.

It is interesting to note that the two markets that are closest to optimizing state of charge management are primarily single-state markets: CAISO and NYISO. California and New York also happen to be two of the most progressive states in the country, and both have energy storage deployment mandates in place. This indicates that there may be some interaction between state policy and market rules, with policy pushing market design towards a more optimal outcome for all actors. As the market matures, private actors may be more willing to give up resource control as they begin to trust that market optimization processes will increase their individual revenue streams and not just optimize social value to the market. It is also worth noting, and will be explored further in Section VII, that the sole objective of market rule design may not be to maximize net value through efficient market design. Instead, market design decisions may be driven by institutional objectives, perceptions of control and autonomy, or state policy goals

C. Excluded Value Streams

Although FERC Order 841 made excellent progress towards increasing participation opportunities for energy storage and thereby creating additional private and social value in the industry, there is still a gap between services a storage resource can provide versus services a resource can actually be compensated for. Said differently, Order 841 was not exhaustive and not all storage value streams exist. Notably, avoided cost from deferred transmission and distribution upgrades remain difficult to quantify in order to monetize in a revenue stream. Much work beyond FERC Order 841 will be necessary to fully fill the gap between theoretical and actualized revenue streams, and thereby further eliminate deadweight loss in the storage market. A report from the Interstate Renewable Energy Council (IREC) discusses this challenge:

> *"In all states, the value of storage to network or distribution services, such as avoiding substation or circuit upgrades, are not currently priced or monetized. Presently, the "value" of such services is typically assumed to be the avoided cost of the alternative, traditional solution, which does not account for other supply or load benefits that storage can provide.* (Stanfield et al., 2017)

The solar industry is facing many of the same challenges, especially for distributed solar resources. The state of Minnesota has struggled to develop a methodology to quantify the value of distributed solar in order to set compensation rates for community solar gardens. Currently the Minnesota value of solar is one static number across the state, despite the fact that resource value varies meaningfully based on location on the grid the impacts that location has on local infrastructure – either triggering distribution/substation upgrades or helping avoid upgrades. Quantifying the private value storage offers to support existing infrastructure and delay necessary upgrades remains a future challenge for storage markets to grapple with.

Returning to the concept of value stacking, as the storage industry matures it should also shift the focus from private, individual value stacks to stacks of the full market value – including both private and social values. Figure 12, below, illustrates this full value stack in the context of the current storage market. Without a more complete definition of value stack that takes all social values into account, private incentives to deploy storage will be insufficient to deploy all socially beneficial storage. Efficient markets where these two value streams are maximized (in the tallest stack!) is where the United States will see game-changing, rapid deployments of energy storage.

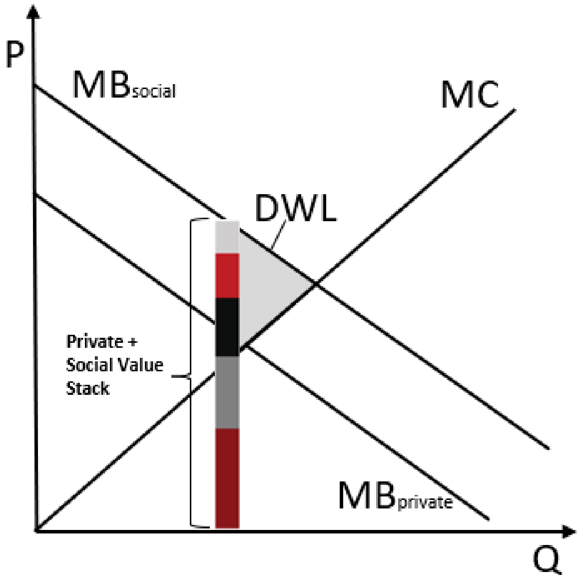


Figure 12. Private + Social Value Stack Illustration

VII. Discussion & Conclusion

A. Barriers to Market Efficiency

The diversity of approaches in Section VI B begs the question: what is preventing FERC-regulated markets from optimizing both private and social value, for state of charge management and all market rules that apply to energy storage? Why are market failures still present?

First, it is worth acknowledging the reality that perfectly efficient markets do not exist. Especially in the energy industry, competition is often non-existent thanks to monopoly service territories, demand fluctuates unpredictably in real time, and a variety of social costs and benefits continue to be excluded from the market. Achieving perfect market efficiency is not possible. However, for energy storage resource participation, many market rules remain far from the “optimal” realm even after FERC Order 841.

Therefore, we must look beyond economic theory for barriers preventing RTO/ISO markets from maximizing the value stack of private and social value.

The lack of optimized storage participation rules may simply be due to organizational resource constraints. Energy market rulemaking requires thoughtful modeling and analysis, and markets with fewer resources may err on the side of "compliance only" instead of ongoing iterations and stakeholder processes which help refine optimal rules over time. Similarly, the timeline for submitting filings and actually implementing tariff changes for FERC Order 841 may have prevented optimal rulemaking in some markets. For markets with no existing participation model for energy storage, limiting the implementation strategy to what could reasonably be accomplished by December of 2019 was a must. That may explain why some markets, such as SPP, offered no optimization for state of charge management – they may have simply needed more time to develop the complex software necessary for SOC optimization. In addition, RTO/ISO markets may need financial support or outside expertise to develop the necessary optimization software to manage state of charge across an extended time window. This could be an opportunity for federal funding and intellectual support from the DOE.

Institutional barriers may also play a role in preventing optimized private-social value relationships. Today, RTO/ISO participation is voluntary in the United States. Not all utilities participate in an organized market, especially in the western states. RTO/ISOs are hesitant to overstep their authority and isolate or upset members. In early 2018, Xcel Colorado withdrew from the Mountain West Transmission group to avoid joining the SPP market. Stakeholders familiar with the situation say that Xcel Colorado feared joining SPP would limit the utility's operational freedom (Bade, 2018). Similarly, when CAISO realized no utility outside of California would agree to join the CAISO market for fear of California state legislative oversight, they created the western EIM. CAISO is still tiptoeing through the expansion of the EIM to ensure participating members feel that their individual freedoms are protected. In this way, private-social value dynamics are playing out at multiple levels: between utilities and RTO/ISOs, and between independent power producers/project owners and RTO/ISOs.

RTO/ISO's with members who are more sensitive to limitations on autonomy and individual control may be more likely to design market rules to protect that private autonomy instead of working to maximize grid-level benefits. Although this strategy does leave value on the table, it may be a necessary strategy to increase the number of participating members.

Finally, RTO/ISO markets may not be achieving optimal net private and social value because they are not experiencing a strong enough push from state policy, federal policy, or the private sector. In California, state policy that mandated energy storage procurement drove CAISO to launch its energy storage participation model development in 2010. As a result, when FERC finally demanded RTO/ISOs develop an adequate participation model for energy storage through Order 841, the CAISO market found itself years ahead of other energy markets. Similarly, while private sector activity surrounding energy storage (particularly battery storage) is growing rapidly, it still represents only a tiny fraction of the generation and dispatchable load capacity available in the United States. As a result, there is not a strong push from the private sector for more sophisticated market rules and participation models for energy storage. Without a push from FERC, many RTO/ISOs would still be encouraging energy storage resources to use existing participation models instead of providing custom participation options. An ideal energy storage market with perfectly priced value streams would not require any policy mandates, but U.S. storage market rules are still very much in development and not yet fully optimized. Policy, such as state-level deployment mandates, may be required to continue pushing the market towards efficiency. Learning-by-doing thanks to policy mandates may expand total available value by reducing soft costs and reducing risks associated with project financing.

B. FERC Order 841 and Storage Value for Decarbonization

For U.S. energy markets to operate efficiently, it is important for them to be technology neutral. Appropriately, most of the Order 841 compliance filings do just that[11]. As previously discussed, storage resources are not exclusively useful for grid decarbonization. In fact, depending on the implementation of the resources, energy storage can even increase carbon emissions on the grid. As market rules for energy storage shift and markets aim for optimization, it is important to consider decarbonization as a type of social value and how storage resources can most appropriately contribute to social decarbonization goals.

First, an efficient market must include all relevant costs and benefits. In U.S. energy markets, the social cost of carbon is not incorporated in market transactions[12]. As a result, carbon intensive resources like natural gas and coal remain economical and often it is more affordable for energy storage resources to charge off of these resources. The

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[11] PJM’s filing may not be technology neutral given the ten-hour run time requirement.

[12] Except in California and New England where there is a carbon price on electricity, but it is below the social cost of carbon (“State Actions,” 2019)

simplest fix for this market failure would be to add a tax on carbon emissions for all energy generating resources (Keohane & Olmstead, 2016). For storage resources, this would incentivize charging from lower carbon resources like wind, solar and nuclear because the market prices for carbon-intensive resources would increase and reduce the profitability of energy arbitrage for storage. Although the idea of a national carbon tax makes economic sense, it remains politically infeasible in the United States and is unlikely to pass in the near future. The most feasible attempt at a state-level carbon tax was on the ballot in Washington state in fall 2018, and it failed to pass for the second time (D. Roberts, 2018). Many advocacy groups hoped this state carbon tax could serve as a model policy for other states, and its failure does not bode well for other state-level efforts.

Second, recent modeling work has shown that longer duration storage resources offer more grid-level value for decarbonization. Minimum run time requirements for storage resources are generating significant controversy in the Order 841 compliance filings, with PJM requiring a ten-hour run time to offer forward capacity. Energy storage advocates and industry groups are outraged over this requirement because it excludes many already-built resources from participating fully in the market, despite the fact that it aligns with decarbonization objectives. Given that the objective of Order 841 was to increase participation opportunities for storage, the outrage over further limits to participation is expected. With a ten-hour duration requirement, most currently financeable energy storage resources – like lithium-ion battery systems – will be excluded from participating in the PJM capacity market.

The current prevalence of short duration lithium-ion battery technologies creates a risk of technology lock-in for the storage market. If new market rules increase participation opportunities for these shorter-duration resources, that may further increase the market dominance of lithium-ion battery technology and prevent further R&D work on long duration technologies that can offer higher social value for decarbonization. A policy response may be appropriate here. At the federal level, R&D funding should be allocated specifically for developing long duration storage (defined as storage that can operate for at least ten consecutive hour). Current technology solutions, with the exception of pumped hydro, are not cost effective at such long durations. At the state policy level, states can offer tax incentives for energy storage that only long duration resources are eligible for. This could incentivize the deployment of additional long duration storage that otherwise would not be cost effective, and hopefully prevent technology lock-in in the U.S. storage market.

Third, policy can encourage storage resources to provide services that are complimentary to renewable generation resources. Among the many services that energy storage can provide to the grid, the following align well with renewables: energy time shift, frequency regulation, and spinning reserves. Without a carbon tax in place, energy arbitrage is a potentially damaging service for the grid if stakeholders are aiming for decarbonization. The federal ITC is doing this well by requiring storage resources to be paired with a renewable resource in order to claim the tax credit.

Finally, optimized state of charge management market rules in the NYISO and CAISO markets indicate that state deployment mandates may be incentivizing or accelerating the development of market rules that optimize both social and private value stacks. Although accurately priced market mechanisms should in theory preclude the necessity of policy mandates, reality indicates that these deployment mandates may be nudging market rules toward efficiency. Similar mandates should be considered in all states as a tool to both accelerate deployment in support of decarbonization goals, and to push market rules closer to overall market efficiency with minimized deadweight loss.

C. Conclusion

FERC Order 841 was a landmark rulemaking for the energy storage industry. Although energy storage has long played an important role on the grid in the form of pumped hydroelectric, recent cost declines in battery storage technology present an opportunity to make energy storage a much more prominent player in U.S. energy markets. Battery storage offers a multitude of services to the grid, and importantly adds value by operating as both supply and demand. A number of states have addressed storage directly through mandates or incentive programs, and FERC has touched on storage indirectly in a handful of previous orders. However, Order 841 was the first time that FERC released a rulemaking fully dedicated to enabling the growing energy storage industry. Order 841 demanded RTO/ISOs develop full participation models for energy storage in the energy, capacity, and ancillary services markets.

Perhaps the most important takeaway from this work is that FERC Order 841 is not the end of market rule development for energy storage. In fact, in most ways it is only the beginning. Important tensions remain between private value and social value for energy storage, and there is room for additional optimization to increase overall net benefits from storage deployment by further eliminating market failures. Importantly, Order 841 excludes behind-the-meter resources. As the Rocky Mountain Institute identified in their 2015 report, BTM may in fact be the optimal location for energy storage resources because they are able to capture the maximum number of revenue streams from a BTM location (Fitzgerald et al., 2015). FERC is already moving forward with an order to address BTM aggregation for wholesale market participation, which could dramatically change the revenue opportunities for BTM storage resources. These resources are incredibly versatile but will be even more challenging to value and compensate than distribution or transmission connected storage resources.

There are a variety of reasons why RTO/ISOs are not maximizing net private and social value from energy storage resources. For one, time and resources may be a constraint. Additional support from the federal government, industry associations, or nonprofits may be needed to expedite the process of continued participation model development. From the academic community, more research is needed on the institutional barriers for market optimization at RTO/ISOs in the United States. In what ways are concerns about autonomy and control getting in the way of potential value-maximizing rulemaking, and what market structures could make participants still feel in control while optimizing both private and social value from energy storage resources?

State and federal policy is needed to ensure that as storage deployment continues to accelerate, it is installed and operated in a way that aligns with social decarbonization goals. Market rules can and must remain technology neutral to support efficient market operations. Policy, however, can be used to nudge market operations towards social goals potentially via state-level storage deployment mandates.

The market rules and policy surrounding energy storage are changing every day. In many ways, that made it challenging to complete this work. Most resources from before 2015 are too outdated to still be relevant. In addition, Order 841 is an active proceeding and FERC is still responding to the filed proposals with requests for additional information and change requests. The final tariffs may look different than the versions on file today. However, this research is a first step towards further adaptation of market rules for energy storage. Comparing and learning from the strategies filed for FERC Order 841 will be critical to determine the appropriate next steps for actors at the local, state, and federal level seeking to expedite the deployment of energy storage to build a cleaner, more resilient U.S. electric grid.

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