Unlocking the Flexibility of Hybrid Resources

A Report of the
Energy Systems Integration Group's
Hybrid Resources Task Force

March 2022

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Suggested Citation

Hybrid Resources Task Force. 2022. *Unlocking the Flexibility of Hybrid Resources*. Reston, VA: Energy Systems Integration Group. https://www.esig.energy/reports-briefs.

This work was supported by funds from Sequoia Climate Fund.

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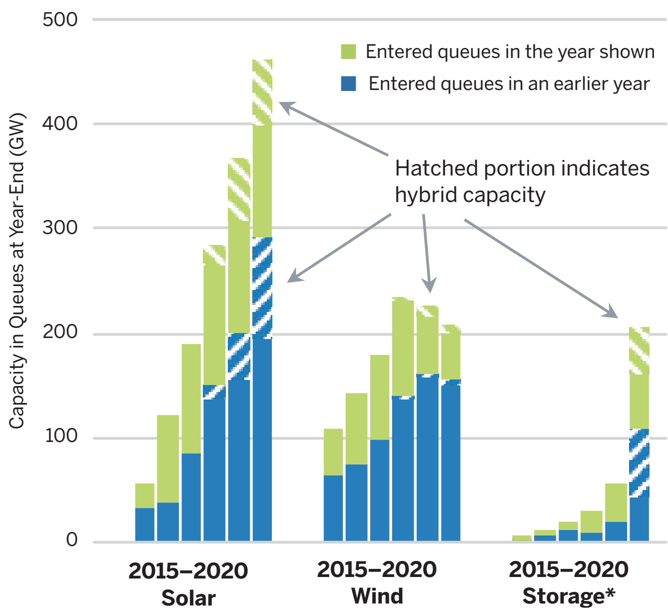
Introduction

Recent cost declines and tax incentives for battery energy storage have led to rapid growth in the size, number, and types of hybrid energy systems. Currently, the most common form of hybridization is battery storage combined with utility-scale solar projects and other generation technologies (Figure 1), but new forms of hybrids are on the rise. In as little as three years, the total number of hybrid resources proposed in U.S. interconnection queues has increased from almost nothing to more than 150 GW, constituting approximately one-third of all new solar proposals and over half of new storage proposals (Bolinger et al., 2021). Similar trends are also occurring globally. This report discusses what hybrid resources are, why the industry is seeing increasing hybridization across technology types, and how these resources interconnect to the grid. It concludes with some initial recommendations for system planners, market designers, and policymakers as they define market rules and requirements that govern hybrids' use.

FIGURE 1
Wind, Solar, Storage, and Hybrid Project Capacity in U.S. Interconnection Queues



Increasing amounts of proposed wind, solar, and storage projects in U.S. interconnection queues. Hashed portions indicate hybrid capacity that combines solar, wind, and/or storage.

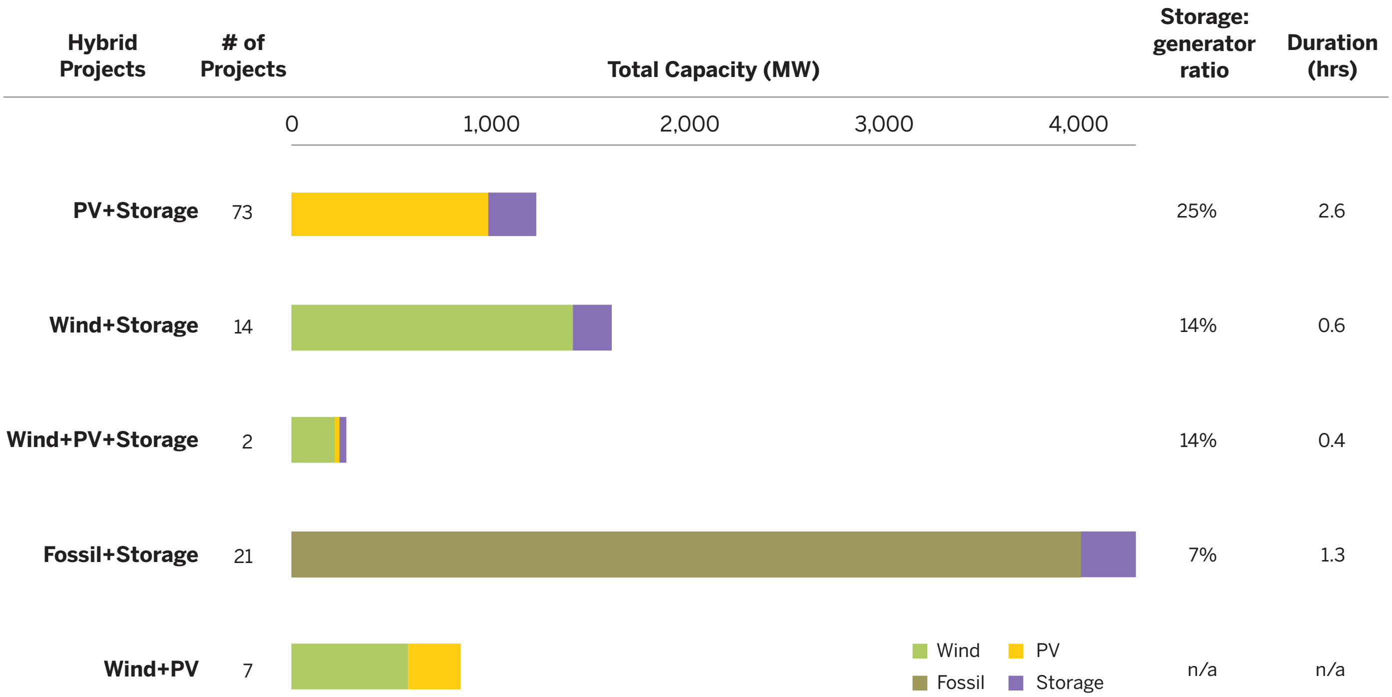
* Hybrid storage capacity was estimated using storage:generator ratios from projects that provide separate capacity data. Storage capacity in hybrids was not estimated for years prior to 2020.

Source: Bolinger et al. (2021); Lawrence Berkeley National Laboratory.

Hybrids as a Key Enabler for Flexibility

Wind, solar, and battery energy storage systems are all inverter-based resources and thus use a common technology to interface with the grid. This commonality of system components, along with the modularity of these systems, can make hybrid configurations particularly economic and reduce engineering challenges. The power electronics in the inverter allow for a common control system that can coordinate the output and utilization of the distinct components. In many respects, a hybrid resource is as much of a software and controls amalgamation as it is a combination of physical resources. By combining renewable energy, storage, controls, and/or flexible loads, a hybrid plant could in theory be designed to emulate traditional generation, if necessary, and can provide significant flexibility and a wide spectrum of grid services to an increasingly high-renewables grid. Figure 2 (p. 2) gives an overview of existing hybrid projects in the United States as of 2020.

FIGURE 2
The Capacity, Storage Ratio, and Duration of Hybrid Resources in the United States as of 2020



A breakdown of proposed hybrid projects by technology and resource type, including the total number of projects and a breakdown of storage duration and ratio between storage and generation capacity.

Note: Not included in the figure are the hybrid configurations with smaller number of projects, including but not limited to wind+fossil, PV+fossil, wind+fossil+storage, and wind+PV+fossil+storage.

Source: Bolinger et al. (2021); Lawrence Berkeley National Laboratory.

Re-evaluation of Market Rules and Interconnection Requirements

The growth of hybrids is requiring independent system operators (ISOs) and regional transmission organizations (RTOs) across the United States to re-evaluate market rules and interconnection requirements regarding what constitutes a generator. Each ISO/RTO has a unique definition, and because hybrids are still in their infancy, terminology and definitions are fluid. At its most basic level, a hybrid energy system is a combination of two or more resources at a single location, or, as defined by the North American Electric Reliability Corporation (NERC), "a generating resource that is comprised of multiple generation or energy storage technologies controlled as a single entity and operated as a single resource behind a single point of interconnection" (NERC, 2021). As with any nascent technology, there are multiple definitions and potentially confusing terminology. In this case, the term hybrid resource is sometimes used interchangeably with co-located resource, virtual power plant, and power plant aggregation. One distinction among these various concepts is nicely summarized by the Federal Energy Regulatory Commission (FERC):

> The terms hybrid resource, co-located resource, and mixed technology resources, among others, are all commonly used by industry to refer to resources that share a point of interconnection and incorporate at least two different resource types. . . . These resources are often broken into two general categories: (1) co-located hybrid resources, generally referring to sets of resources that are modeled and dispatched as two (or more) separate resources that share a single point of interconnection; and (2) integrated hybrid resources (also referred to as co-controlled or integrated control hybrid resources), generally referring to sets of resources that share a single point of interconnection, and are

For the purposes of this report, the term hybrid resources refers to FERC's "integrated hybrid resources," in which the hybrid plant shares a common point of interconnection and is controlled as a single resource by the system operator.

modeled and dispatched as a single integrated resource (FERC, 2021).

For the purposes of this report, the term hybrid resources refers to FERC's "integrated hybrid resources" above, in which the hybrid plant shares a common point of interconnection and is controlled as a single resource by the system operator. While the definitions of hybrid resources are often (intentionally) vague, there is some consensus that a hybrid includes the following five elements:

- Consists of more than one resource, which may include different types of generation (wind, solar, fossil, etc.) and/or controllable end-use loads
- Includes some amount of energy storage
- Is located behind a single point of interconnection
- Is operated and coordinated to appear as a single resource to the system operator
- Incorporates controls that coordinate the output across multiple resources to maximize value to the system and/or plant owner

These definitions, however, should not be understood overly narrowly, or as static. For nascent technologies it can be beneficial to keep definitions intentionally imprecise, to ensure that market constructs and interconnection rules remain malleable for future changes. For example, if a hybrid resource were narrowly defined as a generation technology and battery energy storage, the definition could quickly become obsolete if new types of storage become commercially viable or when flexible loads are integrated in the future. In some cases, rules that narrowly define a hybrid based on certain technologies or market constructs could limit flexibility in the services that hybrids provide. Requirements for hybrid resources should be defined in a technology-neutral manner and not be overly prescriptive about how grid needs are met, in order to afford flexibility and creativity in the design and implementation of new technologies in the future high-renewables grid.

Why the Trend Toward Hybridization?

As the renewable power industry accelerates, utilities, grid operators, plant owners, and developers continue to seek new functionality from wind and solar technologies. This is driven in part by system reliability needs, as grid services formerly provided by thermal generation—like inertia, fast frequency response, operating reserves (regulation and spinning reserves), and capacity—must be replaced. Hybrid systems can provide grid services that solar or wind alone often cannot economically provide. Hybrids can also help to reduce the need for transmission upgrades.

For their part, project developers and owners of hybrid resources continually look for ways to make projects

Hybrid systems can provide grid services that solar or wind alone often cannot economically provide. Hybrids can also help to reduce the need for transmission upgrades.

more economical. By combining multiple technologies, these market participants can access additional revenue streams, including from ancillary service and capacity markets or from federal and state tax incentives. In addition, hybrid technologies afford an opportunity to reduce interconnection costs by helping to minimize the need for transmission upgrades near the project's point of interconnection. And these technologies can often share components such as inverters, transformers, switchgear, and other transmission infrastructure, further reducing costs.

In the near future, it is likely that many, and potentially most, new renewable projects could be built with some level of hybridization. Key drivers for hybridization are listed in Table 1.

Under current federal tax policy in the United States, storage systems charged predominantly from solar energy are eligible for investment tax credits, constituting an important driver for hybrid resource value. However, this factor is unlikely to persist, because it will likely diminish in importance as either the solar investment

TABLE 1

Key Drivers for Resource Hybridization

Rank	Key Driver	Description
1	Tax incentives (investment tax credit)	If storage resources are charged predominantly from on-site renewable resources, they are eligible to receive the U.S. federal investment tax credit.
2	Avoided transmission and distribution upgrades	A shared point of interconnection for multiple resource types can minimize the need for interconnection upgrades while maximizing available energy and grid services that can be provided at the point of interconnection.
3	Avoided curtailment	The curtailment of wind or solar resources can be reduced through combination with battery storage or on-site load flexibility. Wind or solar energy generated during periods of surplus renewable energy can be used to charge batteries, and energy provision shifted to periods of system need.
4	Reduced development costs	Shared costs for engineering, land, interconnection, and equipment for multiple resources can reduce overall costs.
5	Reduced financing costs	Combining multiple resources can reduce long-term risk and thus lower the cost of debt financing.
6	Captured DC clipping losses	Clipping losses—which occur when solar plants are designed with a high inverter loading ratio to increase production but lead to some curtailment—can be captured if battery storage is DC-coupled to the solar resource.
7	Market design rules that limit the participation of solar or wind alone	Stand-alone wind and solar resources may not qualify for certain market products, but could with the addition of storage.
8	Simplified procurement for utility off-takers	A single power purchase agreement of bundled energy, storage, and grid services may simplify the procurement process for utility buyers.
9	Hybrids' flexibility	The addition of battery storage to generation resources serves as a hedge against future market conditions and volatility, as alternative control schemes and storage can change operations based on system conditions.
10	Land constraints	Combining multiple resources at a single location can reduce the land needed for renewable projects.

This ranking of key drivers for resource hybridization was generated by the members of the Energy Systems Integration Group's Hybrid Resources Task Force.

Source: Energy Systems Integration Group.

tax credits expire or a stand-alone storage tax credit is enacted. At that point the other key drivers will increase in importance, a trend that will likely accelerate as the power system continues to decarbonize.

Additional Flexibility with Evolving Hybrid Configurations

As the importance of the key drivers shifts, so too will hybrid configurations. An advantage of hybrid systems is the flexibility in their design, which can be tailored to fit specific site conditions, grid needs, interconnection rules, and market conditions. Developers and plant owners have the unprecedented ability to optimize their systems to maximize financial returns or minimize system costs.

Today, the most common hybrid is a combination of solar photovoltaics (PV) and battery energy storage, or solar + storage. This pairing is currently the most common for a few reasons. The first is that the battery storage can claim the investment tax credit if charging originates from the solar resource. Batteries associated with wind plants, which claim the production tax credit instead, cannot claim this benefit. In addition, the consistent diurnal pattern of day and night affords a unique opportunity for storage to charge and discharge on the same daily cycle. In contrast, wind resources' periods of high or low generation are typically more sustained.

In the solar + storage configuration, solar PV is the source of energy, which can either be delivered directly to the

Ultimately, market design and regulatory requirements should allow for hybridization across many new types of resources and technologies, as this will allow engineers, developers, and asset owners to creatively design systems that meet the physical and financial needs of the system in a reliable and cost-effective manner.

grid or be used to charge an on-site battery energy storage system for use at a later time, when it can feed energy onto the grid or provide grid services. This hybrid can be either DC-coupled or AC-coupled. In a DC-coupled system, the solar and storage connect to the grid using a shared inverter, and the maximum output of the system is typically based on the shared inverter rating. In an AC-coupled system, the solar and storage have separate inverters, and the maximum output of the system is typically based on the point of interconnection grid limit (Figure 3). Thus, an integrated hybrid resource is differentiated from a simple co-located resource in that the output is coordinated across the plant.

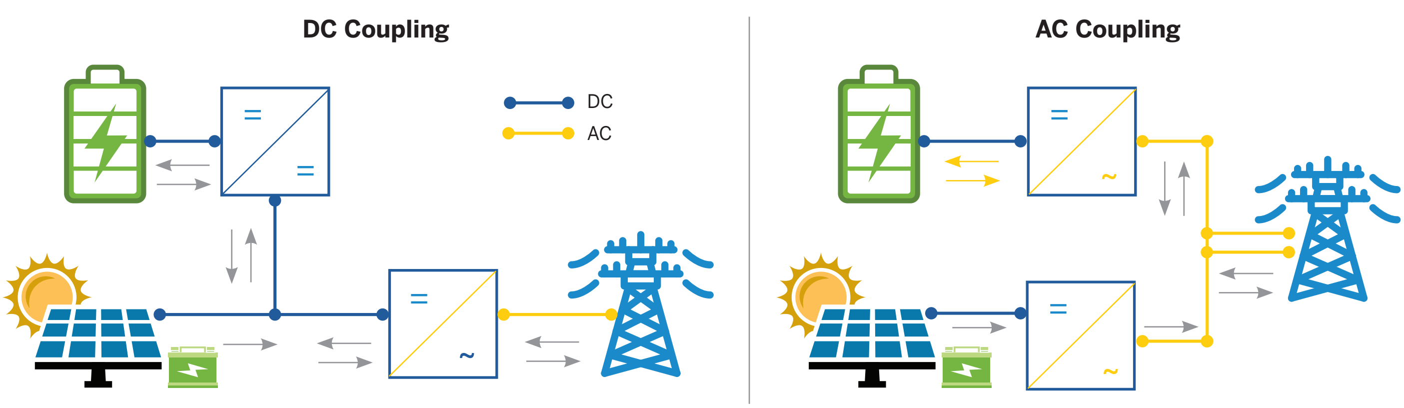
While the above solar + storage configurations are the most common type of hybrid being implemented today, this could change in the future. Ultimately, market design and regulatory requirements should allow for hybridization across many new types of resources and technologies, as this will allow engineers, developers, and asset owners to creatively design systems that meet the physical and financial needs of the system in a reliable and cost-effective manner. This approach, however, will require unique market participation models that allow asset owners some degree of flexibility in state-of-charge management and internal operations. Future hybrid systems may aggregate future types of generation, multiple different types of energy storage, and controllable loads, as well as implement other innovative concepts. By combining these resources behind a single point of interconnection, as highlighted in Figure 4, and coordinating output via common controls, the hybrid system can be offered into the market (or system operator) in a flexible manner that simultaneously meets both the system and individual asset owner's needs (Ahlstrom, 2021).

Guiding Principles for System Operators and Policymakers

Because hybrid resources are still in their infancy, it is important that system operators, policymakers, and regulators take care in how they define market rules and requirements that govern hybrids' use. The following guiding principles should be considered when implementing market policies, interconnection requirements, and incentive mechanisms for hybrid resources:

Because hybrid resources are still in their infancy, it is important that system operators, policymakers, and regulators take care in how they define market rules and requirements that govern hybrids' use.

FIGURE 3
Schematic of DC Coupling Versus AC Coupling of Solar+Storage Hybrids

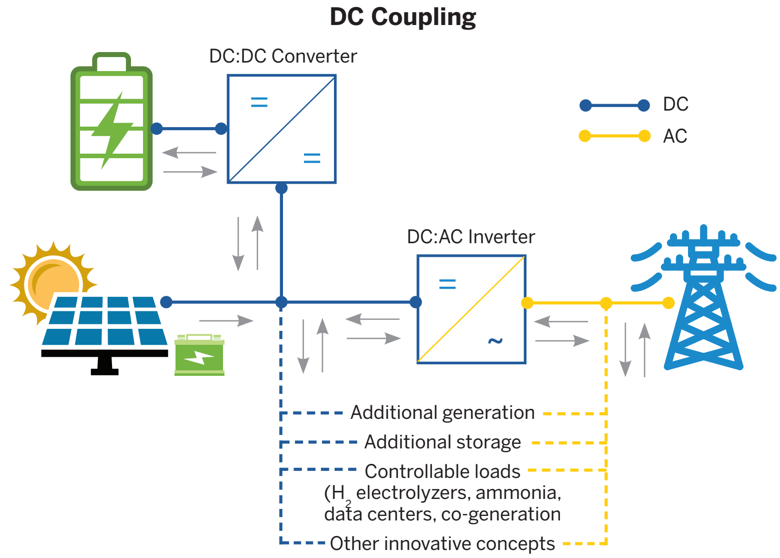


Alternative coupling of solar + storage technologies, with DC coupling (left) sharing the same DC:AC inverter and single point of interconnection with the grid, and AC coupling (right) having distinct DC:AC inverters.

Source: Telos Energy.

FIGURE 4

Schematic of Potential Future Hybrid Resources



Potential future hybrids will combine multiple types of generation, storage, load flexibility, and new opportunities for resource diversity.

Source: Energy Systems Integration Group.

- Become less prescriptive and more technology-agnostic with definitions
- Leverage existing points of interconnection for additional resources
- Create multiple participation model options to facilitate greater flexibility and innovation, while allowing resources to provide all services they are technically capable of
- Develop broad participation models in advance for technologies that have not yet been tested
- Give the asset owner the option to manage internal operation of the hybrid facility when they choose to do so, as long as they aim to meet performance targets defined by the system operator
- Consider synergistic effects and diversity benefits of combining complementary resources
- Reconsider traditional requirements that close doors for future flexibility and services in a transforming grid

In the sections that follow, the report adds to these general recommendations by providing more specific guidance on the transmission interconnection of hybrids, the market rules and operations for hybrids, and the contributions of hybrids to resource adequacy. All three considerations are essential for the continued deployment of hybrid resources and their important contributions to a reliable, decarbonized power system. The final section of the report offers guiding principles for hybrid integration, market design, and interconnection rules.

Transmission Interconnection of Hybrids

Hybrid resources can offer a way for resource owners and developers to significantly reduce transmission interconnection costs. In some cases, however, interconnection study assumptions and rules have not kept up with the opportunity provided by these resources.

Institutional and Tariff Rules

As noted above, a primary benefit of hybrids is that they can reduce the transmission network upgrades that are required to interconnect new generating resources to the grid. In most areas with high-quality renewable resources, low-cost and easy points of interconnection have already been utilized. Renewable projects must therefore pay for expensive network upgrades to the bulk power system when interconnection studies indicate they will overload existing equipment or cause instability on the transmission system. This cost is most often paid by the developer of the renewable project, rather than the system operator or load-serving entity. As a result, transmission interconnection for renewable generators is a significant barrier for further development (Caspary et al., 2021).

The design and operation of a hybrid resource can reduce these costs by providing a destination for excess energy and keeping the instantaneous injection of power by the resource below the threshold that would trigger expensive network upgrades. Wind + solar hybrids can also reduce the need for upgrades, because wind and solar output tend to have a complementary relationship on both a daily and seasonal basis. As shown in the hypothetical example of a wind + solar + battery hybrid in Figure 5 (p. 9), battery storage can absorb wind and solar output above that threshold and release it once renewable output is lower.

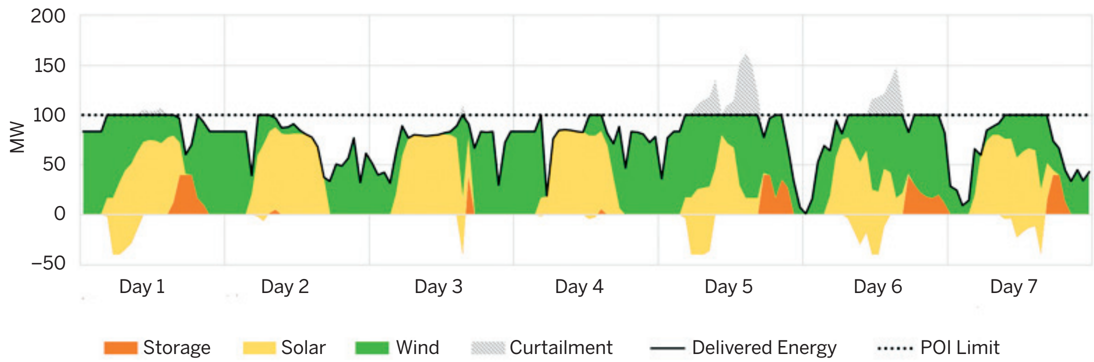
A primary benefit of hybrids is that they can reduce the transmission network upgrades that are required to interconnect new generating resources to the grid.

The assumptions used in generator interconnection studies have a major impact on the costs assigned to renewable projects, and thus the value battery storage can provide. Because of the computational intensity of the power flow and stability studies used in interconnection studies, such studies typically only evaluate a few snapshots in time, such as system peak demand or light load conditions. However, to accurately value battery storage, a more holistic approach to transmission planning is needed. This approach should study transmission upgrade needs across more periods of the year, given that renewable projects shift both the timing of transmission congestion and the timing of peak net load. Continual increases in computational power will eventually make these studies possible.

In the interim, assumptions used for reliability assessments in interconnection studies can evolve to better reflect the likely dispatch of resources and the ways in which renewable resources are changing transmission system needs. These studies typically make assumptions about the dispatch of the resource being studied as well as all other resources on the power system—assumptions that in some cases may be unrealistic. For example, unlike relatively inflexible thermal generators that may be unable to cycle on or off quickly or may be ramp-rate limited, power provided by battery storage is highly flexible; in addition, battery storage, when charging,

FIGURE 5

Hypothetical Example of a Battery Hybrid Shifting Excess Renewable Output to Avoid Transmission Limits



Wind + Solar + BESS Hybrid

100 MW wind

+ 100 MW_{dc} PV

+ 40 MW 4-hour storage

240 MW of resources

100 MW POI

	Capacity Factor of Wind	Capacity Factor of Solar	Capacity Factor of the Hybrid Resource	Curtailment of the Hybrid Resource
New York	32%	23%	48%	1.5%
Texas	40%	34%	63%	1.2%
California	37%	38%	61%	2.6%

A week-long example of chronological generation and storage charge/discharge behind a single 100 MW injection limit, with total plant capacity factors provided across three representative regions.

Note: POI = point of interconnection.

Source: Energy Systems Integration Group. Data from the National Renewable Energy Laboratory's National Solar Radiation Database and WindToolkit.

is able to help co-located resources avoid exceeding transmission limits. In most cases, the dispatch of storage based on locational marginal prices will ensure that storage is not exacerbating transmission congestion. Storage is unlikely to charge on peak load or discharge during very light load conditions; in most cases it should be fully discharging on peak load and fully charging during light load (subject to state-of-charge limits). An example of dispatch assumptions for battery storage in the California Independent System Operator (CAISO) is provided in Table 2 (p. 10), though CAISO does not require batteries that follow market dispatch instructions to pay for network upgrades needed to accommodate charging.

These issues around assumed dispatch conditions also point to more fundamental questions regarding who—the transmission system operator or the generation owner—should decide how to optimize between larger network upgrade costs, on the one hand, and the cost of curtailment and a resource's inability to deliver capacity or energy during some time periods, on the other. A generation developer is typically better positioned to optimize economic trade-offs between the level of investment in high-capital-cost network upgrades versus reduced revenues attributed to curtailment. However, there is also a role for the grid operator in ensuring that during times of peak need, resources can deliver at least the amount of generation for which they are receiving capacity credit. Giving project developers more agency in making economic determinations about the value of network upgrades will likely result in a more accurate valuation of how hybrid resources can reduce the need for grid upgrades while still ensuring the project can realize economic value from being able to deliver energy and capacity.

In recent years, FERC has been actively engaged in generator interconnection issues, with the issuance of Order 845, "Reform of Generator Interconnection Procedures and Agreements," in 2018 and an advance

TABLE 2

CAISO Reliability Assessment Dispatch Assumptions

Condition	Peak	Peak Charging	Shoulder Peak Charging	Off-Peak Daytime	Off-Peak Night-time Charging
Load level[a]	1-in-10 years	1-in-10 years	75% of peak	50%~65% of peak	40% of peak
Solar generation	Pmax	Pmax	0	85% of Pmax	0
Wind generation	Pmax	50–65% of Pmax	50% of Pmax	Pmax	Pmax
Energy storage dispatch	Max discharging[b]	Max charging[c]	Max charging	Max discharging	Max charging
Other renewable	Pmax	Pmax	Pmax	Pmax	Pmax
Thermal generation	Pmax	As needed to balance load	As needed to balance load	As needed to balance load	As needed to balance load
Hydro generation	Based on historical data	Based on historical data	Based on historical data	Based on historical data	Based on historical data
Import levels	Historical max flows adjusted to accommodate output from renewable generation as needed				

CAISO representative dispatch conditions by resource type are given across five representative conditions used in interconnection studies.

a Forecasted demand levels for peak conditions are in likelihoods (1-in-10 is a 1-in-10-year likelihood) and are based on historical data for off-peak conditions that are then scaled to selected study years.

b Maximum steady-state with the maximum net output in the interconnection request

c Maximum steady-state negative output for re-charging of the energy storage facility

Source: North American Electric Reliability Corporation (2021). Data from the California Independent System Operator.

notice of proposed rulemaking in 2021. FERC Order 845 does not directly address hybrid resources, which is not surprising because it grew out of a 2015 petition and 2016 technical conference that preceded the surge in interest in hybrid resources. However, many of the order's provisions directly affect hybrid resources. The primary reforms in Order 845 allow an interconnection customer to:

- Request a level of interconnection service that is lower than the generating capability of the facility
- Use surplus interconnection service at existing points of interconnection
- Change technology during the interconnection study process without affecting its queue position

The ability to request a level of interconnection service that is less than the facility capability is directly beneficial to hybrid resources. As discussed above, the nameplate capacity of the components of hybrid resources often greatly exceeds the interconnection capacity with minimal curtailment. The provision for the use of surplus interconnection service, which allows for an expedited process outside of the queue to interconnect new facilities at existing generators that have surplus capacity, is also highly beneficial for hybrid resources.

Regarding changes made to the technology during the interconnection study process, there has been considerable debate over what constitutes a "material modification" to a proposed plant that requires an interconnection customer to submit a new interconnection application. For example, should projects in the queue be permitted to adjust submissions to incorporate additional resources behind the point of interconnection? Should existing facilities be able to add resources behind a point of interconnection without entering the interconnection queue? As noted above, because storage can be highly flexible in response to locational marginal price signals or direct utility dispatch signals, storage is unlikely to exacerbate, and should reduce, the transmission congestion and overloads that are a primary focus of interconnection studies.

RTOs have now submitted filings detailing their compliance with FERC Order 845. While there is a great deal of regional variation, in general most RTOs seem to have done what is necessary to comply with the letter of the law, although in most cases they did not go beyond Order 845's requirements and further facilitate the development of hybrid resources. Given the large potential for hybrid resources to reduce interconnection challenges, and the unlikelihood that adding storage to a planned or operating resource would exacerbate transmission congestion, future RTO or FERC action could further unlock opportunities for hybrid resources.

The hybrid resource controller(s) should be designed to achieve a single, coordinated response of the entire plant to disturbances on the grid, where all of the component resources of the hybrid plant are pulling in the same direction, thereby maximizing the grid-supporting capabilities from the collective resources.

Physics and Controls Considerations

Although hybrid resources are similar to many individual inverter-based resources, hybrids require additional coordination and modeling of their component resources and plant-level controls to ensure stable operation, and to maximize the net grid-supporting capabilities they can provide to the system.

Addressing Adverse Interactions Between Resources

Two or more resources that are interconnected to the grid at the same point of interconnection, whether it is a coordinated hybrid resource or two separate resources, typically have a large degree of electrical coupling between them. The underlying physics—rather than contracts or control schemes—determine how the behavior of one resource will impact the other. This coupling, or interaction, can exist between different types of resources, whether they are inverter-based or synchronous machines, and between different sizes of resources. With any coupling between more than one resource, there is the potential for adverse interactions. Among the most common forms of adverse interaction is reactive power "fighting" in which one resource supplies reactive power while another resource consumes it, in their individual attempts to control voltage on the grid. This is akin to simultaneously running a heater and an air conditioner in a room to achieve a moderate temperature. The counteractive reactive power provision is inefficient and leaves the resources poorly positioned to respond to a grid disturbance if one were to occur.

The potential for a resource to interact with others nearby has long been known, and the industry has developed various means of mitigating these interactions. In the case of hybrid resources, where the close electrical interconnection of resources is by design and the potential for interaction known, the approach to coordinating the resources to avoid adverse interactions should be established early in the plant design. Several approaches can be used, most of which involve special configuration and tuning of the plant controller or controllers. Mitigating this challenge is a shared responsibility among the ISO, the asset owner, and the equipment manufacturer.

The hybrid resource controller(s) should be designed to achieve a single, coordinated response of the entire plant to disturbances on the grid, where all of the component resources of the hybrid plant are pulling in the same direction, thereby maximizing the grid-supporting capabilities from the collective resources. Hybrid resource designs can utilize a single controller for the entire plant (often described as a hybrid plant controller), where all commands to the resources are issued from a single controller. The advantage of this approach is that the performance of the entire plant tends to be very good. However, this approach can be challenging when trying to interface equipment (such as inverters and plant controllers) from different manufacturers. Alternatively, multiple plant controllers can be used, for instance, one for a PV system and another for a battery system. With this "two brain" approach, the two plant controllers have to be coordinated, which can be done with passive approaches like voltage droop or with active schemes in which data are passed between the controllers in real time. While there can be some added complexity in coordinating multiple plant controllers, this approach can avoid challenges in interfacing equipment from different manufacturers.

Adjustments to Dynamic Grid Simulations

All utility-scale hybrid resources are required to be modeled for dynamic grid simulations that are performed by the system operators as part of system-wide, regional, and/or interconnection studies (NERC, 2021). Nearly all of the expectations of inverter-based resources with regard to interconnection requirements also apply to hybrid resources that are fully or partially inverter-based. In addition, in some instances the expectations of hybrid resources exceed those of non-hybrid resources because of hybrids' enhanced capability for absorbing active power from the grid, thus enhancing grid stability. This modeling includes frequency response characteristics (which should also be simulated during charging when active power is being absorbed), appropriate representation of battery energy and power limits, and the inclusion of reactive power capability from battery systems, to name a few. While the commonly used tools for dynamic grid simulations, positive-sequence modeling tools (PSSE, PSLF), have generic models suitable for many hybrid plant configurations, special care and attention is needed as these generic models have a limited ability to represent complex or unusual hybrid configurations. Additional consideration is also needed when setting the initial operating conditions of the model, as a hybrid plant uses a combination of resources and thus can achieve a given active power output level in many ways. These initial conditions, which are typically set independently of the dynamic model data in the power flow case, must be set with care to ensure that limits are respected and that the model reflects the intended operating condition. NERC's recently published *Reliability Guideline: Performance, Modeling, and Simulations of BPS-Connected Battery Energy Storage Systems and Hybrid Power Plants*, covers the key differences and best practices for dynamic grid simulations (NERC, 2021).

Addressing Potential Interactions Under Weak Grid Conditions

Certain grid interconnections that pose a challenge for any inverter-based resource are also likely to challenge interconnection of a hybrid resource. One is a weak grid, a region or interconnection point that is not supported by many conventional power plants and/or has a high concentration of inverter-based resources. Interconnecting to weak grids presents a special stability challenge that can be exacerbated by the hybrid plant if careful coordination does not take place. Weak grids are challenging to most inverter-based resources because the grid voltage responds more dramatically to changes in the power injected by an inverter-based resource, and an overly dramatic response in grid voltage can cause the inverter-based resource to become unstable and trip offline. In a weak grid condition, there tends to be higher coupling between resources, because the electrical behavior of one resource impacts the other resource relatively more in a weak grid condition than in a strong one.

This increased potential for interaction should be evaluated early in the design stages of a hybrid resource so that appropriate mitigation—typically in the form of controls tuning—can be accomplished, which is often an iterative process. It is possible that hybrid resources that include a grid-forming resource, such as a grid-forming battery system, may offer advantages to system stability and plant stability, even if the resource with which the first is paired does not have grid-forming capability. The extent to which this is true and the means for quantifying the stability benefit are the subject of ongoing research.

Recommendations for System Operators on Interconnection

Given the transmission interconnection and controls considerations of hybrid resources, system operators should update interconnection study assumptions to account for how the evolving resource mix is shifting the timing of peak net load and transmission congestion, and increasing the value of adding storage resources to reduce transmission congestion.

Market Rules and Operations

Since hybrid resources are an emerging technology, the rules and operational designs for how they supply power, energy, and various grid services, as well as participate in wholesale electricity markets, are also emerging. Some market regions in the United States, such as CAISO, the New York Independent System Operator (NYISO), and the Midcontinent Independent System Operator (MISO), have developed market participation models that can allow these resources to participate in the markets and provide services while accounting for their unique capabilities and characteristics. In this section, we explore these and other designs that have been proposed or implemented and evaluate what actions may be helpful for encouraging efficient and reliable market participation by hybrid resources in the future.

Participation Models

The U.S. electric industry has used the term "participation model" since at least the 2016 FERC Notice of Proposed Rulemaking on Electric Storage Participation in Markets Operated by RTOs and ISOs.[1] There, FERC defined participation models as "a set of tariff provisions that accommodate the participation of resources with particular physical and operational characteristics in the organized wholesale electric markets of the RTOs and ISOs" (FERC, 2020). In FERC Order 841, FERC further defined participation models as the tariff revisions that consist of market rules that, recognizing the physical and operational characteristics of the resource, facilitate its participation in the electricity markets. While not stated by FERC, ISOs, RTOs, and others in the industry generally consider the software representation of technologies within the ISO market clearing software to also be an important consideration for participation models. Essentially, it is the model that includes eligibility of participation, the way in which a particular resource interfaces with the ISO, what data are shared back and forth, and how the resource is represented within its market clearing software.

Types of Participation Models

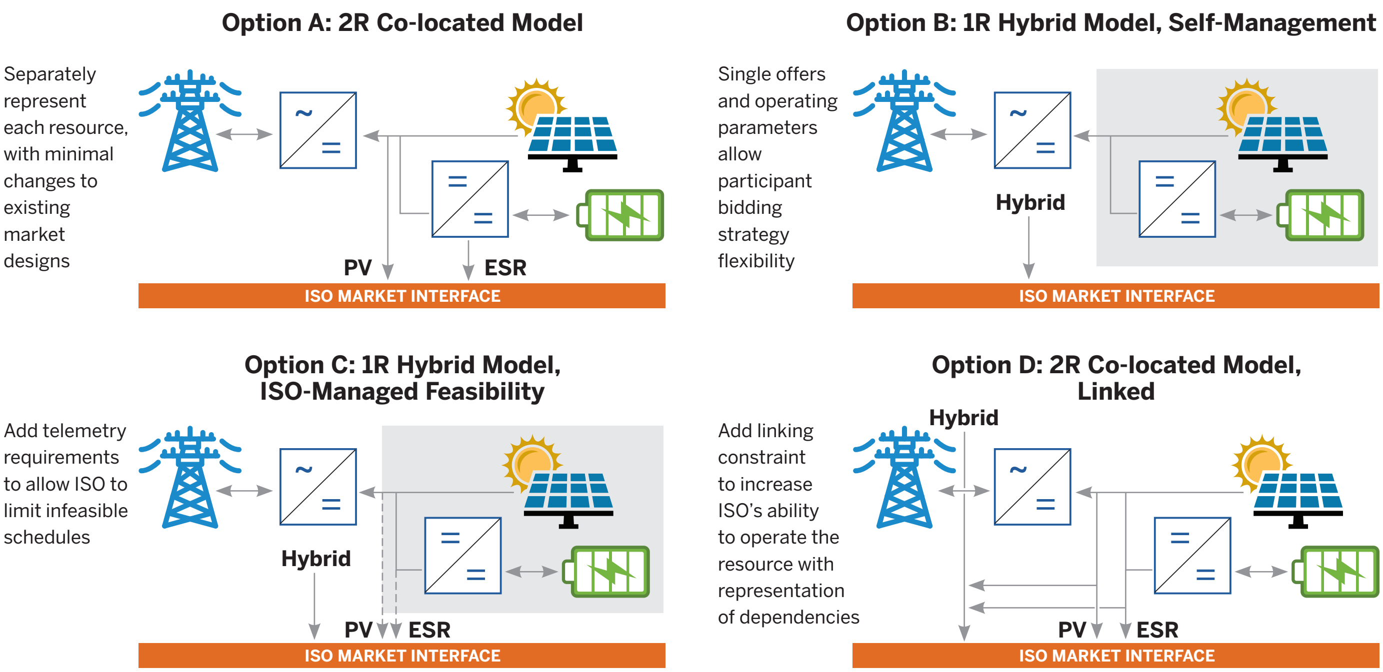
Participation models exist for a multitude of technologies. Generic thermal generators, variable renewable resources, demand response resources, electric storage resources, and combined-cycle resources all have somewhat distinct participation models. FERC Order 841 provided the guidance for the ISOs and RTOs to establish participation models for electric storage resources, including parameters that were necessary to exchange with bids, eligibility, rules around payments and sales, size requirements, metering practices, and state-of-charge management. FERC Order 2222 established similar guidelines for aggregations of distributed energy resources. Neither order established rules for large-scale hybrid facilities consisting of two or more technologies.

For plants with multiple resources, the key question becomes whether the participation model would consist of the resource interfacing with the market as a single resource or as two or more separate resources.

1 See https://www.ferc.gov/sites/default/files/2020-06/RM16-23-000_AD16-20-000.pdf.

FIGURE 6

Possible Participation Models for Hybrid Resources



A comparison of different potential participation models available to hybrid resources, where 2R refers to two resources and 1R refers to a single resource interface with the grid operator.

Source: Electric Power Research Institute (2019).

For plants with multiple resources, the key question becomes whether the participation model would consist of the resource interfacing with the market as a single resource (referred to as a 1R or hybrid model) or as two or more separate resources (the 2R, or co-located model). Figure 6 provides a few examples of participation models being proposed and/or considered at the various ISOs and RTOs (EPRI, 2019). Option A is the straight co-located model, where each individual technology is treated separately, with the only connection being an injection limit at the point of interconnection (e.g., CAISO calls this the aggregate capability constraint). Option B is the hybrid model, where the information being exchanged with the ISO is about the hybrid and not any of its individual components. Option C is a variation of option B, where the resource is treated as a single, integrated hybrid, but information such as variable renewable energy forecasts or telemetered state of charge of the storage resource is being monitored by the ISO and used only during emergencies. Option D is the linked co-located model where the two resources are treated as distinct generating resources, with additional constraint(s) for the system operator to optimize around. In this example, any linking constraint that reflects how the combined facility would operate differently than each individual component is represented in the market clearing. This is similar to some of the advanced combined-cycle modeling constraints that model each unit of the plant individually (single-train, dual-train, duct-firing operations, etc.), but also represent how costs and parameters of the units are a function of the plant configuration. An example of a linking constraint could be a grid-charging limitation for resources taking advantage of the investment tax credit.

Advantages and Disadvantages of the Participation Models

Each participation model comes with advantages and disadvantages to the asset owner, the ISO (in terms of reliability and economic efficiency), and the consumer. Advantages and disadvantages may pertain to societal costs, system reliability, emissions and other environmental

FIGURE 7

Challenges Impacted by Choice of Participation Model

Eight challenges that should be considered when developing new market participation models.

Source: Gorman et al. (2020).

Each participation model comes with advantages and disadvantages to the asset owner, the ISO, and the consumer.

attributes, profitability of the asset owners, simplicity, and feasibility, and may depend on the strategy or the perspective of the asset owner in any of the different participation models.

Figure 7 shows a few of the associated challenges that need to be considered depending on the participation model chosen (Gorman et al., 2020). Forecasting is an important tool in system operations as part of a way to ensure system reliability. For different participation models, operators should understand what each forecast represents so they have the most accurate information to maintain reliability. Market mitigation and physical withholding rules are another cornerstone of electricity market design, where market operators use verifiable resource costs and rules to prevent resource market power from causing high prices not reflective of system costs, either due to excessive offers or physical withholding (i.e., not supplying so that prices rise). Different participation models may require different mitigation techniques, and they must be evaluated to ensure that market power does not go unmitigated. Scheduling software and complexity of the software is another key aspect to be aware of, as different participation models may lead to different levels or types of complexity and, in some cases, difficulties in solving market clearing within market clearing windows.

Other important factors are capacity accreditation (discussed in the next section), must-offer rules, and offer parameters and the degree of flexibility in how those parameters can be used for a strategy. Interconnection challenges, discussed in the previous section, and resource planning challenges will need to be addressed in order to understand the economic justification of building new resources and how they may be operated when interconnected. Finally, the metering and telemetry requirements will differ based on the choice of participation model, and these data must also be accounted for differently in ISO systems. Each of these challenges must be accounted for in the development phase of the hybrid resource and in the operational phase by the ISO and the hybrid asset owner or market participant.

Table 3 shows the potential pros and cons of the different participation models illustrated in Figure 7. It is important to note that these pros and cons may differ based on one's perspective, and modifications to the details that define each participation model may alleviate the disadvantages when effectively implemented. Advantages across all of the models include the flexibility to utilize effective strategies for the resource, ability to ensure reliability and theoretical economic efficiency, costs and time associated with market rule and software changes, and impact on computational capabilities.

For many of these participation models there are significant costs associated with battery and hybrid resources that are not easily incorporated into existing participation models. This relates to degradation costs—impacts from the way the battery technology is operated that can affect its wear-and-tear and ultimately its lifespan. These costs are highly nonlinear and cannot easily be added to an energy offer based on MWh. While CAISO attempted a model that incorporated these costs, it found it difficult to implement. Other ways of incorporating these costs have been proposed (Xu, 2018), but not, to our knowledge, implemented. Incorporating these costs into offer strategies, either directly or indirectly through flexible offers, would increase efficiency and thus benefit both the storage and hybrid asset owners as well as system operators and consumers.

Variables in ISOs' Development of Participation Models

ISOs and their stakeholders must first determine which participation model options they should pursue. Different models require different software changes and tariff changes that can require considerable time and money to implement. In ISOs' annual prioritization processes, new designs must make the cut—through internal and

TABLE 3

Pros and Cons of Different Participation Models

	Pros	Cons
1R Hybrid self-managed model	• Asset owner has full flexibility to offer in full facility operation including impacts not included in market clearing model • Avoids computational issues with simpler market clearing software model	• Can reduce system reliability when infeasible schedules are produced • May not lead to theoretical economically efficient solution because state-of-charge management is not performed by the ISO • Subject to challenges associated with understanding verifiable cost rules, mitigation, and other market design features
1R Hybrid ISO-managed feasibility model	• Same as for the 1R hybrid self-managed model • Improves reliability by ensuring that infeasible schedules are not produced	• Same as for the 1R hybrid self-managed model except that it is not subject to impacted reliability from infeasible schedules
2R Co-located model	• Models mostly already exist; therefore, few rule and software updates needed • ISO has information to ensure reliability and feasible schedules • Is an economically efficient solution if the ISO manages feasible state of charge and uses solar and wind forecasts	• Less flexibility regarding offering strategies • May not be able to account for degradation costs • May impact the project's ability to meet requirements for the U.S. investment tax credit, as storage may sometimes be charged from the grid • Has software and computational limitations
2R Co-located linked model	• Same as for the 2R co-located model • Allows for projects to meet requirements for U.S. investment tax credit	• Same as for the 2R co-located model except that its ability to meet requirements for U.S. investment tax credit is not impacted

Note: These advantages and disadvantages may differ based on one's perspective.

Source: Energy Systems Integration Group.

stakeholder processes—in order for an ISO to contribute staff and resources to the implementation. Alternatively, if FERC decides that new models are necessary for fair and just treatment and establishes a directive, then the features of that market design option are automatically prioritized. If more than one participation model is introduced by an ISO, the hybrid resource asset owner (or the designated scheduling entity on their behalf) must determine which model best suits their offering strategy—or they may wish to use one model during some periods and another during others. Recent surveys have shown diverse perspectives on whether the co-located or hybrid model is preferred (GPI, 2021). As long as the participation models generally do not adversely impact power system reliability, and are feasible to solve within existing market timelines, then allowing resources to select from multiple participation models can be beneficial, as the resource owners learn which will lead to efficient operation of their facilities and the ISOs learn which will lead to efficient operation of the system.

While the participation options may continue to evolve, there are a few enhancements that have been suggested across all of the models. One is the ability to adjust offers closer to real time. Most ISOs require offers to be submitted at least 30 minutes (in some cases, up to 75 minutes) prior to an hour and for those offers to remain constant for that entire hour. This impacts hybrid resources since, when information becomes available closer to real time, the offers originally provided may no longer be practical or additional capabilities could be available that may go unused. The suggested enhancement, if feasible, could benefit hybrid resources as well as other generation types. Some issues regarding market power mitigation checks may need to be resolved for resources to be able to update bids as frequently as before every 5-minute dispatch period.

In regions outside of organized electricity markets, hybrid resources are typically operated to minimize operating costs of the system. In these regions, the utility controls the hybrid to provide energy during the times of the day when it is most beneficial to reduce system costs. Various agreements may also dictate that the resource provide energy during certain time periods. In Hawaii, a unique power purchase agreement structure was developed and applied to hybrid solar + storage resources. Project owners sell the energy production from the facility, along with the rights of battery scheduling and dispatch, to the utility. In return, the utility pays a fixed monthly payment for the energy and capacity of the plant. This is different from most variable renewable plants, which are paid solely for energy production. For solar + storage in Hawaii, resource availability and minimum output requirements are stipulated in the contract and enforced with penalties.

U.S. ISO/RTOs' Development of Participation Models

The ISOs and RTOs in the United States are on different timelines in their development of participation models and other market rules for hybrid resources. CAISO has developed both a co-located and hybrid model, with the majority of its mixed-fuel resources currently using the co-located model. The co-located model requires two bids from each resource, and the ISO will establish two dispatch schedules for each, whereas the hybrid model requires one bid and the ISO will create one dispatch schedule. Outages and metering arrangements are separated for co-located resources. Both models require meteorology data for the variable renewable resource component. Currently, co-located resources are only eligible to provide energy and not ancillary services due to implementation difficulties with the aggregate capability constraint (the constraint that reflects how much power can be injected by the combined facility), although this limitation on eligibility is likely to be lifted soon. Co-located energy storage resources can deviate from dispatch to compensate for positive forecast error from the variable renewable energy component to meet the schedule and respect the interconnection capacity limits.

NYISO also has an approved co-located storage model and is working on the design for its hybrid storage model. The NYISO co-located storage resource model includes both an injection scheduling limit (similar to CAISO's aggregate capability constraint) and a withdrawal scheduling limit, which can allow for grid-charging limits of the resource. Other ISOs and RTOs, though not as far along as CAISO and NYISO, have recently responded to FERC's request for information to describe potential plans in their regions. This includes present-day practices and efforts regarding both independent co-located models and any forms of hybrid models, as well as the use of existing participation models, terminology differences, eligibility requirements for different services, and other aspects related to capacity value and interconnection (FERC, 2021).

Economic and Reliability Value of Hybrids into the Future

Understanding the value of hybrid resources requires understanding how they contribute to the system compared to alternatives and the values that they offer to the resource owners. Hybrid resources can supply energy when needed, contribute to the system capacity needs, provide arbitrage across low-cost time periods with high-cost time periods, and generally provide a suite of ancillary services. One approach to determining their value is to compare the value of hybrid resources with the alternative technology, such as a peaking gas turbine. Another approach is to compare the hybrid with the individual resources of the same size, with the energy storage resource component sited optimally (in terms of value to the system) within the power system.

In a recent study, researchers found that co-locating storage with wind or solar technologies could lead to a penalty of $2 to $50/MWh compared to independently sited locations due to reduced revenue from siting batteries at less valuable locations, with an average of about $1.60 to $12.50/MWh across all ISOs and across all years dating back to 2012, depending on battery integration assumptions (Gorman, 2021). The upper range of these penalty estimates included interconnection limits set at the renewable facility's capacity and grid-charging constraints for the co-located scenario, which can limit, at times, the storage charge and discharge capabilities. These types of values can be compared to cost savings from co-location to help determine whether the hybridization of these facilities is economically beneficial. Experts have estimated that hybridization can provide an estimated $5/MWh in cost savings and an additional $10/MWh in savings with the investment tax credit (Montañés et al., 2021), ultimately outweighing the potential value reduction and making hybrid resources more cost-effective than independently sited facilities. Other studies have found a wider range of potential values to developers and owners of hybrid resources (Ahlstrom et al., 2021). These studies should continue as market designs and outcomes evolve, policies advance (including the development of a stand-alone storage tax credit), and technology and project costs continue to change.

The value and prevalence of hybrid resources will likely continue to rise in the future as the electricity sector heads toward decarbonization. New hybrid technologies and combinations are likely, including those that may have longer-duration storage to meet the needs of a decarbonized power system. As hybrid resources become more prevalent, an obvious question arises: Should

Should market designers and wholesale electric supply regulators wait until the technologies are demonstrated before developing the rules, eligibility provisions, and participation models? Or should we consider the possible participation options that can, to the best of our ability, capture as many future participating combinations and technologies as possible?

market designers and wholesale electric supply regulators wait until the technologies are demonstrated before developing the rules, eligibility provisions, and participation models? Or should we consider the possible participation options that can, to the best of our ability, capture as many future participating combinations and technologies as possible? The latter makes sense and can allow for innovation in and evolution of business models in advance of these resources' physical development. However, ISOs and RTOs also have finite budgets and time, and go through lengthy priority processes with stakeholders to trim the list of initiatives and market design changes to a reasonable number each year. Unless funding, time, and engineering resources are made available, some balance is probably the next-best solution.

Recommendations for Wholesale Market Design, Participation, and Operations

Based on the observations above, the following actions may be considered as they relate to market design rules, participation models, and operations for hybrid resources:

- Develop participation models that reflect various objectives and strategies of asset owners, as these can lead to lower costs for consumers and efficient and fair profits for asset owners, while ensuring reliability and tractability within market clearing timelines, particularly for systems with high shares of hybrid resources
- Investigate the possibility of allowing resources to provide offer updates regularly and closer to real time, while ensuring that market power mitigation tests can still be processed
- Research the true costs of hybrid resources in various scenarios given opportunity cost bidding, to ensure that market power mitigation procedures can be applied adequately and in similar ways to other technologies
- Understand the technical capability of hybrid resources to provide ancillary services with their ability to sustain output, and ensure that duration requirements for services are based on true system needs
- Continue to assess the value of existing and new hybrid make-ups against their alternatives; and continue to develop the techniques for studying resources and comparing values to costs in order to help the industry determine the value of hybridization into the future
- Anticipate participation models that may allow for the market participation of multiple technologies in efficient ways, and avoid waiting until the technology is demonstrated before creating rules for participation

At this point in time, a viable and promising way forward is for participation models to be designed such that each new combination or new technology is allowed to participate in its preferred way. This would include self-managed operation or operation in which parameters are shared with the ISO, which can allow the ISO to optimize the resource based on system conditions to minimize total system cost (which often leads to profit-maximizing behavior for each technology). ISOs and others responsible for system reliability should continue to evaluate the ways in which new resources participate to ensure that they can maintain reliability, ensure fair treatment across all technologies, and avoid the practice of market power. ISOs should continue to anticipate the potential of emerging technologies and eliminate any barriers to their participation, including offering eligibility for various services as soon as feasible to do so.

Resource Adequacy and Capacity Accreditation

Currently, revenues for most wind and solar projects come largely from wholesale energy markets and the sale of environmental attributes—often renewable energy credits to meet a state's renewable portfolio standard or corporate renewable energy goals. Other revenue streams that represent a larger portion for thermal resources, such as ancillary services and capacity payments, tend to be a more minor source of revenue for wind and solar plants. This is because while wind and solar are technically capable of providing ancillary services, they typically do not because it would require self-curtailment. In addition, wind and solar resources often have a lower capacity value because their generation may not align with system (net) peak demand.

Hybrid resources that include energy storage, however, can access ancillary service and capacity revenue streams. While ancillary service revenues currently make up a large portion of the incremental value that hybridization brings, they are likely not a long-term value proposition since ancillary service markets—or system needs—are relatively small, and the market is therefore shallow and prone to saturation (at least under current market designs). Capacity revenues, on the other hand, are poised to benefit from the opposite trend. As thermal generation retires and the capacity value of wind and solar resources continues to diminish as their levels rise, the capacity revenues for hybrid projects will likely continue to increase as a portion of the overall revenue mix.

As thermal generation retires and the capacity value of wind and solar resources continues to diminish as their levels rise, the capacity revenues for hybrid projects will likely continue to increase as a portion of the overall revenue mix.

As a result, capacity rules, and specifically resource adequacy and accreditation methods, will become increasingly important for hybrid resources. In addition, as the power system further decarbonizes and retires thermal generation, renewable resources—and hybrid systems specifically—will play an growing role in the reliability services traditionally served by the fossil fleet.

Resource Adequacy Benefits of Hybrids

The capacity revenues of a resource are typically dependent on its capacity value—its likelihood of availability during times of system need. Capacity values are determined via resource adequacy analysis, bulk system reliability planning and requirements that ensure there are sufficient resources available to serve load under a wide variety of elements of uncertainty, including weather, generator outages, and load. Resource adequacy criteria—the minimum level of acceptable reliability risk on a system—are designed to be highly reliable, ensuring that load is served more than 99.9 percent of the time. Shortfall events resulting from resource adequacy deficiencies are exceedingly rare, and often occur for only a short period of time.

Increasing amounts of wind and solar inherently improve resource adequacy, as they increase the amount of capacity available to serve load. However, their ability to improve resource adequacy is limited because the resource availability is variable, and in high-renewable systems the periods of highest risk, measured as loss of load expectation (LOLE), often shift to periods later in the day without solar or occur in seasons with lower wind availability (RRATF, 2021). But adding storage to wind and solar allows these resources to shift their energy to time periods when it is needed most, thus increasing their capacity credit. As a result, all other things being equal, a hybrid resource can receive higher overall revenues from providing capacity than can stand-alone wind or solar resources.

Capacity Accreditation Methods

The ability of a resource to meet the resource adequacy needs of the bulk power system and improve reliability is measured by its capacity accreditation, or the capacity value of the resource. In contrast to a resource's name-plate capacity, a capacity accreditation assigns a capacity that will likely be available during times of tight supply conditions.

For thermal resources, this capacity value is typically measured in unforced capacity (UCAP), which starts with the seasonal dependable capacity of a resource (its nameplate capacity minus derates due to seasonal ambient conditions) and reduces it by the generator's forced outage rate. This process assumes that the unit is available to produce at its full capacity during times of system need but will at times be unavailable due to an outage.

The capacity accreditation for wind and solar resources, in contrast, is based on the statistical likelihood of their being available during periods of system need depending on weather conditions. As a result, the capacity value of these resources is typically a fraction of their total name-plate capacity. For storage and other energy-limited resources, the capacity value is a function of the installed capacity (MW), resource duration (MWh), and avail-ability of energy required to charge the storage device. Accreditation of hybrid resources, therefore, must combine these considerations.

There are multiple ways to accredit wind and solar resources, which vary by region. Each of these can also be applied to hybrid resources, but it requires informa-tion or assumptions on when and how storage resources will be utilized. Options for accrediting wind, solar, and hybrid resources include the following (EPRI, 2021):

- **Output during predetermined hours.** This approach uses resources' average or median (or other percentile rank) output during a pre-defined capability period—typically highest load or highest net-load periods. For example, NYISO currently accredits wind and solar based on their average capacity factor during hour ending 3 PM to hour ending 6 PM during June through August for the summer period, and a similar window during the winter season. A similar process is used by the Independent System Operator for New England (ISO-NE).
- **Average output during highest net load hours.** Rather than use a pre-defined time period, this process averages a resource's output during peak load hours or peak net load hours (load minus available wind and solar). For example, the Southwest Power Pool (SPP) accredits wind based on its 60th percentile of production during the top 3 percent of load hours.
- **Effective load-carrying capability (ELCC).** ELCC methods measure the ability of a resource to reduce

FIGURE 8

Challenges for Quantifying Capacity Value for Hybrids and Energy-Limited Resources

Saturation Effects

Daily load profile flattens, any additional shift of energy will reduce reliability during charging.

Forecast Uncertainty

Wind and solar forecast errors could yield sub-optimal storage scheduling.

Multi-Day Events

Sustained low output of wind or solar limits ability to charge battery.

Competing Objectives

It is likely that assets are used for multiple services (arbitrage, reserves, transmission and distribution, etc.), which may compete with capacity needs.

Unexpected Outages

An unexpected generator outage could occur after storage discharge (not just about peak load).

Energy for Charging

Capacity value of storage is dependent on availability of resources to charge.

Six challenges associated with resource adequacy modeling and capacity accreditation methods for wind, solar, storage, and hybrid resources.

Source: Stenclik et al. (2018); GE Energy Consulting.

loss-of-load events in a probabilistic resource adequacy analysis. Specifically, ELCC measures the amount of load that can be added to a system as a result of adding the resource being analyzed, while maintaining the same level of reliability for the system (measured as loss of load expectation or loss of load probability).

- **Exceedance approach.** The exceedance approach measures the minimum amount of generation produced by the resource in a certain percentage of included hours.

The first two accreditation approaches use a heuristic to approximate the time periods of system risk, which may change over time due to changes in the load and resource mix. The third approach, ELCC, is based on resource adequacy analysis and a resource's ability to reduce a system's likely loss-of-load events. As a result, the use of ELCC is becoming prominent for wind, solar, storage, and hybrid resources across much of North America (Schlag et al., 2020).

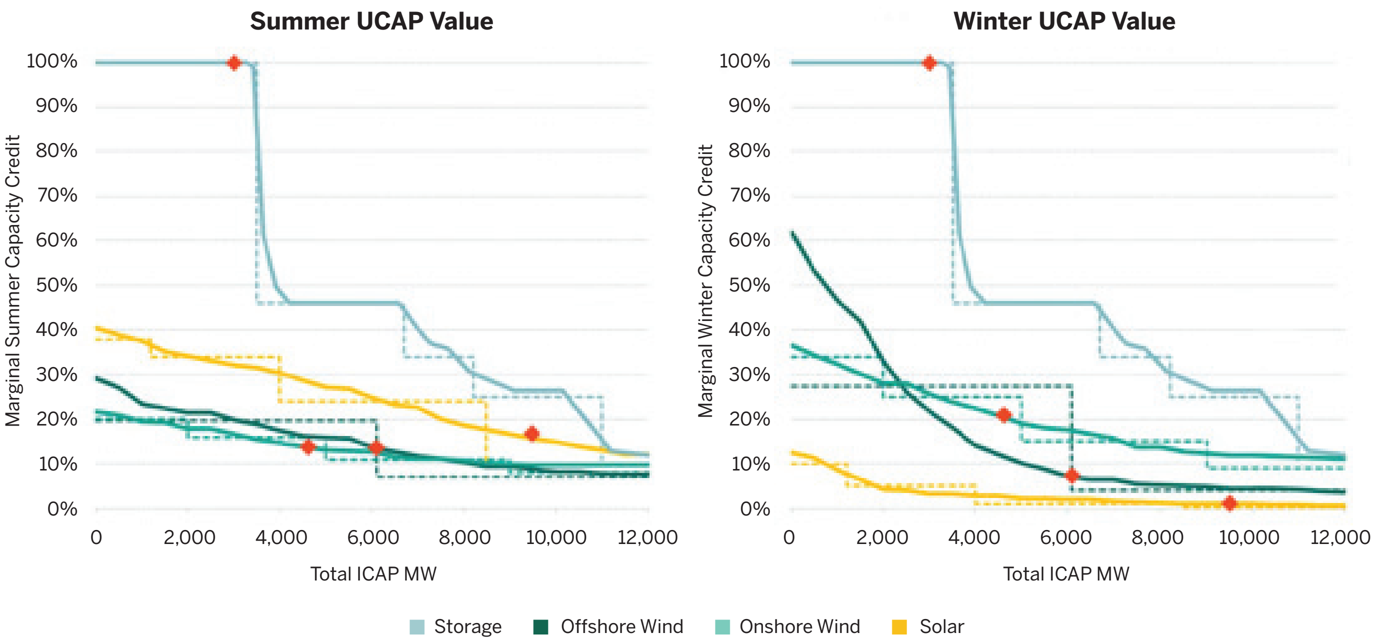
While ELCC can provide a useful metric on the capacity contributions of a particular resource, there are numerous challenges that must be considered for hybrid resources. Six of these challenges are highlighted in Figure 8 (Stenclik et al., 2018).

As the reliability of power systems becomes more dependent on variable renewable energy and energy-limited resources, the system will become less capacity-constrained and more energy-constrained (RRATF, 2021). The availability of a hybrid resource is dependent not just on its capacity, but also on the availability of energy to charge the storage resource and shift production to later hours.

One key challenge is saturation effects, discussed further in the next section, which cause the ELCC to diminish as the installed capacity of a specific resource type increases and shift system risk to time periods when the resource is not providing power. This true for both stand-alone and hybrid projects. Figure 9 (p. 23) shows the marginal capacity contribution of wind, solar, and storage in New York as the amount of each resource increases (Spees et al., 2020). Figure 10 (p. 23) illustrates how the saturation of energy-limited resources occurs by showing the duration needs required to reduce net load, based on an annual net load duration curve (left) and daily load profile (right) (Stenclik et al., 2018).

FIGURE 9

Installed Capacity Versus Marginal Capacity Credit in New York



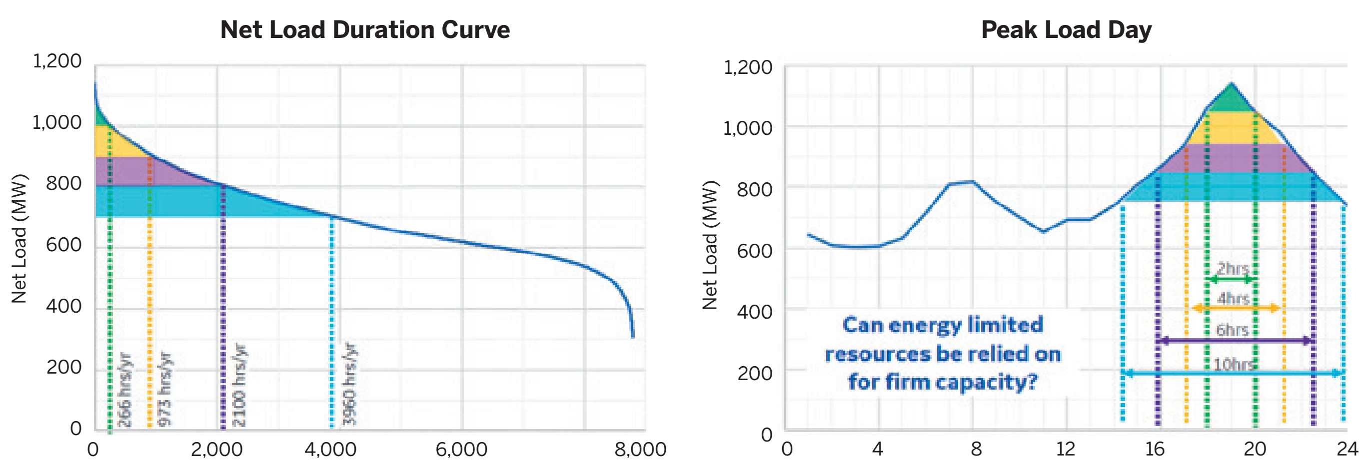
A comparison of declining ELCC and marginal capacity credit for wind, solar, and storage in New York across summer and winter seasons. Solid lines represent smooth marginal capacity credit values, and dashed lines are simplified model inputs for inframarginal value purposes. Marginal ELCC is indicated by red dots.

Note: UCAP = unforced capacity; ICAP = installed capacity; ELCC = effective load-carrying capability.

Source: Spees et al. (2020); The Brattle Group.

FIGURE 10

Saturation of Energy-Limited Resources for Capacity Benefits in Hawaii



Representative increasing storage duration requirements for full capacity accreditation, comparing an annual net load duration curve (left) and average peak load day (right) in Hawaii.

Source: Stenclik et al. (2018); GE Energy Consulting.

In addition, the ability of a hybrid resource to provide capacity is dependent on ensuring that the state of charge of its storage resource is sufficiently high when the resource is needed. These time periods are not known with certainty and must be forecasted so that state of charge can be managed appropriately. This uncertainty can be caused by generator outages that occur outside of the typical risk hours or by forecast uncertainty of the weather (renewable resource availability) or of market prices, both of which influence storage charging and discharging schedules.

Including these considerations in the resource adequacy analysis is challenging, in part because this requires long historical records of weather and its influence on resource availability, but also because the strategies used by storage and hybrid resources are dependent on generation owners' decisions and perceptions of opportunity costs as well as risk aversion. However, properly accounting for saturation effects in capacity accreditation methods affords an opportunity for hybrid resources—as it allows individual projects to address saturation effects in isolation, without relying on systemic changes.

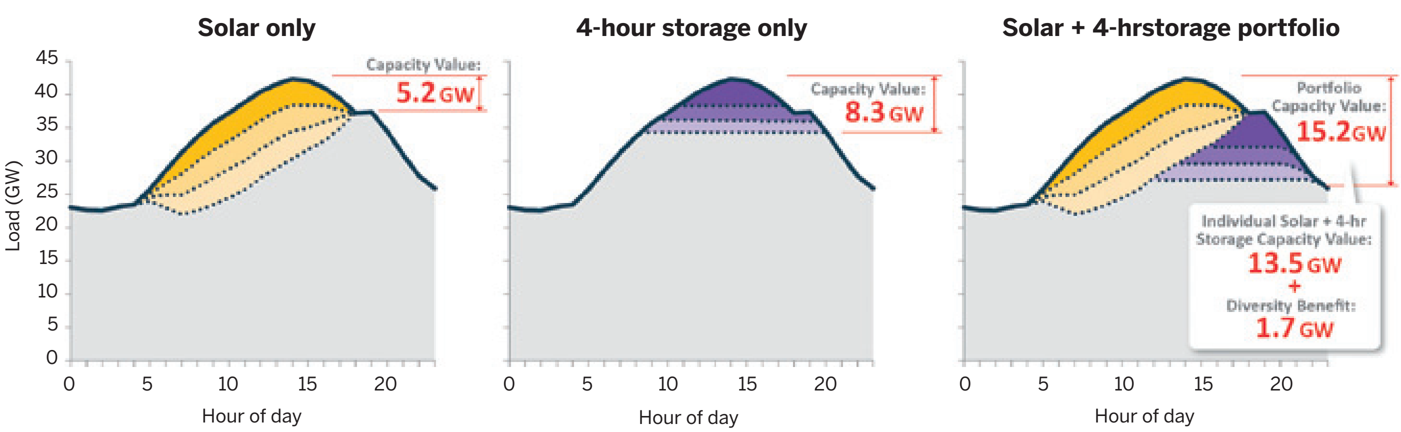
Portfolio Effects of Capacity Accreditation

While the previous section identified challenges associated with accrediting hybrid resources, it did not evaluate the complementary benefits that hybrid resources can provide for reliability. Specifically, the saturation effects discussed above assumed that the resources are added in isolation from one another. However, there are benefits from resource diversity—either within an individual hybrid resource or at the system level: "while resources with similar operating characteristics yield diminishing returns, combining resources with complementary characteristics can produce the opposite effect, a total ELCC that is greater than the sum of its parts" (Schlag et al., 2020). The interactive effects of resources added in conjunction with one another can yield additional capacity value benefits that are not captured by an independent evaluation of the individual resources—and, if they are studied independently, the order in which the resources are added will lead to different results.

For example, the complementary resources in solar + storage projects yield multiple benefits (Figure 11). The addition of solar narrows the system net peak load,

The interactive effects of resources added in conjunction with one another can yield additional capacity value benefits that are not captured by an independent evaluation of the individual resources.

FIGURE 11
Portfolio Benefits for Solar + Storage in Capacity Accreditation



An illustrative example of the complementary benefits of solar and storage resources for capacity accreditation.

Source: Schlag et al. (2020); E3.

improving the ability of an energy-limited resource like storage to cover the peak load risk. In addition, the solar adds energy to the system that can be used by the storage resource to charge.

Another example of the portfolio effects is provided in Figure 12, which shows the amount of capacity of a four-hour energy storage resource with full peak demand reduction credit relative to the amount of solar on the system (Denholm et al., 2019). As the figure illustrates, rising levels of wind and solar increase the capacity value of energy storage.

While the examples above focus on the system level, the observed saturation and portfolio effects are also true from the perspective of an individual plant. One benefit of the hybrid resource perspective is that allocating the capacity accreditation of the portfolio benefits is more straightforward for an individual plant and single owner than benefit allocation across many different plants and owners, as is required for system-level portfolio effects.

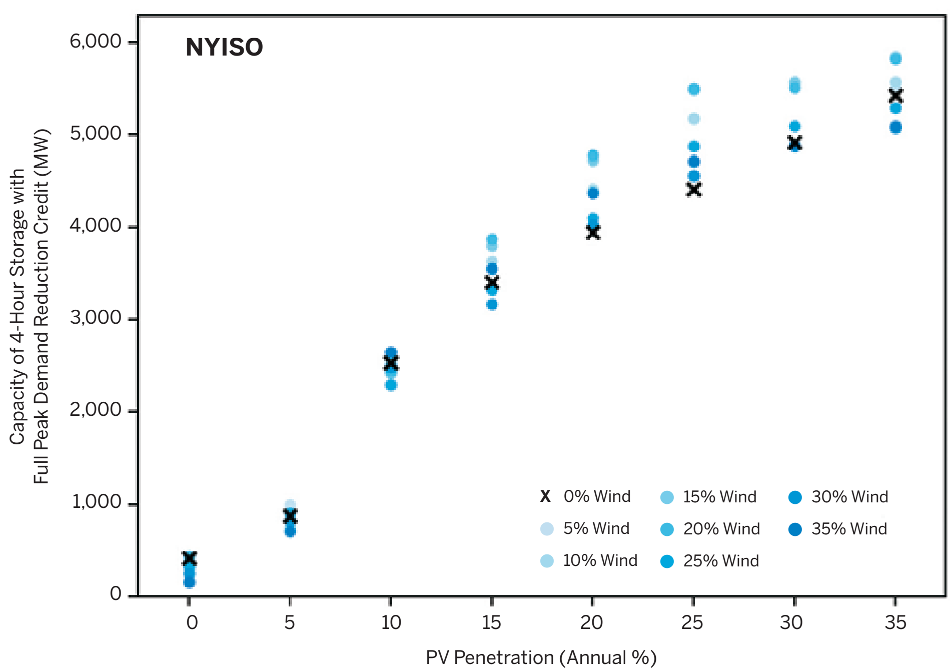
In contrast to allocating portfolio benefits on a system level assuming separate renewable and storage resources, the hybrid resource "brings its own energy" for capacity accreditation—in a sense, looking like a self-charging battery of a sort. The allocation of portfolio benefits—at the system level—becomes increasingly important as the system becomes more energy limited. In addition, the hybrid resource can be designed with high inverter-loading ratios and extra amounts of renewable capacity (in excess of the injection limit at the point of interconnection) to ensure that the storage system is available nearly every day at 100 percent of its available capacity, regardless of the overall larger system conditions.

Two Options for ELCC Calculations for Hybrid Resources

There are two options for calculating the ELCC for hybrid resources (Table 4, p. 26). The first is to calculate the ELCC of each hybrid component separately, sum the individual pieces together, and limit the total capacity

FIGURE 12

Capacity Value of Storage Relative to Share of Renewables on the System



The relationship between the full capacity contribution of 4-hour storage (y-axis) at increasing levels of PV penetration (x-axis).

Source: Denholm et al. (2019).

TABLE 4
Two Options for Hybrid Resource ELCC Calculations

OPTION A	OPTION B
Individual Resource Accreditation	**Aggregate Resource Accreditation**
Is a sum of ELCC individual hybrid resources, capped at the point of interconnection	Evaluates the hybrid plant ELCC at the aggregate plant level as a unique resource
Advantages	
• Is simple to implement and understand • Does not require unique modeling for all hybrid configurations	• Evaluates the specific characteristics of the hybrid plant • Considers charging constraints • Considers benefits of higher inverter loading ratios and DC coupling
Disadvantages	
• Does not account for portfolio effects at the plant level • Does not consider charging constraints • Does not consider benefits of higher inverter load ratios and DC coupling	• Requires individual analysis of each hybrid resource on the system • Is computationally burdensome and analytically time-consuming

Note: ELCC = effective load-carrying capability.

Source: Energy Systems Integration Group.

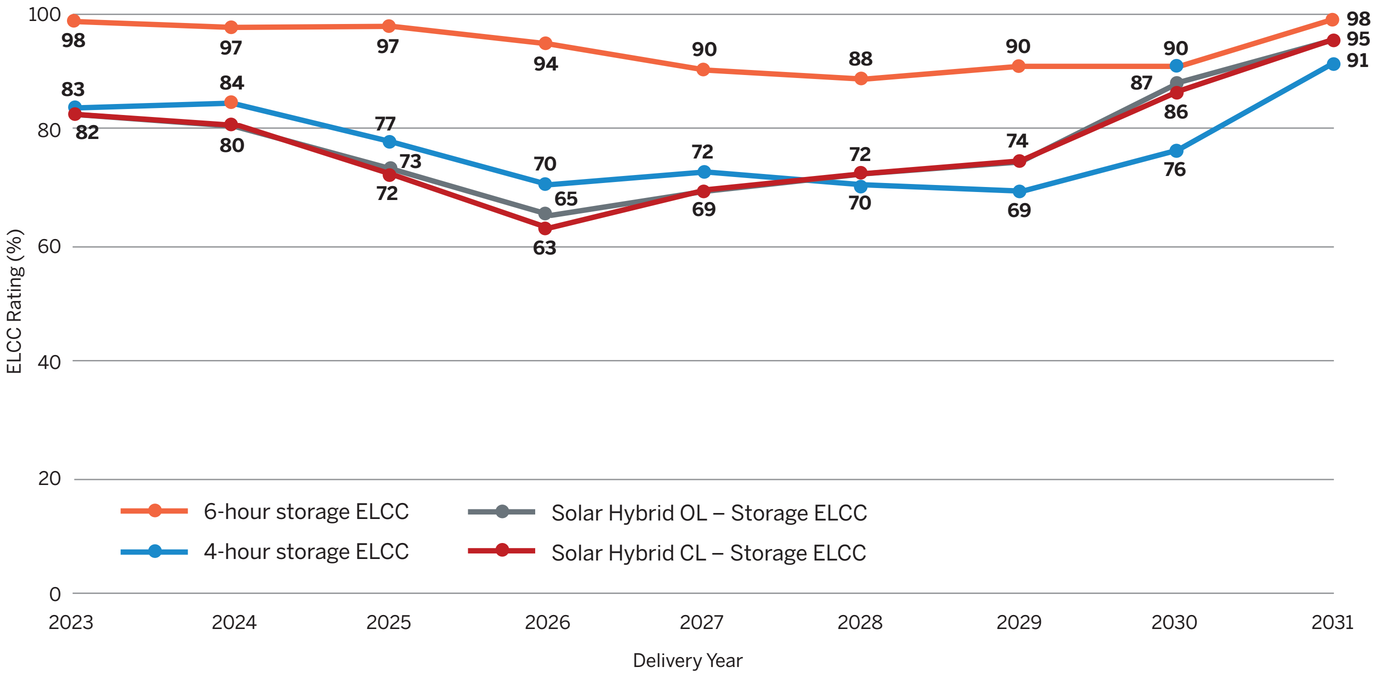
accreditation by the injection limit. This "sum of parts" approach is attractive because it is simple to implement and understand (provided that the individual ELCCs are calculated correctly) and does not require hybrids to be modeled across many different potential configurations. However, the approach does not, by itself, account for the portfolio effects at the plant or system level. In addition, it does not consider potential charging constraints, or the benefits of high inverter loading ratios which add increased energy from the wind and solar resources.

A second option is to evaluate the combined hybrid resource as a single, coordinated plant in the ELCC analysis—as a distinct resource type. For this option, the resource is modeled in the resource adequacy analysis with its specific configuration, charging constraint, and other plant parameters to calculate the plant's ability to be available during time periods with a higher likelihood of shortfalls. The benefits of this method are that it explicitly captures the portfolio effects, the benefits of higher inverter loading ratios, and potential charging constraints. However, given the large number of potential unique configurations of hybrid resources, each plant requires an individual analysis, which can be computationally burdensome and analytically time-consuming.

The second option was recently implemented by PJM in its ELCC redesign method, and the results compare the capacity contribution of a stand-alone four-hour storage resource to the four-hour storage component of a solar + storage hybrid resource. The hybrid was evaluated under an open loop assumption where it could charge from the grid if needed, and a closed loop assumption where it could charge only from the associated solar resource (PJM, 2021). The results of the two methods are nearly identical (Figure 13, p. 27). Interestingly, however, there is a crossover point at which the capacity value of the hybrid storage resource becomes more valuable than that of the stand-alone resource. This indicates a point at which the additional energy from the hybrid resource outweighs potential limits imposed by a shared point of interconnection, which may limit the simultaneous output of each resource component.

FIGURE 13

Increasing Battery Storage ELCC at Increasing Installations in PJM



Projected ELCC ratings for storage resources in PJM, both stand-alone and combined with solar in a solar + storage hybrid.

Note: ELCC = effective load-carrying capability; OL = open loop; CL = closed loop.

Source: PJM Interconnection © 2021.

There has not been enough research yet to determine which of the ELCC accreditation methods is appropriate for hybrid resources given the trade-off between accuracy and complexity. According to FERC,

> [c]ommenters note that, as an initial approximation of the capacity value of these resources, it is possible to use a sum of the component parts of the resource. However, [the Electric Power Research Institute] notes that its research suggests that the addition of storage to solar or wind materially changes the capacity value of the hybrid resource. Regardless, some commenters, such as MISO, note that they believe that existing methods of capacity valuation can accommodate co-located hybrid and integrated hybrid resources in the near term, explaining that once verifiable performance data is available, new methods based on operational experience may be developed (FERC, 2021).

Additional analysis and evaluation comparing the different accreditation methods is needed.

Other Considerations for Hybrid Resource Accreditation

There are additional considerations that warrant further evaluation for hybrid resource capacity accreditation, including charging constraints, energy market must-offer rules, and transmission interconnection constraints, as well as long-term challenges for ELCC.

Grid-Charging Constraints

An important potential difference between stand-alone storage and storage that is one component of a hybrid resource involves constraints on grid charging. The capacity accreditation of both resources is dependent on the resource having sufficient state of charge during tight reserve and potential shortfall conditions. This requires that the storage resource be able to charge during preceding hours or days. In a high-renewables grid, the periods of risk of a shortfall are often associated with days with high load and low wind and solar availability, meaning the battery may at times require grid charging.

Because the investment tax credit requires that hybrid storage resources be charged by the paired renewable resource, grid charging may not be acceptable to some parties or in some particular circumstances. However, the investment tax credit is a financial—rather than technical—operating constraint. The tax credit does allow for some amount of grid charging (up to 25 percent of total annual energy), but any grid charging will proportionally reduce the credit. As a result, while the hybrid storage may, for tax purposes, charge predominantly from the paired renewable resource, it need not do so exclusively. Some amount of grid charging may be highly beneficial from a reliability and capacity accreditation perspective. It is important that power purchase agreements and grid interconnection rules allow for sparing amounts of grid charging, specifically in periods of low renewable output prior to potential scarcity events.

Table 5 and Figure 14 (p. 29) depict the example of a hypothetical 100 MWdc solar + storage hybrid facility in southern California. The number of days per year that a four-hour battery ranging from 40 MW to 100 MW (160 MWh to 400 MWh) is unable to charge exclusively from the paired renewable resource is small. For the smaller battery configuration, this occurs only five days per year, while even with a pairing of equal solar and storage capacity, it occurs only 64 days per year. On a percentage of energy basis, only 0.3 to 4.5 percent of total charging energy would need to come from the grid to ensure 100 percent availability across all days. More

It is important that power purchase agreements and grid interconnection rules allow for sparing amounts of grid charging, specifically in periods of low renewable output prior to potential scarcity events.

TABLE 5

Paired Solar vs. Grid-Charging Needs in Southern California

Metrics	Storage Size			
	40 MW	60 MW	80 MW	100 MW
	160 MWh	240 MWh	320 MWh	400 MWh
Annual Metrics				
Days without enough solar energy to charge fully	5 days	16 days	32 days	64 days
Solar charging	58,213 MWh	86,584 MWh	113,881 MWh	139,412 MWh
Grid charging needed for 100% availability	187 MWh	1,016 MWh	2,919 MWh	6,588 MWh
Grid charging, percentage of total	0.3%	1.2%	2.5%	4.5%
Summer-Month Metrics				
Days without enough solar energy to charge fully	0 days	0 days	1 day	2 days
Solar charging	19,520 MWh	29,280 MWh	39,025 MWh	48,636 MWh
Grid charging needed for 100% availability	0 MWh	0 MWh	15 MWh	164 MWh
Grid charging, percentage of total	0.0%	0.0%	0.0%	0.3%

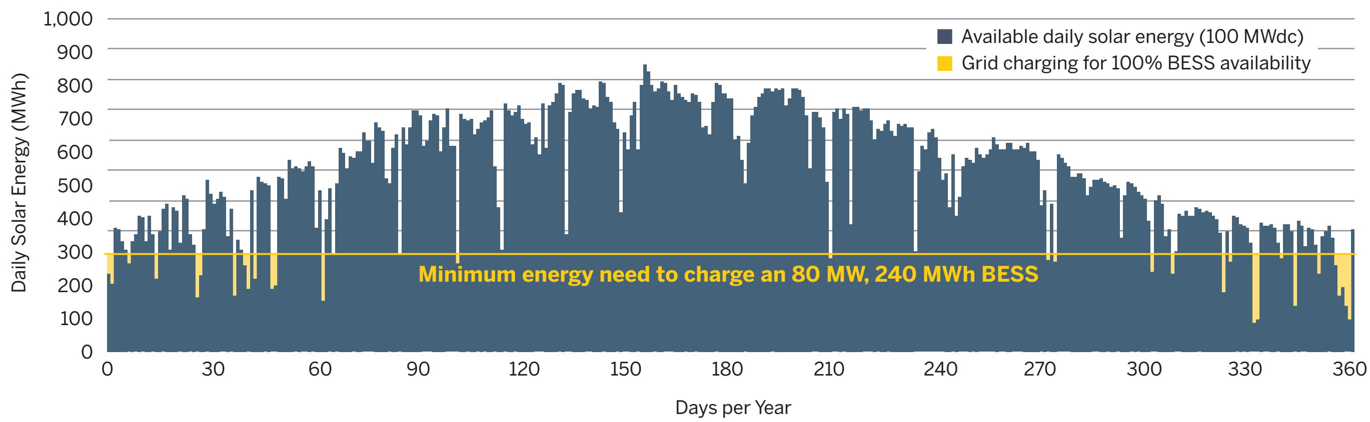
The amounts of solar charging and grid charging necessary for 100 percent availability of hybrid storage for a 100 MW_{dc} solar + storage hybrid facility in southern California.

Note: This assessment depends on the location of the facility and the underlying times of capacity needs.

Source: Energy Systems Integration Group. Data from the National Renewable Energy Laboratory's National Solar Radiation Database.

FIGURE 14

Grid-Charging Needs for Hypothetical Solar + Storage Hybrid Resource in Southern California, All Days of the Year



Daily grid-charging requirements (in yellow) for 100 percent hybrid storage availability across an entire year in southern California.

Source: Energy Systems Integration Group. Data from the National Renewable Energy Laboratory's National Solar Radiation Database.

importantly, the grid-charging needs are significantly lower during the summer reliability risk period from May through September, when solar production is highest.

Point of Interconnection Constraints

As discussed in the second section of this report, one of the primary advantages and enablers of hybrid resources is the ability to overbuild renewable and storage capacity behind a single point of interconnection, thus deferring the need for transmission upgrades. This interconnection limit is appropriate in most cases given constraints on the transmission system. However, injection limits are designed based on snapshot analysis, not across all potential operating conditions. Of particular interest are reliability scarcity events and emergency situations that require additional capacity in order to avoid load shedding. During these periods, emergency overloads of the transmission constraints may be warranted, provided that they do not jeopardize system security. A more dynamic interconnection limit could unlock additional capacity value during scarcity events and should be evaluated further.

Must-Offer Rules

In most capacity markets there is a must-offer rule that requires resources that receive accreditation from the capacity market to offer their awarded capacity into the day-ahead energy market each day. Variable renewable energy is typically excluded, and its offer is based on the available or forecasted generation. However, hybrid resources are unique. Although they will often have an ELCC rating below the nameplate capacity of the resource (based on availability during high-risk periods), they will have surplus availability during much of the year. This raises a question as to the must-offer requirement: Should hybrid resources be required to offer into day-ahead markets for their full capacity, or should their obligation be limited to their capacity accreditation amount, leaving any surplus capability free to offer as the generation owner wishes? Further consideration of this topic is warranted, and it may need to be considered as part of other work on the future meaning and use of the concept of capacity and energy.

Long-Term Considerations for Capacity Accreditation

As the grid transitions to a decarbonized energy portfolio, the capacity needs will also change. Today, ELCC serves as a reasonable method to accredit resources in a consistent manner. This creates a uniform capacity product, which is useful in capacity auctions and procurement. However, the capacity needs of a future grid will be more dynamic and less uniform. Our current definitions of capacity may no longer apply in a

high-renewable future. Allowing for flexibility in hybrid configurations and accreditation methods will ensure that system reliability is maintained throughout the grid transition.

Recommendations for System Operators on Resource Adequacy and Capacity Accreditation

As this section identified, resource adequacy and capacity accreditation are an integral component of a hybrid resource's economic value. Therefore, there are several important aspects for system operators to consider when developing resource adequacy programs and capacity accreditation methods for hybrid resources, which can be summarized in the following list.

- Capacity accreditation methods should consider the portfolio effects, which include the complementary benefits of multiple resources for resource adequacy. This is true for resource combinations at the system level as well as resources within an individual hybrid plant.
- Additional research and analysis are needed to understand whether hybrid accreditation should be based on the sum of individual resources, capped at a point of interconnection limit, or done on an aggregate basis for each unique hybrid plant. It is currently unclear whether the additional analytical effort required for the latter is justified.
- Power purchase agreements and interconnection rules should be designed to allow for grid charging, even if sparingly, which can yield significant resource adequacy benefits and improved system reliability.
- Further evaluation should be considered of must-offer rules for hybrid resources that can fully leverage the flexibility of the resource in a way that is equitable based on its capacity accreditation.

Guiding Principles

This report offers a broad perspective on the types and key drivers of hybrid resources and provides details on the transmission interconnection, market rules and operations, and resource adequacy considerations for these resources. It should be acknowledged that the industry is still in a state of infancy with respect to hybrid resources. As recently as 2018, there were essentially no hybrid projects and only a limited number of proposed projects in U.S. interconnection queues, and today, hybrid resources represent one of the fastest-growing technologies in the electric power sector.

In the coming years there will continue to be rapid advancement in technologies, business models, and regulatory structures with regard to hybrid resources. It is imperative that flexibility be afforded to these new resources, as they will set the stage for future power system changes and novel forms of flexibility. The following guiding principles offer a framework for integrating hybrid resources across the power sector's planning, policy, and regulatory functions.

1. Definitions should remain flexible and broad.

Hybrid technologies and combinations will change. It is important to establish a framework that allows creative thinking, combinations, and controls of resources and thereby provides opportunities for innovative solutions. The solar + storage hybrid is only the first step, with limitless possibilities to come. Definitions should be broad and technology-agnostic.

2. Existing points of interconnection should be leveraged for additional resources.

Existing points of interconnection are a valuable and timely resource for adding, upgrading, and replacing resources. As such, they are a logical location for hybrid resources and other enhancements or replacements that

can accelerate the deployment of renewable resources, reduce their costs, and increase the system services they can provide. Utilizing existing points of interconnection can bring a range of benefits to developers, ratepayers, and system operators.

3. Multiple participation model options allow for greater flexibility and innovation.

The more participation models the better, not just for hybrid resources but for all resources. Some hybrid resource owners will be best served through separate co-located models while others may prefer single hybrid models, with the choice depending on the make-up of the resource, existing market design, and strategy of the asset owner. Asset owners should be given the opportunity to choose the participation model that works best for them while providing the services that the power system needs and values in a performance-based, technology-neutral manner. The participation models should generally lead to reliable and fair operation, while considering computational complexity and limitations of market clearing software.

4. Broad participation models should be developed in advance for technologies that are not yet tested.

System operators and planners should anticipate the rules and participation models that may allow for the participation of multiple technologies in efficient ways, as well as combinations and technologies not yet known or tested. If possible, they should create rules for participation even before a technology is demonstrated to avoid slowing technological innovation and adaptation of business models.

4. Asset owners should be given the option to manage internal operation of the hybrid facility when they choose to do so.

Forecasting, opportunity costs, and battery degradation are all important considerations informing the operation of a hybrid facility. Market constructs should be developed in a manner that allows asset owners to retain control over hybrids' operation when that strategy is desired. To ensure that system reliability can be maintained, and market power mitigation effectively tested, it may be appropriate for the system operator to monitor self-managed operation of hybrids, particularly at higher levels of hybrid resources.

5. Resource adequacy analyses should consider synergistic effects among the components of hybrid resources and the diversity benefits these resources bring.

Resource adequacy methods should consider the synergistic effects between the hybridized components—which can provide additional value—and how they can operate as a system, as well as the benefits of the hybrid resource within the system's resource portfolio.

6. Traditional requirements that close doors for flexibility and services in a transforming grid should be reconsidered.

Highly flexible resources can respond quickly and will often have more capabilities than conventional resources in real time. Gate-closing windows in day-ahead and real-time markets that were convenient in the past for conventional resources may now be unnecessary or even detrimental. In addition, storage duration requirements should be aligned with system needs, recognizing the growing population of dynamic, digital, and flexible resources in the system.

As hybrid resources continue to proliferate on the grid, they have the potential to unlock new forms of flexibility for renewable resources. To ensure that hybrid resources can continue to grow, there must be carefully crafted changes to transmission interconnection, market participation models, and capacity accreditation methods. These changes will be essential as the capacity and grid services historically provided by coal and natural gas resources are replaced by a portfolio of variable renewables, storage, and load flexibility. Hybrid resources will also provide a unique opportunity to integrate additional renewable energy while minimizing necessary transmission upgrades for interconnection—eliminating a key barrier to the clean energy transition.

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Unlocking the Flexibility of Hybrid Resources

A Report of the Hybrid Resources Task Force of the Energy Systems Integration Group

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The report is available at https://www.esig.energy/reports-briefs.

To learn more about the recommendations in this report, please send an email to info@esig.energy.

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