A 2023 Perspective: What Is the Value of Hybridization?

Matthew Kotarbinski, Brinn McDowell, Jonty Katz, Genevieve Starke, and Nicholas Riccobono

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Preface

This report is the first of a two-part research project. The second report, *Control Strategies and Validation in the Hybrid Optimization and Performance Platform (HOPP)* (Starke, Martin, and Bhaskar forthcoming), focuses on the validation of the National Renewable Energy Laboratory's (NREL's) Hybrid Optimization and Performance Platform (HOPP). HOPP, in collaboration with NREL's Advanced Research on Integrated Energy Systems platform, allows developers globally to design and develop bankable hybrid power plant projects. In the second report, HOPP is validated using NREL wind and solar assets, as well as utility-scale wind and solar plants, culminating in a field test that applied HOPP dispatch strategy to a physical battery. More information regarding HOPP can be found in the appendix.

This report takes a wind developer's perspective and provides a summary of the current and future state of hybrid facilities, and ultimately seeks to answer the question: "Are hybrid power plants a pivotal tool for meeting future energy and decarbonization targets?" The intention is not to provide an in-depth system-level technical analysis of hybrid facilities, but to showcase a high-level overview of the hybrid facility ecosystem and its potential future directions. Lastly, the authors acknowledge and recognize that non-renewable generation technologies can be integrated into a hybrid facility, however these technologies are outside the scope of this report.

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List of Acronyms

AC	alternating current
BIL	Bipartisan Infrastructure Law
CO_2	carbon dioxide
BOS	balance of system
CCUS	carbon capture, utilization, and storage
DER	distributed energy resource
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
FERC	Federal Energy Regulatory Commission
FLORIS	FLOw Redirection and Induction in Steady State
GW	gigawatt
H2Hubs	Regional Clean Hydrogen Hubs
HOPP	Hybrid Optimization and Performance Platform
HPP	hybrid power plant
IEA	International Energy Agency
IRA	Inflation Reduction Act
ISO	independent system operator
ITC	investment tax credit
kg	kilogram
kWh	kilowatt-hour
LCOE	levelized cost of energy
LCOS	levelized cost of storage
MW	megawatt
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
NERC	North American Electric Reliability Corporation
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PTC	production tax credit
PV	photovoltaics
PWA	prevailing wage and apprenticeship
ROCOF	rate of change of frequency
RTO	regional transmission organization
SAM	System Advisor Model
USD	U.S. dollar
VRE	variable renewable energy

Executive Summary

The United States' decarbonization targets and cheaper renewable energy technology options have driven increased uptake in variable renewable energy (VRE) generation and storage technologies. However, as the share of VRE resources continues to grow, it will be increasingly challenging for new single-technology VRE projects to generate sufficient revenue for relevant stakeholders. These barriers can be attributed to a number of challenges, such as those associated with the variable generation profiles of renewable energy resources, as well as constraints related to U.S. grid and transmission operation and expansion. From the plant operator perspective[1], hybrid facilities[2] can provide more flexible and reliable clean electricity and energy vectors.

Hybrid power plants (HPPs) and hybrid energy systems (HESs) are becoming a growing share of energy projects that are entering the interconnection queues. This report references the most up-to-date International Energy Agency (IEA) Wind Technology Collaboration Programme Task 50 effort, to define HPPs as "a combination of two or more electricity generation and/or storage technologies, used to provide electrical power services that are coordinated at a single point of connection." This report further leverages the IEA Task 50 efforts to define HESs as "one or more HPPs, which provide an energy and/or non-energy product such as electricity, hydrogen, heat, or fresh water, to accommodate specific end-use needs" (Das and King 2023).[3]

Hybrid facilities may help facilitate an energy transition to achieve the U.S. targets of 100% renewable generation by 2035, and net-zero greenhouse gas emissions by 2050 (The White House 2023). Hybrid facilities have the potential to add value or alleviate concerns in the following areas (in no specific order):

- **Infrastructure and transmission.** Sharing infrastructure and plant components can result in project cost savings. Grid-connected HPPs can benefit developers and plant owners by maximizing power production without expanded transmission, which avoids costly upgrades, extended timelines, and additional permitting. Hybrid facilities operating in an off-grid configuration can shorten timelines associated with interconnection queues from 5-8 years to 3-5 years and avoid transmission interconnection costs.
- **Economic and market participation.** Various economic and market participation considerations that support hybrid deployment include more efficient use of grid interconnection points; new revenue streams in addition to electricity production such as hydrogen; and tax credit stackability, which allows for the election of multiple respective credits for individual components within a single hybrid facility. This would allow the plant owner to potentially elect additional credits that otherwise would not be possible for a single-technology project.
- **Industrial decarbonization.** Hybrid facilities provide a pathway to decarbonize hard-to-abate sectors by pairing zero-emission technologies together with conversion technologies. Conversion-based hybrid facilities have the capabilities to produce emissions-free hydrogen and ammonia feedstocks that can replace emissions-based

[1] This report takes a wind developer's perspective on hybrid power pants and hybrid energy systems.

[2] This report uses the terms "hybrids," "hybrid facility(ies)," and "hybridization" to encompass both hybrid power plants and hybrid energy systems, when referencing both design configurations within the same context.

[3] The authors recognize both IEA Task 50 definitions are not finalized, and therefore are subject to change as hybridization continues to evolve. As a result, these definitions are not intended to interpret any current ongoing efforts regarding how these hybrid facilities are defined.

processes. Hybrid facilities have the potential to be leveraged to decarbonize industrial processes including steel, cement, freshwater, and long-distance transportation.

- **Grid support.** HPPs are less sensitive to fluctuating resource profiles than single-technology VRE projects and therefore have the technical capabilities to provide bulk power and peak demand. HPPs that utilize complimentary VRE resources, like solar and wind, often can provide power more consistently than single-technology VRE resources. Additionally, an HPP integrated with storage technologies can enable ancillary services through its load-shifting and ramping abilities.
- **Land use.** Acquiring land for a single-technology VRE project can be challenging due to barriers such as ordinances, landscape considerations, suboptimal resource areas, and access to infrastructure. Hybrid facilities can experience the same development barriers, however, can leverage multiple generation sources and/or storage technologies to increase energy generation per land area. Further, hybridization can expand potential regions for development that historically have not been considered viable for single-technology VRE resources.

Despite the advantages that hybrid facilities can provide, their novelty can create uncertainties that influence deployment and adoption. The following list highlights some of the complexities and challenges associated with hybrid facilities:

- **Existing market rules.** HPPs' participation in electricity markets is an evolving discussion that includes metering and how these technologies are deployed. Existing electricity market rules often presume that technologies typically integrated within an HPP, such as generation and storage components, will be located separately. As such, existing market participation rules may not realize the full capabilities of hybrid facilities to support grid functions, such as charging from the grid and ancillary services, therefore impacting revenue potential.
- **High-cost technology.** Although renewable generation technology is cost competitive with traditional technologies, conversion technologies are still relatively expensive (Tashie-Lewis and Nnabuife 2021). The U.S. Energy Information Agency projects that the costs of these technologies will decline over time; however, upfront costs are currently a challenge for unlocking additional revenue streams (Energy Information Administration [EIA] 2022).
- **Design complexities.** HPP and HES configurations can differ substantially depending on the intended end use. Market conditions, region-specific characteristics, as well as the facilities asset management strategy—operated for financial or technical optimization—can influence the design of a facility. Due to these factors, the developer, plant owner, or operator, need to evaluate many plant design considerations that can influence the economics of a project.
- **Operation and reliability.** HPPs contain interfaces between different systems. As a result, system integration and reliability can be a challenge associated with plant customizability. There are also greater sensitivities to any type of connection disruption within a hybrid facility when compared to an equivalent-capacity collection of standalone single technology facilities that are all connected to the grid separately, where the loss of one connection would not affect the connection of the others.
- **Policy uncertainties.** The available policy incentives are a major driver of hybrid adoption; however, there is uncertainty regarding what may be an optimal tax credit election within hybrids due to the various plant configurations and ownership structures.

This complexity makes it unclear what the optimal tax credit strategy will be to maximize profitability.

Though hybridization presents both benefits and challenges, it also represents a promising new dimension to the energy transition. To support the continued deployment of HPPs and HESs, further technology cost reductions need to be achieved, continued innovation of systems integration, plant design and control, and updated regulation and market participation rules to reflect the capabilities provided through hybridization. This report qualitatively highlights several future research opportunities and innovations to further realize the benefits that hybridization can provide.

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1 Introduction: What Is Hybridization?

As the United States seeks to reduce emissions and increase renewable electricity generation, we also need to modify and improve the variable renewable energy (VRE) plants we build to meet the evolving needs of the energy transition. One way to improve VRE plants is through hybridization or combining multiple generation or storage technologies into a single facility. Hybrid facilities could play a role in helping achieve the targets of 100% renewable energy by 2035, and full decarbonization by 2050 that have been announced by the Biden administration, in conjunction with the U.S. Department of Energy (DOE), U.S. Department of Commerce, and U.S. Department of the Interior. The variability in electricity generation that comes from single-technology renewable energy resources can cause an unpredictability in supply that not only can be challenging for grid operators who need to balance electricity use with generation, but also for industry members using clean power to reach decarbonization goals. Because of their combination of technologies, hybrid facilities[4] can optimize generation, storage, and production of end-use products through complementary generation profiles and shared elements such as controls and infrastructure, when viewed from a plant developer's perspective. These benefits not only allow for more flexibility, predictability, and resilience, but also allow for cost savings and increased competitiveness compared to traditional power plants. More information on how we define hybrid facilities and their variations can be found in Section 1.1.1.

As renewables capture a growing share of total generation on the grid, renewable energy project developers are increasingly having to deal with transmission constraints, difficulties procuring land, and subpar project financing due to power plant underperformance. Though renewables continue to grow, small- to midsized project developers are having more difficulty penetrating markets where electricity is not the end product, losing competitive bids to larger players and projects that use natural gas feedstocks. For example, although efforts are currently underway to enable cost parity globally, low-carbon hydrogen manufactured through processes that use natural gas with carbon capture and sequestration, or blue hydrogen, is more economically viable than processes that use clean electricity to manufacture carbon-free, or green, hydrogen (International Energy Agency 2022). Hybridization can help renewable project developers address these issues. By combining multiple technologies, e.g., installing battery storage and solar photovoltaics (PV) on a utility-scale wind plant to form a "wind-based" HPP, a plant owner can develop economies of scope in terms of land usage, electrical and physical infrastructure, and operational expenditures. An HPP increase project value by capitalizing on revenue streams through avenues such as forward-looking capacity markets, operation in markets with time-varying energy pricing, and ancillary service markets. Furthermore, the impact is not limited to electricity generation, because HPPs and HESs are well-suited for integration into other sectors such as transportation, buildings, industry, and agriculture, which illustrates the wide-reaching effects that this multifaceted approach to generation can have on our energy system.

1.1 Taxonomy

Because of the novelty and nuances of HPPs and HESs, the definitions and qualifications for these plants vary greatly among stakeholders. Governments, academics, and research

[4] This report uses the terms "hybrids," "hybrid facility(ies)," and "hybridization" to encompass both hybrid power plants and hybrid energy systems, when referencing both design configurations within the same context.

organizations use inconsistent taxonomy to discuss hybridization. As a result, the authors chose the defined terms and types of hybrid facilities mentioned in this report to best align with globally accepted terminology and modeling capabilities.

1.1.1 Definitions

According to the Federal Energy Regulatory Commission (FERC), the terms "integrated hybrid resource," "co-located resources," and "mixed technology resources" are commonly used by industry members to refer to resources that "share a point of interconnection and incorporate two or more different resource types" (FERC 2021). Currently, various definitions and sub definitions for hybrid facilities exist. More specifically, HPPs and HESs are defined to varying degrees by different stakeholders. For example, FERC defines integrated hybrid resources as a "set of resources that share a single point of interconnection and are modeled and dispatched as a single integrated resource," and co-located hybrid resources as a "set of resources that are modeled and dispatched as two or more separate sets of resources that share a single point of interconnection." The *Hybrid Resources White Paper* published by FERC in May 2021 also acknowledges the current discussions surrounding definitions, and specifically mentions the differing definitions submitted by the various regional transmission organizations (RTOs) and independent system operators (ISOs) when seeking approval. For example, the Pennsylvania-New Jersey-Maryland Interconnection (PJM) uses terms such as "open-loop" and "closed-loop" systems when referring to HPPs. An open-loop system can use the grid to charge a storage component, whereas a closed-loop system charges the storage component with resources within the integrated or co-located hybrid plant (FERC 2021). Wind Europe defines a renewable HPP as "combining at least two renewable generation technologies sharing one single connection point to the grid and may include storage" (Graso 2020). For this report, we reference the International Energy Agency (IEA) Wind Technology Collaboration Programme Task 50 definition, which defines an HPP as "a combination of two or more electricity generation and/or storage technologies, used to provide electrical power services that are coordinated at a single point of connection."

A similar discussion on taxonomy exists around HESs. For example, a report proposing HES taxonomy by Murphy, Schleifer, and Eurek, titled *A taxonomy of systems that combine utility-scale renewable energy and energy storage technologies*, describes hybrid energy systems as "…projects comprising multiple technologies that could also be deployed separately (or independently)" (2021). For this report, we define an HES as "one or more HPPs, which provide(s) an energy and/or nonenergy product such as electricity, hydrogen, heat, or fresh water to accommodate specific end-use needs" (Das and King 2023). While the definitions of HESs differ because of the perspective or applications which they are derived from, the foundational concept of combining multiple technologies for a specific purpose, that may include the production of electricity or other energy products, remains. The definitions chosen for this report are not meant to interpret the current discussions around standardization of the terminology, but rather provide a baseline understanding and reference.

1.1.2 Types of Hybrid Facilities

Hybrid facilities are highly customizable for specific end uses through plant design, controls, and operations. This customizability provides a broad range of features and unique plant characteristics that can be accommodated for each specific end use.

HPPs can be categorized into two different types: generation or storage. A generation-type HPPs uses two or more generation technologies that are integrated into the same plant. This hybrid type most commonly includes renewable energy generation technologies; however, the integration of traditional energy sources, such as natural-gas and diesel generators, have also been deployed. Solar-and-wind-generation-type HPPs are currently the most anticipated configuration for future renewable HPP development due to their complementary generation profile (Clark et al. 2022; Harrison-Atlas et al. 2022). Using technologies that have complementary, or negatively correlated, generation profiles allows these types of HPPs to increase the capacity factor of the power system and provide more consistent energy (Schleifer et al. 2023). An example of negatively correlated complimentary resources would be a location where solar is the primary generation source during the day and wind is the primary generation source during the night. Additionally, through co-locating complementary generation technologies, generation-type HPPs can unlock new project locations that would otherwise be considered economically challenging for single-technology development (Harrison-Atlas et al. 2022).

Storage-type HPPs are defined as at least one type of storage technology that is integrated into the plant, and paired with either a generation technology or another storage technology. These storage technologies can include, but are not limited to, electro-chemical storage such as lithium-ion batteries, physical batteries such as a pumped storage hydropower, and mechanical batteries such as compressed air storage. The integration of storage in an HPP can help with smoothing the electricity output and avoiding the curtailment, or loss, of excess electricity by storing it for later distribution. Additionally, if an HPP contains bidirectional storage or is paired with conversion components to operate as an HES, it can further help with providing grid resiliency, energy reliability, and other ancillary services by pulling electricity from the grid or pushing electricity to the grid in response to grid disturbances.

An HPP providing electricity to a facility that produces end-use products through conversion technologies is then referred to as a HES or a conversion-type HES. In a conversion-type HES, the electricity produced is then used in a conversion process to create a new product or vector (Ørsted n.d.), such as green hydrogen, ammonia, or freshwater. Conversion technologies have been identified as a key driver in helping decarbonize hard-to-abate industries, such as steel production and chemical processing, and are sometimes referred to as power-to-X applications. While the addition of a battery to an HES is not necessary for reaping the end-use benefits that hybridization is able to provide, storage can help with optimizing operations by ensuring consistent and reliable electricity flow into the conversion process.

2 Current and Future Hybrid Considerations

In recent years, decreasing costs of renewable generation and battery technologies, and increasing policy support have reduced barriers for deployment. The type of hybrid facility and location depends heavily on technology maturation and market drivers that will continue to factor into future deployment. The following section expands on the market drivers of hybrid development and provides a current snapshot and outlook of hybrid deployment.

2.1 Driving Market Factors

Two market drivers of HPPs are the decreasing costs and increasing policy support of renewable energy generation and battery technologies. These factors, over time, have driven the expansion of single-technology VRE projects and electro-chemical storage, which has helped increased hybrid deployment (Seel et al. 2022).

2.1.1 Decreasing Cost of Renewable Technologies

The growth of hybrids is underpinned by the broader deployment of renewable generation, driven by cost declines in solar and wind energy. According to Lazard, the historical mean unsubsidized levelized cost of energy (LCOE) of solar PV (-84%) and wind (-66%) have decreased substantially from 2009, making them two of the most cost-competitive energy sources on the market today (Bilicic and Scroggins 2023). As a result, VRE projects have proven to be more economical than traditional power plants in many locations. According to the *Annual Energy Outlook 2022*, it is anticipated that levelized costs of wind and solar will continue to decrease until 2050 (EIA 2022).

The combined effects of decreasing costs of renewable technologies, and various energy and emissions targets have influenced deployment trends in the United States. Renewable generation has been steadily growing, as shown in Figure 1, and has reached 21.5% of the U.S. generation share in 2022 (EIA 2021; Clark et al. 2022). Figure 1 shows the installed annual capacity from 2005 to 2021, illustrating that VRE sources such as solar and wind have increased their capacity substantially, more than tripling installed capacity since 2005. Solar increased its capacity by 21 gigawatts (GW) in 2021, followed by wind at 17.1 GW, leading to the increased capacity of renewable energy generation on the grid (EIA 2021).

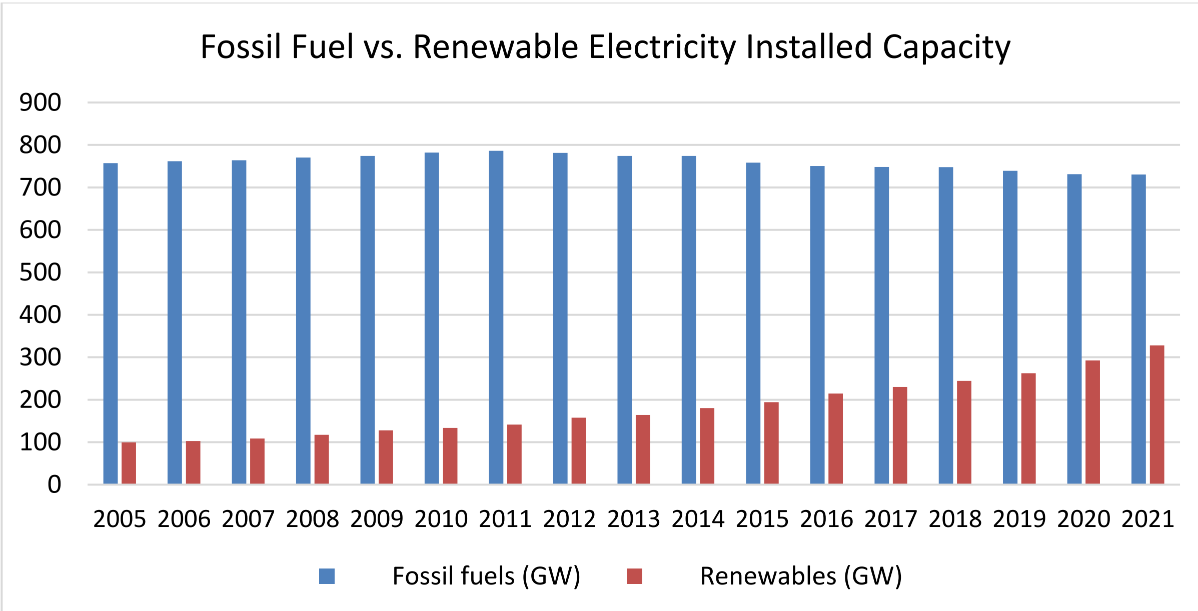

Figure 1. Fossil fuel vs. renewable energy electricity annual installed capacity from 2005 to 2021. ***Figure from EIA (2021).***

Note: GW = gigawatt

In recent years, declining costs have also made energy storage technology more economically feasible, allowing for increased deployment of storage-type HPPs. The cost of lithium-ion battery packs across all sectors declined from $1,306/kilowatt-hour (kWh) in 2010 to $151/kWh in 2022 (Feldman et al. 2023). Furthermore, the additional capital expenditure (CapEx) by combining storage and solar PV averages to approximately $10/megawatt-hour (MWh)-PV for a battery sized at half the PV capacity. In contrast, storage-plus-solar PV can allow for increased prices of $8–$21/MWh-PV depending on the region and dispatch assumptions (Gorman and Seel 2022). Increased revenue is achieved by dispatching stored solar power in periods of high demand and providing grid services that would not be possible without battery storage.

2.1.2 Increasing Policy Support

Hybrid development has been further facilitated through supportive policy and incentives. FERC orders, which include rules and guidance for regulating transmission and wholesale sale of electricity in interstate commerce, have lowered barriers to market participation for hybrid facilities, allowing for new revenue stream creation, interconnection approval processes, and participation in demand response services. Additionally, financial incentives on both the federal and state levels have helped offset the higher initial capital expenditures traditionally faced by renewable energy developers, which further encourages renewable energy and hybrid deployment. Some of the most significant policies that have supported deployment include:

- FERC Order 841 and 841-a
- FERC Order 845
- FERC Order 2222
- Inflation Reduction Act of 2022
- Bipartisan Infrastructure Law
- State-level policy support.

2.1.2.1 FERC Order 841 and 841-a

FERC Order 841 and 841-a direct RTOs and ISOs to create tariff revisions that allow storage resources to be bid into the energy markets in a way that is equitable to other power producers. Both of these FERC orders "ensure that a resource using the participation model for electric storage resources is eligible to provide all capacity, energy, and ancillary services that it is technically capable of providing in the RTO/ISO markets" and "account for the physical and operational characteristics of electric storage resources through bidding parameters or other means" (North American Electric Reliability Corporation [NERC] 2021). By allowing storage providers to bid into energy markets, new revenue streams have been created for the providers' services.

These orders ultimately incentivize additional energy storage technology integration, whether the technologies are stand-alone or integrated into a hybrid configuration, by making storage technology more financially feasible (FERC 2018a). Orders 841 and 841-a have also helped guide the taxonomy and configuration of hybrids by setting requirements for the state of charge and for the minimum run time for energy storage resources.[5]

2.1.2.2 FERC Order 845

FERC Order 845 acts as a revision to several provisions within the large generator interconnection agreement, which includes rules and protocols for any generator nameplate capacity larger than 20 megawatts (MW). The revisions in the 2018 order include but are not limited to:

- Expanding the definition of generating facility to include electricity storage
- Allowing for interconnection requests that are lower than the capacity of the generating facility
- Recognizing energy storage as an individual resource rather than making it adhere to the rules of generation technologies (FERC 2018b).

Regarding hybridization, this policy allows for more opportunities to co-locate generation technologies with energy storage. Before the passage of Order 845, a co-located generator and storage power plant would be studied in the interconnection queue as a sum of the two capacities. Now, the revisions allow for the facility to be studied based on the original generator capacity if the production stays below that at any given time. Not only does this revision to interconnection studies allow for an expedited approval process because it can be approved outside of an interconnection queue, but it also allows for use of the capacity that is not typically optimized using variable renewable sources. As a result of this order, interconnections with a capacity that is lower than the capacity of the generating facility will enable the hybrid facility to avoid potentially costly transmission upgrades for the developer and interconnection upgrades.

2.1.2.3 FERC Order 2222

Distributed energy resources (DERs) refer to "any resource located on the distribution system, any subsystem thereof or behind a customer meter," per FERC Order 2222. These DERs include but are not limited to "electric storage resources, distributed generation, demand response,

[5] In FERC Order 841, paragraph 29, "a resource capable of receiving electric energy from the grid and storing it for later injection of electric energy back to the grid" (FERC 2018a).

energy efficiency, thermal storage, and electric vehicles and their supply equipment" (Zhou, Hurlbut, and Xu 2021). The order allows for multiple DERs to be aggregated into a single virtual resource. Historically, DERs have provided benefits exclusively to the end-use customer who owns them. However, now these resources can participate in the capacity, energy, and ancillary service markets under the assumption that aggregated DERs are greater than the apportioned value of individual DERs. Additionally, RTOs and ISOs have some flexibility in how the rules are designed for DERs in specific markets, as long as double counting is prevented. One of the major motivators for the creation of FERC Order 2222 was to improve wholesale power markets to allow for a wider variety of price-responsive demand, which hybrids are capable of. A few additional key motivators to the creation of FERC Order 2222 are the increase of variable renewables leading to more power system flexibility and ancillary services, and the need for power system reliability (Zhou, Hurlbut, and Xu 2021).

FERC Order 2222 provides hybrid-applicable guidelines that help to:

- Maintain market neutrality
- Enhance market competition
- Ensure smooth operation.

2.1.2.4 Inflation Reduction Act of 2022

The IRA, which was signed into law in August of 2022, is the U.S' largest and most comprehensive clean energy bill, allocating nearly $370 billion for clean energy investments (U.S. Congress 2022; Satyapal 2022). The scope of the IRA expands beyond clean energy investments, however. The funding for clean energy is designed to decrease emissions, lower the cost of clean electricity, and reduce deployment barriers for continued clean energy production. Within this law, there are numerous policy incentives that could help drive hybrid facility deployment. The IRA includes previously existing policies that have been renewed or modified, as well as new innovative credits, including:

- The production tax credit (PTC) (provision 45) and its emissions-based technology-neutral PTC counterpart (technology-neutral PTC) (provision 45Y)
- The investment tax credit (ITC) (provision 48) and its emissions-based technology-neutral ITC counterpart (technology-neutral ITC) (provision 48E)
- The clean hydrogen production tax credit (H2 PTC) (provision 45V)
- The CCUS credit (provision 45Q).

The Inflation Reduction Act also includes other applicable policy considerations, including the 5X credit multiplier known as the prevailing wage and apprenticeship requirement (PWA), and bonus credits, including the energy community, domestic content, and low-income communities bonus credits. The IRA now makes credit stacking possible; therefore, facilities can claim more than one credit per facility, as long as these components are eligible for their respective credits. While these credits can be applied to single-technology projects, it is credit stacking that can allow hybrid facilities to leverage multiple policy incentives to have a greater impact on reducing clean energy costs.

Provision 45—also known as the PTC—is an electricity generation credit that expired prior to the enactment of the IRA. This PTC has historically been a technology-specific credit, often applied to wind generation technologies; however, the IRA has both renewed and modified this credit to apply to additional generation technologies. This credit has an initial rate of 0.3 ¢ per kWh in 1992 U.S. dollar (USD) valuation. The rate is then adjusted for inflation for every year of the 10-year duration that a facility claims the credit. Because this is a production-based credit, the PTC is best applied to a facility that is expected to have a high capacity factor or is located in an area with great resources. Provision 45 is set to expire at the end of 2024 and will be replaced with the technology-neutral PTC, also known as provision 45Y, on January 1, 2025. The technology-neutral PTC (45Y) is an emissions-based credit, and qualified facilities must have an emissions rate of zero or negative kilograms of carbon dioxide (CO_2) equivalent to be eligible to claim this credit. [6]

Provision 48, also known as the ITC, is a credit that allows the taxpayer[7] a percentage credit—which can vary between 6% and 50%, and even up to 70% under certain circumstances—of the total amount of capital expenditures that went into installing and constructing a facility, or for a specific component within a facility. If a facility elects the ITC, then it can claim this one-time credit within the first year it is operational. This credit is then reflected in the taxpayer's federal tax return. For wind-based projects, the ITC is often used for a facility or for components within a plant that is located in areas with suboptimal resources, or that require very high capital expenditure, installation, and construction costs, such as with offshore wind. The ITC prior to the IRA was also a technology-specific credit typically associated with solar; however, other technologies are now able to claim this credit. Further, storage with a minimum capacity rating of 5 kWh can claim the ITC credit. Storage can include for example, lithium-ion battery storage systems or hydrogen storage, such as salt caverns and aboveground storage, including pipes. The U.S. Department of the Treasury and the IRS have released new guidance in November of 2023 that allows the ITC to be applied to the storage component's grid interconnection costs for projects that do not exceed 5 MW (2023). The ITC is set to expire at the end of 2024, and will be replaced with the technology-neutral ITC (provision 48E) on January 1, 2025. The technology-neutral ITC (48E) is an emissions-based credit, and qualified facilities must have an emissions rate of zero or negative kilograms of CO_2 equivalent to be eligible.

Provision 45V, also known as the H2 PTC, is claimed for the hydrogen production process segment of a facility. This credit is emissions-based. The level of emissions from the hydrogen production process determines the eligibility for which credit value can be claimed. If the hydrogen production process uses renewable electricity, then the taxpayer can claim either the base full credit value of $0.60/kilograms (kg) of hydrogen, or the maximum $3/kg if certain workforce requirements are met by meeting prevailing wage and apprenticeship use requirements. Additionally, and as a result of the IRA, facilities that are qualified for the H2 PTC now have the option to elect the ITC in lieu of the H2 PTC. Provision 45V is not eligible for any bonus credits.

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[6] Definition according to the U.S. Environmental Protection Agency: A metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). Carbon dioxide equivalents are commonly expressed as "million metric tons of carbon dioxide equivalents ($MMTCO_2Eq$)." The carbon dioxide equivalent for a gas is derived by multiplying the tons of the gas by the associated GWP. $MMTCO_2Eq$ = (million metric tons of a gas) * (GWP of the gas). See greenhouse gas, global warming potential, metric ton. For more information, visit https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do;jsessionid=m8VBVf0qTDQxoMdOjr5mQG1A_zTdppdFIZN2iOz07nHcuTNJ5pkR!-1424961126?details=&vocabName=Glossary%20Climate%20Change%20Terms&filterTerm=Carbon%20dioxide%20equivalent&checkedAcronym=false&checkedTerm=false&hasDefinitions=false&filterTerm=Carbon%20dioxide%20equivalent&filterMatchCriteria=Contains

[7] Person or business entity subject to tax under an applicable law.

Provision 45Q, which is the CCUS credit, offers a credit of $17/ton or $85/ton of emissions that are captured, used, or stored, depending on whether the qualifying facility meets PWA requirements. This credit is applied for 12 years and cannot be stacked with the H2 PTC (45V); therefore, only one credit can be claimed by a taxpayer. The CCUS 45Q credit can be applied to plant configurations that use a steam-methane reforming process that produces blue hydrogen. This process is the baseline to which other green hydrogen production processes are compared. However, this credit can be claimed with the technology-neutral PTC (45Y) and ITC (48E) once these credits become active on January 1, 2025.

In addition to the various policies and tax incentives that have been made possible by the IRA, there is also a 5X credit multiplier that is relevant within the hybrid facility scope. The PWA requirement, if met by the taxpayer, increases applicable credit values by 5X. This credit multiplier applies to provisions 45, 45Y, 48, 48E, 45V, and 45Q. To claim the 5X credit multiplier, the taxpayer must pay prevailing wages and make sure that a percentage of the workforce used in the construction, operations, and repair of a facility comprises apprentices from registered apprenticeship programs. If a facility is electing to use an ITC or PTC, then they must meet PWA requirements for 5 years or 10 years, respectively.

Additionally, there are two different bonus credits that apply within the HPP context. These bonus credits apply to provisions 45 and 48, as well as to their technology-neutral counterparts (45Y and 48E) on January 1, 2025; however, the bonus credits do not apply to the H2 PTC (45V) and the CCUS (45Q) credit. Furthermore, these bonus credits are eligible for the 5X PWA credit multiplier. If a facility meets PWA requirements, then the bonus credit values increase from 2% to 10%. The first identified bonus credit is the domestic content bonus credit, which requires that 100% of all the steel and iron used for the construction of a facility is sourced domestically. The second is the energy community bonus credit, which requires that a facility be located in an area that meets at least one of the following requirements:

- The unemployment rate is greater than or equal to the national level, or 25% local tax revenue is generated from oil and gas.
- The area experienced a coal mine closure or a coal power plant retirement.
- The area is a current brownfield site.[8]

There is also a third bonus called the low-income communities bonus credit; however, this credit only applies to projects rated less than 5 MW of total capacity. As a result of the capacity limitation, it is unlikely this credit will be eligible for HPPs because the capacity ratings of the plants are expected to exceed 5 MW.

2.1.2.5 Bipartisan Infrastructure Law

The Infrastructure Investment and Jobs Act, better known as the Bipartisan Infrastructure Law (BIL), indirectly supports the deployment of HESs by allocating $9.5 billion for accelerating hydrogen deployment (The White House 2022).

[8] "A brownfield is a property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant." (U.S. Environmental Protection Agency 2023).

A large portion of BIL funding has been allocated for accelerated deployment of hydrogen. This funding includes $8 billion, as part of the U.S. Department of Energy (DOE) H2Hubs program, of which $7 billion has been allocated specifically to accelerate the development of clean hydrogen technologies through the establishment of 7 clean hydrogen hubs (Office of Clean Energy Demonstrations n.d.). Of these clean hydrogen hubs, the law mandates that a variety of different electricity generation technologies to produce hydrogen are independently demonstrated as separate H2Hubs, including hubs that generate electricity from nuclear energy, fossil fuels with capture, utilization, and storage (CCUS) technology, and renewable energy. The BIL allocates $1 billion in funding to reduce hydrogen production costs, with the goal of achieving the DOE cost target of less than $2 per kilogram by 2026. The final $500 million is allocated for research, development, and demonstration projects for manufacturing processes that can use clean hydrogen production to meet miscellaneous end-use demands. All of these projects may support the long-term growth of HPPs and HESs.

Furthermore, according to analysis conducted by NREL on the combined impacts of the BIL and IRA, both together can increase clean electricity shares—which includes nuclear, fossil fuels with CCUS, and renewables—up to 71%–90% of total generation by 2030, and can increase the cumulative average annual combined deployment rate of wind and solar from 44 GW per year to 93 GW per year over the coming decade. The report concludes that both the BIL and IRA "… have the collective potential to drive substantial growth in clean electricity by 2030," (Steinberg et al. 2023). The combined impact of the BIL and IRA show that policy can drive increased renewable generation deployment that could also encourage hybridization.

2.1.2.6 State-Level Policy Support

Hybrid development has been broadly supported by state-level policies that incentivize the adoption of VRE technologies with energy storage. Currently, state-specific policy addresses residential- and commercial-scale projects. According to the National Conference of State Legislators, "Renewable Portfolio Standards (RPS) require that a specified percentage of the electricity utilities sell comes from renewable resources" (2021). As a result of states requiring electricity suppliers to provide a minimum percentage of electricity sales from renewable resources to customers, the adoption of VRE resources has increased. Through states' RPSs, there are opportunities for continued policy development that explicitly address utility-scale hybrids—which often have larger nameplate capacities or are labeled "front of the meter" facilities—to further support deployment. In the following material, we outline examples of state policies to support hybridization and energy storage.

In Hawaii, the Hawaii Electric Company—the integrated utility for Oahu—offers upfront cash bonuses as well as ongoing monthly bonuses to residential and commercial properties that add energy storage to new or existing rooftop solar systems. This bonus system is approved by the Hawaiian Public Utility Commission and is capped at 40 MW of total storage capacity in Oahu and 15 MW in Maui (Hawaiian Electric 2023a). Further, the utility is explicitly planning for hybridization in its Integrated Generation Plan (Hawaiian Electric 2023b).

Oregon also had a rebate program for combined residential solar and storage systems. Although the funding has already been used, $14 million was allocated through a subsidy program that reduced the initial installation costs of these systems and that further helped the deployment of hybrids (Oregon Department of Energy 2023).

Similarly, in California, the policy emphasis is on the adoption of combined solar power and storage on the residential and commercial levels. California's building standards require that all new residential and commercial construction include both solar power and storage scaled to the size and energy needs of the building (California Energy Commission 2022). For utility-scale storage, California has removed the requirement that these projects also be approved by local authorities (California Legislative Information 2022). This change is likely to accelerate the development of storage and hybridization. Previously, gaining approval from local legislative bodies extended development timelines; therefore, this revised requirement has simplified the process of adding storage to existing single renewable energy plants. Further, the initial adoption of storage projects in California was supported by a procurement mandate that requires major utilities to deploy 1.35 GW of storage that is procured by 2020 and to come online before 2024 (California Legislative Information 2022).

Renewable portfolio standards vary on a state-by-state basis and are not adopted across all states in the United States. However, in the states which have established RPS goals, the increased requirement of leveraging renewable generation technologies can indirectly benefit the continued deployment of hybrid facilities. Renewable portfolio standards have been a strong driver in the deployment of standalone renewables and combined analysis by NREL and Lawrence Berkely National Laboratory has indicated that existing RPS policy could require 122 GW of renewables by 2050 (2016). It is likely that this anticipated growth of standalone renewables as a result of RPS targets might indirectly support the continued hybrid growth due to the synergetic nature of pairing complementary renewable resources within a hybrid configuration.

2.1.2.7 Future Policy Outlook, Gaps, and Opportunities

Due to the novelty of hybrids, supportive policy is essential to successfully implementing these technologies into the market. However, uncertainties surrounding market conditions, changing technologies, and changing administrations make creating effective policy difficult. The policy incentives that have been identified in the previous section are expected to have a major impact on end-use costs. However, it is unclear how future energy policy might shape the deployment of hybridization and it is also unclear whether there will be any additional policy frameworks designed to continue clean energy deployment once the IRA policy incentives expire.

Currently, at the state level, there are no major policies to encourage the adoption of grid-scale hybrid facilities, or the adoption of battery storage, which is likely to be a key component of hybrids. Historically, state policies have been a major driver of renewable energy adoption, particularly with renewable portfolio standards. The introduction of storage portfolio standards, such as the policy California implemented in 2020, could be adopted in other states. These standards can potentially support increased deployment of storage in other states, that can indirectly help drive the continued growth of hybrid facilities paired with storage.

There are a lot of uncertainties around how hybrids will continue to mature, and how future policy may impact the deployment of such plants. Although there are uncertainties, current policy efforts, in addition to the U.S. emissions and energy targets, are driving stakeholders to consider hybridization as a catalyst to help achieve these targets.

2.2 Current and Future Status of Hybrid Power Plants

The HPP pipeline and installed capacity are continuing to grow in the United States, in part, supported by favorable market conditions, policies, technological improvements, and also because they can circumnavigate long interconnection queues. The increase in HPP deployment is expected to continue into the coming years, and even more deployment is expected for the already dominant PV-plus-storage configurations. Three things that will be important to continue this upward trajectory are clarity around market participation, configuration optimization, and further cost reductions. This section focuses specifically on hybrid power plants and not on HESs due to the fact that HPPs are currently more prevalent in deployment.

2.2.1 Current Status of Hybrid Power Plants

Currently, co-located and integrated plants, including PV hybrid, wind hybrid, and fossil hybrid plants, are operational throughout the United States, although trends in development differ across regions. By the end of 2021, there were 298 operating plants with a generating capacity of 35.9 GW and a storage capacity of 3.2 GW. The PV-plus-storage HPPs are the most abundant configuration, with 140 operational plants across the U.S in 2021, and nearly 2.2 GW in storage capacity, as shown in Figure 2. Massachusetts contained the largest number of PV-based HPPs, with 54 plants total. Of those, 49 are PV plus storage, also shown in Figure 2. Nationally, greater than 90% of all HPP facilities in the current hybrid development pipeline comprise PV and storage, which illustrates this configuration's dominance in the U.S. market (Bolinger et al. 2022).

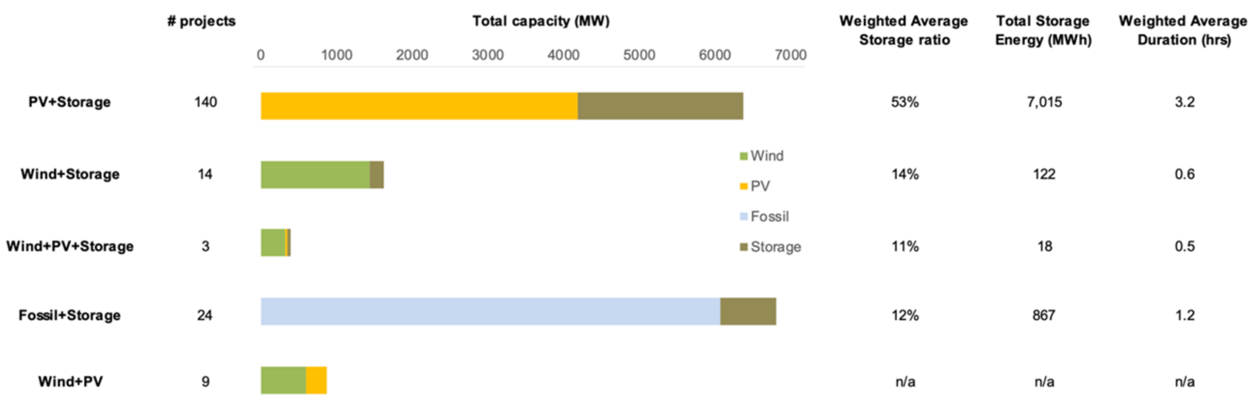

Figure 2. Hybrid power plant projects that were online at the end of 2021. ***Figure from Bolinger et al. (2022)***

Despite wind-based HPPs being relatively uncommon across the United States, there were 14 wind-plus-storage plants, 9 wind-plus-PV plants, and 3 wind-plus-PV-plus-storage plants operating at the end of 2021 (Bolinger et al. 2022). Texas contains 5 of the 10 largest wind-based HPPs by wind capacity, with most of these plants configured as wind plus storage (Figure 3), although wind-plus-storage HPPs experienced stagnated overall growth in 2021. Of the 24 fossil-plus-storage HPPs across the country in 2021, California had 9 installations, which was greater than any other state. Additionally, small amounts of PV have been retrofitted onto fossil-fuel plants across the country (Bolinger et al. 2022). Overall, HPPs are continuing to increase in the percentage share of total generation capacity connecting to the grid. The cost of energy technologies, policy support, and resource abundance will continue to help guide the future development of HPPs (Seel et al. 2022).

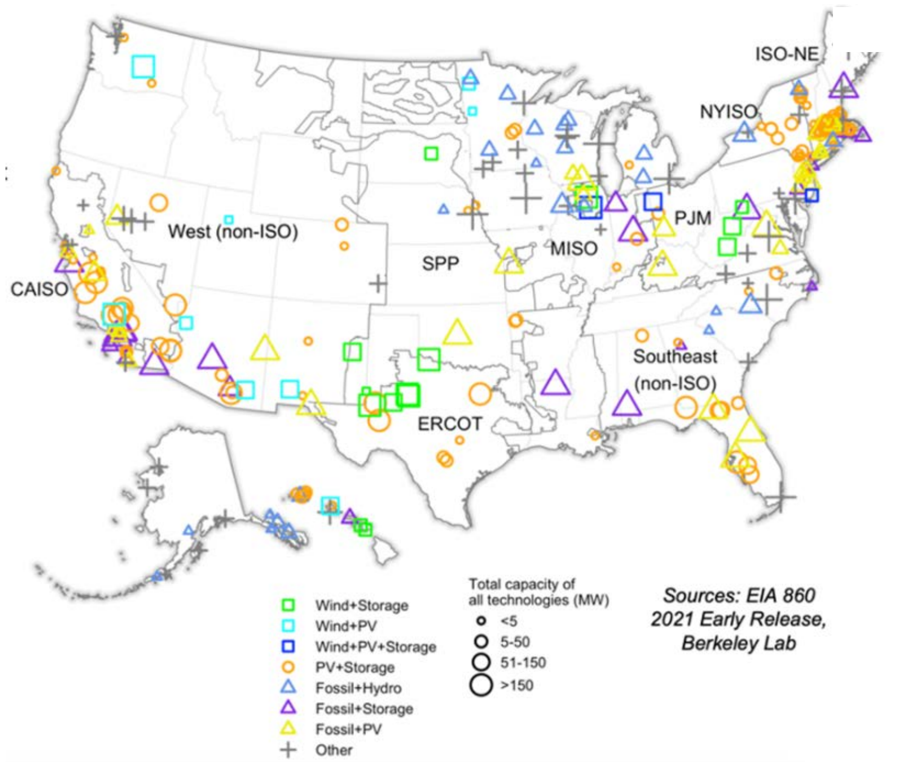

Figure 3. The locations of current operating hybrid power plants as of the end of 2021. ***Figure from Bolinger et al. (2022)***

2.2.2 Future Status of Hybrid Power Plants

In recent years, the number of HPPs in development has grown (Seel et al. 2022). As indicated in Figure 4, HPPs have increased their share of capacity in interconnection queues. Specifically, it shows that, in 2021, HPP configurations comprised 42% solar projects and 8% wind projects. Furthermore, all of the proposed HPP projects have requested to come online before 2026, which might suggest that there will need to be an increased rate of deployment in the upcoming years (Bolinger et al. 2022). However, while HPPs consist of a large portion of the queue, not all of the projects will be built. Lawrence Berkeley National Laboratory research indicates that there are currently a variety of HPP configurations that are viable in the market today; however, the optimal configuration of HPPs will depend highly on location and time at which electricity is discharged (Gorman 2021). As of 2021, nearly 90% of all known hybrid generation capacity in the queue was in the PV-plus-storage configuration, which forecasts a continued dominance of these technologies over the HPP market share, shown in Figure 4. Additionally, the next largest configuration in the queue is wind plus storage. Both of these HPP configurations suggest that the pairing of storage with VRE technologies will continue to be a key plant characteristic for future HPP deployment (Bolinger et al. 2022).

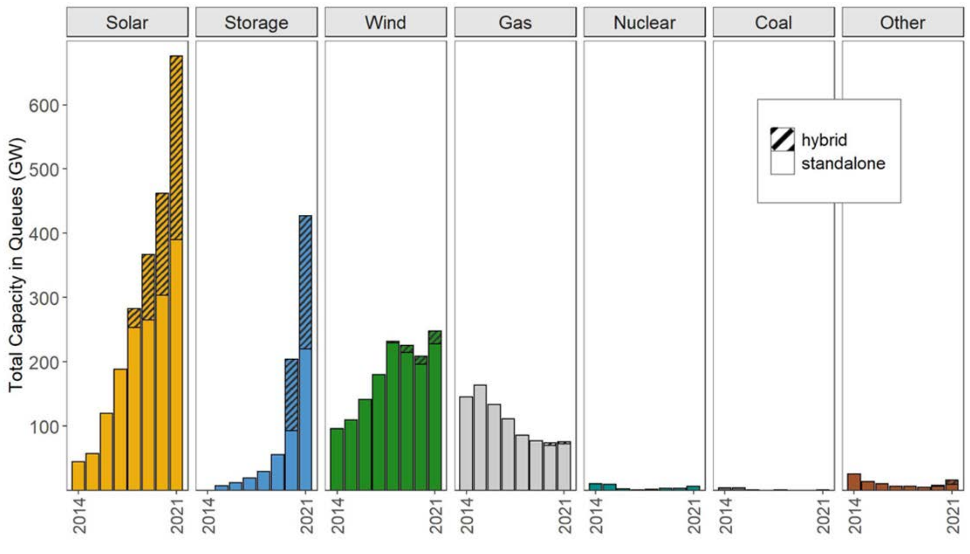

Figure 4. Capacity in interconnection queues as of the end of 2022. ***Figure from Rand et al. (2022)***

As technologies mature, it is likely that there will be a proliferation of different types of hybrid configurations. Furthermore, with an increase in variable generation from single-technology VRE resources, the deployment of wind-plus-PV-plus-storage plant configurations could increase due to their ability to realize higher capacity factors (Fasihi and Breyer 2020). Beyond utility-scale HPPs, there is also increased development potential for behind-the-meter HPPs. Both California and Hawaii have adopted policies to promote solar and storage behind-the-meter HPPs, which sets the foundation for other states to replicate this type of policy framework, as market conditions allow.

In addition to technological improvements and shifting market demands, further adoption of HPPs is likely to be driven by the continuing declining costs of generation and storage technologies. NREL’s Annual Technology Baseline modeling indicates that utility-scale solar PV could decline from an LCOE of $39.2/MWh in 2023 to $18.4/MWh by 2050 in the moderate scenario. Similarly, the LCOE for land-based wind energy could decline from $29.7/MWh in 2023 to $18.8/MWh by 2050. The potential continued decreasing LCOE of solar and wind could drive continued deployment of HPPs by increasing the economic competitiveness of renewable technologies. Additionally, the deployment of HPPs is likely to be further accelerated by the decline in the LCOE of PV plus storage, which is expected to decrease from $93.1/MWh in 2023 to $51.4/MWh in 2050 (-44.7%) (NREL 2023).

Although HPPs are projected to increase in generation capacity, realizing the benefits and mitigating the challenges of HPP development is still essential for successful deployment.

Currently, PV-plus-storage is the most common HPP configuration. Despite PV-plus-storage making up the majority of queue, it is expected that every project will not come to fruition. Furthermore, the estimated cost declines in all renewable technology adds to the uncertainty of which configuration will become the most common. Through optimizing the configuration of HPPs for specific locations and end uses, developers and consumers of HPP electricity and byproducts can maximize the benefits associated with these respective technologies.

3 Benefits, Challenges, and Complexities

As demonstrated by the increasing development pipeline, hybrids offer many benefits that are not realized with single-technology VRE resources. The location of a hybrid facility, in addition to the technologies used within the plant configuration, will dictate what project variables can be optimized to meet specific stakeholder needs. Some of the benefits can include, but are not limited to the following, which we discuss in greater detail in the following sections:

- The decarbonization of hard-to-abate end-use sectors by replacing emissions-intensive energy processes with zero-emissions technologies
- Increasing energy reliability and grid resilience, when compared to single-technology VRE resources
- Decreasing the reliance on constrained grid infrastructure while leveraging suboptimal resources to expand project development opportunities and minimize the land usage on a project-by-project basis
- Newly introduced revenue streams for project developers
- Potential cost savings for developers and ratepayers.

However, due to the novelty of hybridization, there are still challenges that need to be addressed for the full value of HPPs and HESs to be realized. Historically, multiple VRE resources have not been operated as a single resource; therefore, as hybridization continues to mature, complexities regarding market participation and design optimization remain uncertain. Additionally, technologies used within certain HPP or HES configurations are still relatively expensive, when compared to their traditional counterparts. While these factors remain barriers to widespread adoption, hybrids have the potential to be key in achieving the U.S. decarbonization and renewable energy targets while maintaining adequate energy and grid services.

3.1 Customizability for End Use

One of the most unique benefits of hybridization is the ability to be customized to support a variety of end-use technologies and functions. Whether it is integrated into industrial facilities, single-family homes, or remote locations, hybrids can be optimized to help provide for the energy needs of the consumer. Historically, VRE generation technologies have often posed a challenge for integrating clean energy into end uses because of fluctuating generation profiles. With the energy and grid services provided by hybridization, consistent green energy can be integrated into transportation, buildings, and heavy industry like steel manufacturing.

3.1.1 Green Hydrogen Production

To produce green hydrogen, an HES is paired with an electrolyzer that supplies clean electricity for the electrolysis process (Hydrogen and Fuel Cell Technologies Office n.d. a). Green hydrogen can be further used in a variety of end products. One such product is carbon-free electricity, which is generated by using hydrogen to power a fuel cell. Hydrogen fuel cells are currently being used to decarbonize the transportation sector. They provide an alternative clean fuel source for vehicles, vessels, and aviation. Additionally, green hydrogen may play a future role in providing reliable green energy alternatives for homeowners and tenants for residential heating, however significant technical and economic hurdles remain. A trial study is currently underway in the United Kingdom to understand the viability and feasibility of using hydrogen to provide heating for buildings (Department for Energy Security and Net Zero 2023).

With the addition of energy storage to a HES, more consistent and reliable electricity can be supplied for producing green hydrogen. By providing a steady electricity supply, the ramping or variability in the electricity generation can be decreased, which then reduces strain on operations downstream from electricity production. Not only does introducing a battery help with conversion and production services, but it can also help extend a plant's operational life and reduce operations and maintenance costs by sustaining a longer life cycle for an electrolyzer stack. Analysis has indicated that an inconsistent supply of electricity can accelerate degradation, thus increasing performance loss and reducing an electrolyzer stack's life expectancy (Alia, Stariha, and Borup 2019). Therefore, a battery's ability to counteract the variable nature of renewable electricity through a HES can help to greatly reduce capital and operational expenditure costs. Furthermore, maintaining a consistent flow of electricity into an electrolyzer, when integrated with storage or with complementary resources (such as wind paired with solar) enables a higher utilization rate. The higher utilization rate results in more hydrogen production over a given period of time. By increasing the efficiency of electrolyzer production, a project can leverage a smaller electrolyzer to produce the same amount of hydrogen (Papadopoulos et al. 2018). Given the increased costs of larger nameplate capacity electrolyzers, developing a HES that optimizes hydrogen production with a smaller electrolyzer can represent a large costs savings for the project.

The benefits of a HES that produce green hydrogen are also illustrated through the financial support offered from DOE. As previously mentioned, DOE has allocated up to $8 billion to help establish seven regional hydrogen hubs throughout the United States. The Regional Clean Hydrogen Hubs (H2Hubs) program will create new hydrogen networks of production, supply, demand, storage, and other value-added innovative end uses. These hydrogen hubs are an example of large-scale HESs that comprise a complex network of hydrogen producers and consumers, and newly added local infrastructure to help accelerate and rapidly mature the hydrogen market in the United States. These H2Hubs are an example of how the hybridization of technologies can unlock new markets in which hybrids can support new end uses. According to DOE, these large-scale hybrid hubs would provide "another pathway for decarbonizing heavy industry and transportation" (Office of Clean Energy Demonstrations n.d.).

In addition to the H2Hubs program, DOE has announced the Hydrogen Shot goal of reducing the cost of green hydrogen to $1/kg in one decade (Hydrogen and Fuel Cell Technologies Office n.d. c). Together, the H2Hubs initiative and the Hydrogen Shot goal are closely aligned with power-to-X end uses. The Hydrogen Shot goal can be achieved by leveraging HESs, such as H2Hubs, to unlock greater cost savings on a $1/kg basis for clean hydrogen. The increased cost savings help reduce deployment barriers to large-scale HPPs and HESs.

Another focal point for large-scale regional clean hydrogen hubs has been the Advanced Clean Energy Project 1, located in Delta, Utah. This is a large-scale hydrogen storage project with a seasonal storage capacity of 300 gigawatt-hours. The project will use 220 MW of clean energy to produce 100 metric tons of green hydrogen per day, which will be stored in two large salt caverns (ACES Delta 2021). This is a billion-dollar project that has received a loan guarantee from the DOE Loan Program Office for $504 million, which is also the first loan guarantee offered since 2011 and the first for a hydrogen project (DOE 2022). Another project that is worth highlighting is a $4-billion gigawatt-scale wind-to-hydrogen hub in Houston, Texas. This project is a joint collaborative effort with the utility provider AES along with the industrial gas company, Air Products. The project comprises 1.4 GW of wind and solar generation and a hydrogen production capacity of 200 metric tons per day (AES 2022). The announcement of these large-scale projects illustrates the growing importance and advantages that HPPs and respective HESs can provide for end uses through conversion and power-to-X services.

3.1.2 Green Ammonia Production

HESs can also be used to produce zero-carbon ammonia by integrating with a conversion process known as the Haber-Bosch process. The Haber-Bosch process is the main industrial process for producing synthetic ammonia, which is achieved by combining nitrogen and hydrogen at a high pressure and relatively high temperature (National Energy Technology Laboratory n.d.). Currently, most of the hydrogen used in the Haber-Bosch process is produced with natural gas, oil, or coal as feedstock into a steam-methane reforming process, which is highly energy- and carbon-emissions-intensive (Hydrogen and Fuel Cell Technologies Office n.d. b). Therefore, to replace the conventional steam-methane reforming process, green hydrogen can be used as an alternative emissions-free feedstock within the Haber-Bosch process to produce green ammonia. As mentioned in Section 3.1.1, one way that carbon-free electricity can be produced for the electrolysis process is through integrating with a HES.

The green ammonia production process helps decarbonize the manufacturing process of end-use products such as chemicals and fertilizers. Additional uses of zero-carbon ammonia include using it to replace bunker fuel, which can decarbonize ocean freight shipments, providing long-term energy storage in the electricity system, and offering a more cost-effective method for transporting hydrogen (Global Maritime Forum 2020; The Royal Society 2020).

3.1.3 Green Desalination for Freshwater Production

HESs can also provide clean electricity for desalination processes to produce fresh water. Desalination is an energy-intensive process that, according to DOE, "removes salts and other minerals from water to make it suitable for human consumption, irrigation, or industrial uses." The two most common desalination methods are thermal-based and membrane-based processes (DOE's Office of Energy Efficiency and Renewable Energy [EERE] n.d.) Both techniques are energy-intensive, and are traditionally supported by traditional generation technologies because of their ability to provide firm power.[9] Hybridization can replace traditional generation sources by providing consistent electricity by pairing VRE technologies with complementary generation profiles found with PV and wind, or by integrating with dispatchable energy storage technologies. Therefore, hybrids can provide a decarbonization pathway for freshwater production that has typically not been achieved by single-technology VRE sources or traditional energy generation sources like coal, oil, and natural gas. Because of climate change, extreme weather events like droughts are emphasizing the need for decarbonized freshwater production. HESs integrated with desalination units can support the production of potable water for residential and municipal uses, ultimately helping reduce freshwater insecurities in many geographic locations. For example, in both Carlsbad, California, and Tampa Bay, Florida, two areas that typically face freshwater scarcity, desalination plants have been built that use the

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[9] Firm power, according to the IEA is defined as, "power or power-producing capacity, intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions" (U.S. Energy Information Administration n.d.).

abundant nearby seawater as feedstock to provide drinking water to the surrounding areas (Carlsbad Desal Plant 2017; Tampa Bay Water n.d.).

In addition to residential applications, fresh water produced by co-locating a HES with a desalination unit could supply fresh water to industrial processes. Currently, research is being done on the feasibility of pairing offshore wind energy generation with green hydrogen production. By co-locating offshore wind and electrolysis, costs savings may be realized due to shared resources and limited efficiency losses (Greco, Heijman, and Jarquin-Laguna 2021). Because of the remote location of offshore wind turbines, there is a lack of access to fresh water for use during the electrolysis process. However, to overcome this challenge, offshore wind turbine HESs integrated with a desalination unit could use nearby seawater to produce fresh water as feedstock for green hydrogen production.

3.2 Value in Energy and Grid Support

Compared to single-technology VRE sources, HPPs not only can provide power that is more reliable but can also increase grid resiliency. We define reliability in electric systems as ensuring "sufficient, uninterrupted electricity is provided to all customers in nominal operating conditions, or conditions for which that system was designed" (Clark et al. 2022). Resilience, however, is a characteristic of the system in extreme conditions. Energy reliability can be measured through metrics such as power smoothing, loss of load, and power fluctuations. Similarly, resilience can be measured through an electricity system's ability to supply load (Clark et al. 2022). The following sections detail how hybrid power plants specifically, can provide energy reliability and contribute to grid resiliency.

3.2.1 Energy Reliability

To maintain reliability, the grid operator must match demand for electricity with supply generated at a specific frequency on a second-by-second basis. Historically, grid operators have done this with traditional power sources that not only can provide baseload power consistently, but ramp up and down quickly to meet variable demand needs. Baseload power is defined as "the minimum amount of electric power delivered or required over a given period at a steady rate" (EIA n.d.). Further, the ramp rate of a power source is defined as "the speed at which a generator can increase (ramp up) or decrease (ramp down) generation" (EERE 2011). VRE technologies present challenges in providing baseload power and electricity at peak demand times, due to their dependence on fluctuating resource abundance. However, HPPs that include energy storage technologies, as well as standalone storage facilities, can enable ancillary services by providing load-shifting capabilities and maintaining system frequency, which ultimately helps compensate for the challenges faced by single-technology VRE plants.

Electricity generation from VRE sources is often misaligned with electricity usage and is highly dependent on the time and location of the renewable resources. Currently, during the times when the electricity load cannot be supported by VRE sources, traditional energy sources must be used to meet demand. However, traditional energy generation technologies cannot cycle up and down fast enough to compensate for the extreme fluctuations in load. Furthermore, cycling traditional generation facilities on and off is very expensive and deteriorates machinery over time. Therefore, despite an overproduction of low-cost renewable energy in many locations during the day, traditional generation sources must be continuously run, resulting in curtailed, or wasted, electricity. One example of the misalignment between electricity generation and use is shown in California's load curve (Figure 5), known as the, "duck curve" (Jones-Albertus 2017). The net load is calculated by subtracting the forecasted load and forecasted supply of VRE sources like wind and solar. As the penetration of variable renewable energy sources increases, the fluctuations between load and renewable energy supply become more extreme. In California's case, there is an adequate amount of renewable energy production in the middle of the day, as displayed by the lower half of the curve, but that amount wanes as evening approaches, as shown by the steep increase in Figure 5.

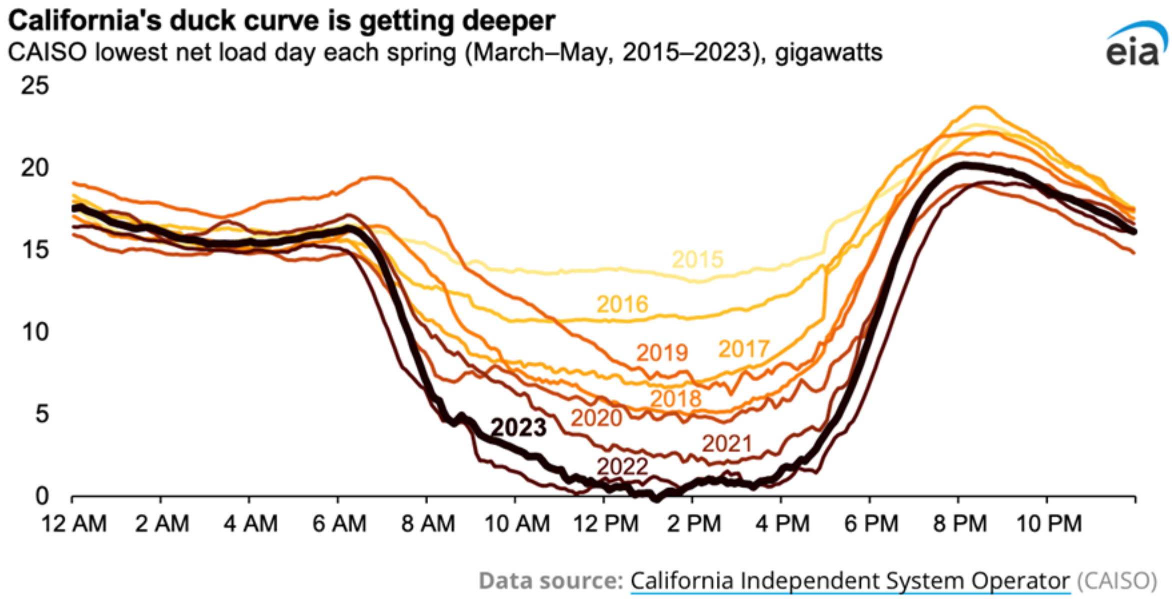

Figure 5. The evolution of California's duck curve as more solar capacity has come online in California. ***Figure from EIA (2023)***

Integrating battery storage within a hybrid power plant can increase reliability through grid firming.[10] For example, by integrating battery storage within an HPP, overproduction of solar generation during the day can be stored and then used when there is an insufficient amount of supply in the evening. This approach helps provide load smoothing in the system, and allows for consistent clean electricity generation. In addition to storage technology, hybrids can manage variable resources to supply reliable energy by pairing technologies with negatively correlated generation profiles, such as wind and solar, in most of the United States. Complementary sources within hybrid facilities can provide an electricity output with less extreme fluctuations, allowing for more reliable energy production, even in the absence of a storage component.

An additional challenge with adding large volume of renewables to the grid is accounting for the drop in the inherent inertia of the grid. System inertia is the ability of a system to oppose frequency changes due to resistance provided by rotating masses, such as synchronous generators, condensers, and motor loads (National Renewable Energy Laboratory n.d.[b]).

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[10] Grid firming, capacity firming, or renewable firming is widely used to keep the grid stable through resource intermittency (wind, solar, or hydroelectric).

Current research is exploring the reliable control of low-inertia power systems, such as grid-forming inverter controls.

Furthermore, HPPs can be paired with storage technologies to increase a plant's ability to perform frequency response. According to NERC, frequency response capabilities are defined as a plant's ability to "respond to underfrequency events while still operating the renewable component at maximum available power (given appropriate interconnection practices and agreements) as well as bringing some certainty to providing this service" (2021). The rate of change of frequency (ROCOF), or how fast frequency changes following a sudden imbalance in load, is one of the main characteristics used to determine the system's ability to respond to frequency changes. If ROCOF increases, meaning that the frequency of the grid is dropping too quickly, then frequency stability can become a risk to energy reliability. One way that ROCOF increases is by decreasing the system's inertia. With increased penetration of variable renewable energy sources, the initial ROCOF will increase as synchronous generators are displaced by inverter-based resources, such as solar PV. Critical inertia is the minimum level of system inertia needed to ensure responsive services—like fast frequency response—are able to stabilize the system. Inverter-based resources typically do not provide fast or primary frequency response, therefore increasing the penetration of these resources on the grid also increases the risk of the system reaching its critical inertia point (NERC 2020). The standard ROCOF value is <0.5 Hz/s, though in very low inertia systems it is predicted that it could reach >4 Hz/s, which is a substantial shift. As the share of renewables increases on the grid, the ROCOF value is expected to increase as well. For example, in Ireland, where there is a large share of renewables deployed on the grid, the ROCOF capability required by the grid code was raised to 1.0 Hz per second in 2015 (IRENA 2022). Both, ROCOF and critical inertia are correlated, where a system with low critical inertia will result in a high ROCOF and a higher fast frequency response requirement. Therefore, finding resources that can provide quick frequency response services has become more important in securing energy reliability.

Storage-type, alternating-current-coupled HPPs, however, can provide fast frequency response services that offer a solution to the frequency response problem that is typically introduced through single-technology variable renewable energy resources. Storage technology can charge and discharge rapidly, which allows storage-type HPPs to respond to quick changes in frequency disturbances on the grid. Currently, solar PV alone would not have this capability because there are no synchronous generators, and wind turbines cannot provide sustainable frequency responses. Optimizing the configuration and resources within the HPP to allow for fast frequency response and to achieve the required sustained time can help provide energy reliability services. Such advantages further exemplify the benefits of HPPs.

3.2.2 Energy Resiliency

With the increasing negative effects of climate change, ensuring grid resiliency during low-probability, high-impact, extreme events is important in maintaining energy supply levels. Hybrid power plants, especially storage-type HPPs, are technically able to perform many ancillary services; however, research into the financial incentives and market participation of resiliency-focused inverter-based resources is newly emerging (Kim et al. 2023). Therefore, quantifying the exact value that HPPs can provide to resiliency is challenging. Previous research has demonstrated that HPPs have the potential to provide resiliency services through capabilities including, but not limited to, black-start and islanding microgrids.

A black-start resource is a "generation asset that can start without support from the grid" (Jain et al. 2020). Historically, black-start capability has been provided by synchronous machine-based power plants; however, with increasing inverter-based resources on the grid, many of the synchronous machine-based power plants typically used for black-start capabilities are being retired. Pilot projects have demonstrated how battery energy storage can be used to start a generator during a black-start event (Colthorpe 2017). Furthermore, NREL modeling has evaluated how multiple inverter-based resources can drive a black start of a motor ("Grid-Forming Inverter Controls" n.d.). This research illustrates the possibility that HPPs, especially with integrated storage components, can quickly restore power to the local grid under certain conditions. Additionally, stand-alone HPPs within a microgrid have been explored as a promising opportunity for promoting grid resiliency.

Islanding is defined as a situation in which distributed energy resources can interact with one another to supply power to a load, even if utility electricity service is unavailable (Federal Energy Management Program 2021). Hybrid power plants have the technical ability to help supply generation to load when the microgrid needs to be islanded, ultimately increasing the resiliency of the area to an extreme event.

Although hybrid power plants provide the capabilities to offer resiliency services, one challenge to hybridization can be the single common point of connection, where the electricity flows through a single point. In this configuration, the loss or disruption of the connection could result in larger reliability and resiliency concerns due to higher utilization of the single interconnection point. There are greater sensitivities to any type of connection disruption within a hybrid facility when compared to an equivalent-capacity collection of standalone single technology facilities that are all connected to the grid separately, where the loss of one connection would not affect the connection of the others.

3.3 Infrastructure and Transmission Constraints

Hybrid facilities can overcome geographic and resource constraints through shared infrastructure and plant components (Barker et al. 2021). Optimizing the design of hybrids to accommodate specific geographic considerations, such as limitations within existing energy system infrastructure and land usage, can help provide reliable and resilient electricity to areas that may not be suitable for single-technology VRE resources or transmission expansion. Through the complementary nature of renewable generation profiles, such as wind paired with solar, in addition to the deployment of storage, hybridization can leverage resources in suboptimal areas. Furthermore, retrofitting existing single-technology VRE facilities by co-locating additional technologies into a hybrid configuration can leverage existing permits and approvals, therefore increasing the permitting and cost efficiencies of a project.

3.3.1 Transmission and Interconnection Upgrade Considerations

Currently, aging and limited transmission infrastructure is a bottleneck for increasing energy capacity on the grid (Grid Deployment Office 2023). Due to a lack of timely and necessary improvements and expansions to maintain grid modernity and reliability, brownouts and blackouts are happening more frequently (Ezrati 2023). These events cause dangerous health and security risks to the people in affected locations. Modernizing and expanding grid and transmission infrastructure is very expensive, requires a substantial amount of intra and interstate permitting, and historically has required an extremely long timeline to complete. According to the NREL report, *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* (Denholm et al. 2022), if the United States were to meet the 2035 clean electricity target by connecting additional renewable generation capacity, then interregional transmission capacity would need to expand between two and three times the current size of the grid. Therefore, it is highly unlikely that transmission build-out will occur at the rate that is needed to meet U.S. clean electricity and decarbonization targets. This inability to expand transmission infrastructure in a timely manner is because of various challenges, such as permitting and siting requirements, and complex topographies.

High levels of grid congestion have substantially lengthened interconnection queues, which can impose significant delays for new grid-connected projects. Lawrence Berkeley National Laboratory found that for successful projects, it took more than 3 years after an interconnection request to fulfill an interconnection agreement (Lawrence Berkeley National Laboratory 2022). However, hybridization can limit the necessary amount of transmission infrastructure expansion needed in two ways: a grid-connected HPP could reduce the amount of transmission needed by more fully utilizing a connection point; and an off-grid HPP is able to operate independently of the grid, thus eliminating the need for a grid connection. By increasing operational flexibility and optimizing existing interconnection points, storage-type HPPs can help avoid costly transmission improvements and expansion caused by increased demand on the grid.

In some regions, it is not possible to enter the interconnection queues due to the number of pending projects. The California Independent System Operator, which oversees California's grid, did not accept any new requests in 2022, and PJM, which oversees a region in the mid-Atlantic, has announced a pause on new interconnection reviews until 2025 because of the lack of interconnection availability on the grid (Rand 2023). These interconnection queue delays are likely to remain a challenge in the coming years as the continued growth of clean energy deployment is expected to outpace transmission build-out. Because of the anticipated issues caused by delayed transmission infrastructure development, research is being conducted on the interplay between transmission buildout and maximizing existing interconnection points by retrofitting single-technology renewable energy plants with a second-generation or storage technology (Kemp et al. 2023). While hybrids offer a promising technical solution to the transmission infrastructure barrier in the United States, market participation and policy are challenges in many energy markets. For example, in PJM and ISO-New England service areas, adding storage to existing projects requires a new interconnection request because the addition is considered a "material modification" to the project and can sometimes result in a project losing its position in the queue, thereby further delaying project development (FERC 2021). Without proper policy support, stakeholders will not be able to fully realize the benefits that hybrids provide by maximizing interconnection points.

Hybridization can also avoid costly transmission infrastructure upgrades and expansions through their ability to function in an entirely off-grid configuration. An off-grid hybrid operates independently from the electricity grid and functions as a stand-alone system (Energy Saver n.d.). Traditionally, renewable technologies have been located in regions where natural resources are highest to optimize profit; however, the most optimal natural resource areas can be far away from large load and demand centers. Transporting these electrons not only results in electricity losses from the grid, but can also necessitate costly and technically challenging grid infrastructure expansion to more remote areas, which often have less developed transmission and grid infrastructure. Certain hybrid plant configurations, however, can be self-sustaining, which is beneficial for providing reliable and resilient power in more remote locations. For example, offshore wind energy paired with hydrogen production within an off-grid HES configuration is currently being explored in the United States (EERE 2022).

Furthermore, by building an off-grid HPP or HES, interconnection queue delays can be avoided. This scenario takes full advantage of leveraging the shorter development timelines associated with not requiring a grid connection. As previously mentioned, a grid-connected facility depends on interconnection queues, which can substantially lengthen a project's development timeline. Such a delay will have negative impacts downstream for a project's economic viability. The development and construction timeline differences between a grid-connected and off-grid hybrid facility are considerable. On average, it takes about 5 years to receive a grid connection, but this wait time can be up to 8 years before a grid-connected facility is operational (Rand et al. 2023). Recent insights, based on market analysis and industry outreach, have confirmed that current timelines for a facility to connect to the grid is closer to 8 years. For off-grid facilities, the timeline depends only on how long it takes to develop and construct a facility, which can be between 3 and 5 years. Hybrid facilities, with optimized plant configurations, can maximize existing interconnection points and operate independently from transmission and grid infrastructure to avoid unnecessary build-out.

3.4 Land Use and Procurement

As renewable energy continues to be deployed, developers and states must consider the increasing land-use footprint of infrastructure development. Maximizing land use for clean energy development is becoming increasingly important as various development and siting barriers, including ordinances, landscape, and existing infrastructure, are limiting the land where renewable energy generation plants can be located (Denholm et al. 2022; Lopez et al. 2023). Hybrid facilities, however, can leverage suboptimal resources to increase economically viable locations for development. Also, hybridization can minimize footprint expansion by co-locating multiple generation and storage technologies on land previously developed for single-technology VRE resources or traditional energy generation.

3.4.1 Leveraging Suboptimal Resources

Hybridization offers a unique ability to maximize suboptimal resources by using complementary technologies and storage, which diversifies where hybrid facilities can be sited. The availability of renewable resources varies across geographical locations within the United States. For example, the solar resource is greatest in the southwest region, whereas wind is more abundant in the Great Plains. NREL research has shown that the complementary nature of wind and solar can enhance suboptimal resources to provide stable electricity production, and increase the number of cost-effective locations for project siting (Clark et al. 2022; Harrison-Atlas et al. 2022). Additionally, the complementary nature of wind and solar enables the two generation types to share resources—such as the interconnection point—without overloading or oversizing the interconnection. Expanding the locations of renewable technology through hybrid development has the potential to decrease congestion and reduce electricity curtailment in areas that already have a high penetration of intermittent resources. Therefore, by bolstering development in areas with geographic constraints, such as lower resource potential or complex topography, more locations for generation development can be unlocked.

3.4.2 Maximization of Land Area and Permitting and Procurement

Besides avoiding additional transmission and grid infrastructure build-out, hybridization can also limit excess land usage by retrofitting existing renewable energy development sites with co-located generation or storage technologies. A challenge associated with single-generation VRE technologies is that they require about 10 times more land per unit of power in watts produced when compared to coal- or natural-gas-fired power plants (van Zalk and Behrens 2018). On the contrary, consider a co-located facility, such as one in which PV solar is developed under existing wind turbines on a wind plant. This scenario maximizes generation within the allocated land area and maximizes interconnection queue allocations if connected to the grid. Co-locating technologies also provides various benefits and avoids deployment barriers associated with land-usage and development challenges because co-location requires a smaller project footprint, and can reduce local opposition to projects that are already socially accepted and permitted. Further, as renewable energy technology improves, efficiencies in electricity production and vector outputs are expected to increase over time, reducing the land required per unit of power produced (Gross 2020). Therefore, co-locating technologies can maximize production in a given land area, and avoid development challenges associated with increased land usage.

There are many challenges to deploying clean energy technologies within the development phase, more specifically with permitting and siting requirements and approvals. However, hybridization can help avoid some of these deployment barriers, again, by retrofitting an existing single-technology facility with additional generation and storage technologies. The deployment barriers can be avoided by leveraging existing permitting approvals, such as with the National Environmental Policy Act, noise assessments, visual studies, and traffic and transportation studies, because these would have already been conducted. Lastly, for co-located and fully integrated hybrid facilities, upfront costs and efficiencies associated with permitting, engineering and construction, and land acquisition could reduce end-use costs when compared to individual plants (Klonari et al. 2019). Therefore, permitting efficiencies can be leveraged to help avoid additional costly and time-consuming assessments typically associated with project development.

3.5 Economics and Market Participation

The technical concept of hybridization presents an opportunity for increased financial viability—when compared to single-technology VREs—through shared infrastructure costs, the introduction of new revenue streams from credit stacking, and unlocked opportunities within market participation. However, until constraints around market design are resolved the full value of hybrid capabilities will not be realized.

3.5.1 Cost Competitiveness

Hybridization can increase project financial viability through shared costs and expanded revenue stream opportunities; however, upfront development costs and market participation rules are barriers to fully recognizing these benefits. The LCOE and levelized cost of storage (LCOS) are two variables that represent the "average revenue per unit electricity generated or discharged that would be required to recover the costs of building and operating a generating plant or a battery storage facility during an assumed financial life and duty cycle" (EIA 2022). Although calculated differently, LCOE and LCOS are often referenced to indicate the overall competitiveness of a generation or storage technology when compared to respective counterparts—lower LCOE and LCOS can indicate a more cost-competitive technology. Some of the key variables included in LCOE and LCOS calculations include capital costs, operations and maintenance costs, and fuel costs. The cost of electricity is included within LCOS calculations. Because single-technology VRE resources have low to zero fuel costs, the main economic barriers to more renewable energy adoption is the capital cost of developing and constructing renewable projects, and the timeline of the facility's return on investment. Additionally, solar PV hybrid power plants are considered to have fewer dispatchability capabilities when compared to generators with a nearly continuous fuel supply. The capital costs of storage technologies are higher than single-technology VRE sources and thus increase the LCOE of hybrids compared to single-technology VRE resources (NREL 2023). As the capital costs for storage technologies decrease, storage-type HPPs will become increasingly economically competitive.

The financial viability of plant development not only considers levelized costs, but also examines the projected energy and capacity value. The projected utilization rate, as defined by the EIA, is "the varying amount of electricity required over time and the existing resource mix in an area where additional capacity is needed" (EIA n.d.). Additionally, the related capacity value, as defined by NREL, is "the contribution of a power plant to reliably meeting demand" (Madaeni, Sioshansi, and Denholm 2012). Currently, determining the proper capacity value for an HPP is a challenge because some stakeholders feel that an HPP's value is not accurately captured with traditionally used capacity calculations. For example, the Electric Power Research Institute claims that the addition of storage to solar or wind can materially change the capacity valuation. However, the Midcontinent Independent System Operator claims that existing methods of capacity evaluation are appropriate for hybrid resources in the near term. One alternative mechanism that is currently being explored for estimating capacity values of an HPP is the effective load carrying capability. This method determines the timing of when a resource can generate electricity and when the grid is likely to need additional capacity. It can also represent the entire project portfolio rather than individual resources (FERC 2021). However, the most appropriate capacity evaluation method for HPPs is still undetermined (Awara et al. 2023).

Another way in which hybrids can increase their cost competitiveness is through potential savings that are unlocked by sharing permitting and siting fees, as well as lower additional costs associated with interconnections and upgrades (Klonari et al. 2019). These potential savings will vary on a case-by-case basis; however, capital costs are expected to be about 8% lower when compared to independently sited systems (Fu, Remo, and Margolis 2018). For example, the balance of system components can provide cost reductions in the range of 12%–16%, depending on the size of the plant (Barker et al. 2021). A large share of balance of system savings are a result of sharing substation infrastructure and a grid connection, with additional reductions from soft costs within management and development. By acting as one integrated unit, hybrids can maximize savings on project development costs.

3.5.2 Tax Credit Eligibility

Another factor that has influenced the financial viability of renewable energy generation and storage facilities has been tax credit eligibility. Policy incentives have been developed at both the state and federal levels to incentivize renewable energy generation and battery storage deployment. Historically, two of the major tax incentives have been the ITC and PTC, which to date, have been technology specific. The general understanding has been those projects with high capital costs and/or lower capacity factors often elect the ITC, such as for solar or offshore wind projects. However, facilities with lower installation costs and/or higher capacity factors often elect the PTC, such as with land-based wind energy projects. Furthermore, as a result of the IRA, the ITC and PTC will transition into technology-neutral, emissions-based credits on January 1, 2025—meaning that these tax credits will not favor one technology over the other in terms of eligibility. The technology-neutral credits are expected to help reduce economic deployment barriers for hybrids because these credits will extend eligibility to additional generation technologies that can be leveraged within a hybrid configuration.

The available policy incentives are a major driver of hybrid adoption; however, there is uncertainty regarding what may be an optimal tax credit election within hybrids due to the various plant configurations and ownership structures. However, wind and solar projects are now eligible to claim either the PTC or ITC; therefore, each single technology or plant component cannot claim more than one credit. Although each component within a facility could only claim one credit, credit stacking allows for the taxpayer to claim multiple credits per facility. This complexity makes it unclear what the optimal tax credit strategy will be to maximize profitability. For example, hydrogen electrolysis can claim either the clean hydrogen PTC or the ITC. Determining which credit election within this example will be most effective remains uncertain, because there are many considerations that can dictate credit selection, such as project costs, resource availability, and asset management strategies. This challenge is likely to be resolved over time as research and analysis tools are developed.

Unlocking optimal credit savings from tax incentives is further complicated by the eligibility surrounding the energy storage property and how the ITC can be applied. To be eligible for the credit, storage must be labeled as an "energy storage property" and "[receive], [store] or [deliver] energy for conversion to electricity" and must have a minimum nameplate capacity of 5 kWh (*26 USC 48: Energy Credit* 2023). This means battery storage that is integrated within a HES producing green hydrogen is not eligible for the credit because the electricity discharged from the battery is used exclusively to smooth the electricity supply feeding into electrolyzer production. Therefore, the battery is not receiving, storing, or delivering energy for conversion to electricity, but rather into an energy product. Further, the ITC can be applied to the grid interconnection costs of a project that does not exceed a capacity of 5 MWs, which can be applied to the storage component of a facility. Due to the high costs of interconnection and the low 5 MW capacity that determines a facilities eligibility to claim this credit, this could make small-scale hybrid facilities more appealing and more cost effective than operating two independent projects. Regarding the clean hydrogen PTC, there is uncertainty surrounding the details of emissions requirements and whether grid-connected systems that have a hydrogen production component would be eligible to claim the credit (Kaufman and Corbeau 2023).

Although this uncertainty does not directly impact off-grid HESs that produce hydrogen, it does impact the potential viability of grid-connected electrolysis processes.

In addition to emissions requirements for the clean hydrogen PTC, language within the IRA has led to discussions of additionality, deliverability, and time matching for existing and grid-connected facilities. Additionality dictates whether only newly constructed HESs can claim the clean hydrogen PTC, or if existing hybrid facilities can retroactively add a hydrogen production process to their facilities so that they can then claim the clean hydrogen PTC. As a result, there is uncertainty as to whether additionality rules will reduce the number of facilities that will be eligible for this incentive. Deliverability requires the direct use of local electricity resources within the same region, as input to an electrolyzer. Both the electrolyzer and electricity generation resources need to be located in the same defined regions, such as power market zones, which will dictate electricity prices. The cost of electricity impacts the downstream price of produced hydrogen, meaning that the location of an electrolyzer, and therefore its clean hydrogen PTC eligibility, can be influenced by deliverability. Finally, time matching requires the electrolyzer to match the output of real-time renewable generation. Hybrid power plants have an advantage over single-technology VRE generation when considering time matching because of their ability to provide more consistent power (Esposito, Gimon, and O'Boyle 2023).

3.5.3 Market Participation Constraints

Due to the novelty of hybrids, how these facilities are allowed to operate within energy markets remains uncertain. While there is increasing policy clarity, such as the various FERC orders discussed in Section 2.1.2, constraints around market design currently prevent the full value of hybrid capabilities from being realized. Some of these market participation constraints include restrictions pertaining to charging battery storage from the grid, and a hybrid facility's ability to participate in all market structures. These constraints are variable and highly dependent on specific market and state rules. In the PJM market, an HPP that includes storage is only allowed to charge from co-located generation sources and is prevented from charging from the grid. These types of constraints limit the ability of HPPs to provide grid management and load smoothing services (FERC 2021). These limitations are often tied to the nature of grid interconnection approval processes, or limitations with how RTOs and ISOs model hybrid power plants. As HPPs and modeling capabilities continue to mature, it is anticipated that market participation rules will become more inclusive of HPPs.

3.6 Beneficiaries

Although market participation and deployment remain uncertain, the benefits of hybrids can be realized by various stakeholder groups. From the procurement and development phase to operation, stakeholders all are beneficiaries of varying degrees. These groups include developers; subcontractors; plant owners and operators; grid and market operators; hard-to-abate sectors; residential and commercial consumers; and governments. Some of the benefits include:

- Developers can build facilities with fewer geographic and plant characteristic restraints.
- Governments have a pathway to achieve renewable electricity and decarbonization targets.
- Grid operators have fewer challenges in managing and balancing the grid.
- Consumers can benefit from low-cost electricity, hydrogen, and other vectors.

3.6.1 Developers and Subcontractors

Hybrid facilities can offer substantial benefits to developers when compared to traditional single-technology VRE facilities. Through the combined management of multiple technologies within one facility, developers and subcontractors can realize associated benefits by sharing resources and costs during planning and approval, site acquisition, and the construction and development stages of a facility.

In the planning and approval phase of a project, bundling multiple technologies can save time and costs when compared to independently developed resources. Some of the benefits for developers and subcontractors include shared environmental planning studies, community engagement and stakeholder management, and grid-interconnection requests. Additionally, in the land acquisition phase of hybrid development, there are two potential advantages for developers within site procurement. First, by co-locating technologies within a hybrid configuration, land use can be maximized by requiring a smaller facility footprint for the same, or greater amount, of power output. Second, through a hybrid's use of suboptimal resources, it can unlock areas for development that would otherwise be considered uneconomic, thus increasing viable locations. Furthermore, in the construction phase of hybrid development, developers and subcontractors can take advantage of reduced project costs through development synergies. Balance-of-system costs have been identified as a major area for cost savings through shared system infrastructure and reduced labor costs (Barker et al. 2021). Finally, if an existing brownfield site is converted into a hybrid facility, there are further advantages. For example, if market rules allow, projects can take advantage of existing interconnections, thus reducing project costs and associated lead times of development.

3.6.2 Owners and Plant Operators

Hybridization provides various operational advantages to the owners and operators, including increased opportunities to participate in energy markets, greater incentive eligibility, and fewer curtailment risks. These benefits can increase project revenue for owners and operators.

Depending on market rules and design, expanded revenue stream opportunities may be available through additional market participation (Ahlstrom 2019). For example, adding storage to a renewable generation resource allows an HPP to participate in ancillary services, such as frequency regulation. In addition, integrating energy storage into a hybrid plant, can minimize curtailment. As a result, owners can maximize their profitability by mitigating economic losses associated with curtailment.

3.6.3 Grid and Market Operators

When compared to a single-technology VRE, hybridization offers system operators improved flexibility and reliability through increased grid service capabilities. Hybrid power plants can be designed to meet specific grid and market conditions, including providing baseload power, peak demand, or ancillary services more effectively, while still generating electricity. These advantages can provide greater flexibility for system operators and can mitigate grid reliability and resiliency issues. Further, HPPs offer these services without the constraints of fossil-fuel generators because these plants do not have lengthy ramp-up times, increased startup costs, or minimum generation levels. An HPP's ability to operate without the constraints shared by fossil-fuel generators can potentially simplify aspects of system operation, and lower electricity costs.

Hence, HPPs have the potential to provide greater operational advantages for grid and market operators.

3.6.4 Hard-To-Abate Industries

Hybrid facilities have been identified as a decarbonization pathway for hard-to-abate – or are very costly or difficult to decarbonize – industries. Such industries include steel manufacturing, fertilizer production, chemical synthesis, and long-haul transportation such as trucking, maritime, and aviation. These industries can benefit from a HESs ability to provide carbon-free manufacturing processes for hydrogen and ammonia. For many of these industries, zero-carbon hydrogen has been recognized as a key catalyst for decarbonization, which can be supported with conversion-type HESs (Julin 2021).

For example, within the steel industry, green hydrogen can mitigate CO_2 emissions. By transitioning from a blast furnace that uses coal into a direct reduced iron process that uses hydrogen and an electric arc furnace that uses clean electricity, CO_2 emissions can be reduced (Nimbalkar 2022). Similarly, for ammonia and fertilizer production processes, clean hydrogen can provide economically viable alternatives to blue hydrogen, which when produced, generates emissions during the steam-methane reforming production process. Thus, the use of green hydrogen eliminates a large source of emissions (Murdoch et al. 2023). Hydrogen also presents a decarbonization pathway for long-haul transportation, because hydrogen-based vehicles refuel much quicker than trucks that must recharge electric batteries (NREL 2021). Although it is unlikely that hydrogen will be used as an alternative fuel for maritime transport, clean hydrogen is being explored as a replacement for bunker fuel within the ocean freight industry (Global Maritime Forum 2020).

3.6.5 Consumers

The net benefits that HPPs offer over single-technology VRE can be passed on to the ratepayer. By leveraging the complementary nature of hybrid configurations, the savings of zero-marginal-cost electricity can lower wholesale rates. Incentivizing clean energy development can allow for greater cost savings to be realized. Studies have shown that replacing power plants with low-cost fuel inputs can allow for systemwide cost savings (Gagnon et al. 2022; Gagnon, Cowiestoll, and Schwarz 2023). Therefore, lower wholesale electricity rates can be passed down to the ratepayer, potentially saving consumers billions of dollars per year. Additionally, low-income households can benefit the most from these cost savings because they often spend a larger share of their income on electricity—this is known as the households' "energy burden" (EERE 2018).

Furthermore, the adoption of hybrids can enable the continued electrification of consumer and commercial end uses. A large driver of this electrification is the replacement of natural gas with electricity for space and water heating (White et al. 2021). NREL's ReStock tool has indicated that continued electrification could increase required electricity generation capacity by 25% to accommodate region-specific winter demand for electrified heating (White et al. 2021).

Additionally, hybrids can meet specific electricity needs for rural consumers. As previously mentioned in Section 3.3.1, off-grid small-scale hybrid facilities can operate independently of the grid, thus reducing a hybrid facility's reliance on grid infrastructure. Such independence could realize greater cost savings. Further, optimizing the configuration of a hybrid facility unlocks regions with suboptimal resources and areas without adequate grid infrastructure, which are often found in less populated environments.

3.6.6 Government

The wider adoption of HPPs and HESs can help advance key government objectives by reducing the reliance on fossil-fuel electricity generation technologies. Hybridization provides many advantages that can be leveraged in achieving the Biden administration's goal of 100% electricity grid decarbonization by 2035 (Donohoo-Vallett, Ryan, and Wiser 2023). Additionally, the continued deployment of conversion-type HESs, specifically in hard-to-abate sectors, has been recognized as a means to help expedite the transition to a net-zero-emission economy by 2050 (The White House 2023). Hybrid power plants and HESs can also improve human health by reducing air pollution, and benefit the U.S. government by providing greater energy security through increased domestic energy independence (International Energy Agency n.d.; U.S. Department of Energy n.d.).

4 Conclusion

Hybrid power plants and hybrid energy systems have been identified by many stakeholders, including industry and academia, as a potential driver in achieving the Biden administration's electricity and emissions targets of 100% renewable energy by 2035 and net-zero emissions by 2050. Even though they are still a relatively novel technology design concept, HPPs and HESs will play a key role in meeting these targets over the coming decades. The customizability of hybrid facilities can support various end uses that otherwise would not be possible with single-technology VRE sources. As detailed in this report, hybrid facilities are capable of providing benefits that exceed those available from single-technology VRE resources, such as developing decarbonization pathways for hard-to-abate sectors, increasing energy reliability and grid resiliency, supporting operations with independence from the grid, and contributing to potential cost savings for the ratepayer. Although single-technology VRE resources can contribute to achieving the respective U.S. electricity and emissions targets, they are not as customizable as hybrid facilities in supporting the evolving needs of the U.S. electricity grid. Grid operators need to match supply to demand on a second-by-second basis at a specific frequency; therefore, as single-technology VRE resources increase their share of the U.S. electricity supply, it becomes harder for grid operators to provide consistent reliable power. Therefore, by leveraging complementary generation profiles and integrating storage technologies on the plant level, hybrid facilities allow for more flexibility, predictability, and resilience when compared to single-technology VRE resources.

Key deployment drivers to ensure growth of hybrid facilities include continued decreasing technology costs and an increasing number of supportive policies. Solar PV costs and wind energy costs have declined (-84% and -66%, respectively) since 2009. Battery technologies are also becoming more cost-effective, decreasing from $1,306/kWh in 2010 to $151/kWh in 2022. Furthermore, NREL's Annual Technology Baseline modeling indicates that the LCOE of solar PV could decline by 52% from 2023 to 2050, and wind LCOE could decline by 37%. Similarly, the LCOE of solar PV-plus-storage configurations are anticipated to fall by 45% (NREL 2023). These declines are expected to increase the economic viability of hybrid facilities, not only achieving cost parity with but also surpassing their traditional generation counterparts. Currently, the most common hybrid plant configuration by far, in the development pipeline is PV plus storage, followed by wind-based hybrid configurations, albeit trailing further behind. Solar PV and wind-based hybrid facilities represent a growing share of future clean energy projects in the development pipeline. In 2017, HPPs made up negligible portions of the interconnection queue, but in 2021 HPP configurations accounted for 42% of solar projects and 8% of wind projects (Bolinger et al. 2022). However, deployment trends will depend on region-specific characteristics, such as local resource profiles, load demand profiles, and access to grid and transmission infrastructure. Furthermore, projects in the queue have requested to come online before 2026. Though realistically, not all of these projects will end up being developed, the number of projects requesting to come online suggests a need to expedite the rate at which hybrids will be deployed in the coming years. Finally, increased policy support on the federal and state levels, such as through financial incentives within the Inflation Reduction Act and the Bipartisan Infrastructure Law, have reduced deployment barriers for hybrid facilities.

Hybridization offers a variety of technical and economic benefits. As detailed in this report, hybrid facilities have the potential to add value or alleviate concerns in the following areas (in no specific order):

- **Infrastructure and transmission.** Sharing infrastructure and plant components can result in project cost savings. Grid-connected HPPs can benefit developers and plant owners by maximizing power production without expanded transmission, which avoids costly upgrades, extended timelines, and additional permitting. Hybrid facilities operating in an off-grid configuration can shorten timelines associated with interconnection queues from 5-8 years to 3-5 years and avoid transmission interconnection costs.
- **Economic and market participation.** Various economic and market participation considerations that support hybrid deployment include more efficient use of grid interconnection points; new revenue streams in addition to electricity production such as hydrogen; and tax credit stackability, which allows for the election of multiple respective credits for individual components within a single hybrid facility. This would allow the plant owner to potentially elect additional credits that otherwise would not be possible for a single-technology project.
- **Industrial decarbonization.** Hybrid facilities provide a pathway to decarbonize hard-to-abate sectors by pairing zero-emission technologies together with conversion technologies. Conversion-based hybrid facilities have the capabilities to produce emissions-free hydrogen and ammonia feedstocks that can replace emissions-based processes. Hybrid facilities have the potential to be leveraged to decarbonize industrial processes including steel, cement, freshwater, and long-distance transportation.
- **Grid support.** HPPs are less sensitive to fluctuating resource profiles than single-technology VRE projects and therefore have the technical capabilities to provide bulk power and peak demand. HPPs that utilize complimentary VRE resources, like solar and wind, often can provide power more consistently than single-technology VRE resources. Additionally, an HPP integrated with storage technologies can enable ancillary services through its load-shifting and ramping abilities.
- **Land use.** Acquiring land for a single-technology VRE project can be challenging due to barriers such as ordinances, landscape considerations, suboptimal resource areas, and access to infrastructure. Hybrid facilities can experience the same development barriers, however, can leverage multiple generation sources and/or storage technologies to increase energy generation per land area. Further, hybridization can expand potential regions for development that historically have not been considered viable for single-technology VRE resources.

Because of the many advantages provided by hybrid facilities, various stakeholders can benefit from investing in hybridization. For example, developers and subcontractors can leverage the flexibility of HPPs because of fewer potential development barriers, such as geographic and plant characteristic limitations. Owners and operators can take advantage of additional revenue streams introduced through ancillary services, and end-use products, such as the production of carbon-free hydrogen and ammonia. Additionally, grid and market operators could experience fewer challenges in managing and balancing the grid through emissions-free generation technologies. Further, industries within hard-to-abate sectors can leverage HESs to produce carbon-free feedstocks, thus opening alternative pathways to support the decarbonization of energy-intensive industries. Residential and commercial consumers can benefit from potentially lower electricity and energy product prices. Finally, governments can leverage hybridization to achieve various electricity and decarbonization targets, in addition to providing greater energy security through the domestic production of electricity and energy products.

Although there are many benefits that hybridization provides, there are still uncertainties due to its relative novelty. It remains unclear how market participation rules in the various markets will evolve to accommodate HPPs and HESs. Furthermore, there are policies that support specific renewable energy technology development that can be indirectly applied within a hybrid context; however, hybrid-specific policies are limited. While levelized costs from hybrids are declining, costs for technologies that are currently being explored for hybrid integration remain high. Because hybridization is maturing, research is underway to understand what the optimal configurations and end uses may look like for a hybrid facility based on various geographic and plant characteristics.

Additionally, due to the novelty and capabilities of hybrids, there have been inconsistent uses of taxonomy between stakeholder groups when defining HPPs and HESs. Standardizing this terminology can help create effective policy that encourages the deployment of hybrid facilities. Furthermore, understanding the complexities surrounding market participation and design optimization are areas that need to be researched further to comprehend the full suite of capabilities that hybrid facilities can support.

Despite these uncertainties, hybridization offers a promising opportunity to help achieve U.S. emissions reductions and net-zero targets. Achieving continued cost reductions, developing a greater understanding around tax incentives and policies, and changing market participation rules to reflect the evolving technology market landscape, can facilitate a pathway for hybridization to have the potential to achieve large-scale impact.

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Appendix. Hybrid Optimization Performance Platform

In light of the growing interest and feasibility of hybrid power plants and energy systems, the National Renewable Energy Laboratory has developed the Hybrid Optimization and Performance Platform (HOPP) as an open-source software tool to model hybrid facilities. The tool was designed to answer the following research question: "When and where do hybrid plants make sense, and how can we design them optimally?" (National Renewable Energy Laboratory n.d.[c]). This modeling platform is a hybrid power plant and hybrid energy system design tool that can determine the general profitability of a hybrid system design.

HOPP primarily comprises simulation and financial modeling components. The simulation component includes multiple technologies that can be combined in any configuration the user chooses. The supported technologies are currently wind energy, solar energy, battery storage, hydrogen production, and concentrated solar power storage. The simulation also includes a grid model that imposes transmission constraints. The idea of the platform is to provide technology modules with a general structure, which allows the user to either select the existing technology models or add their own preferred model for that technology. The inputs on the simulation side include the power rating of the technology, and specific parameters that are outlined in the respective technology modules. HOPP currently supports the National Renewable Energy Laboratory's System Advisor Model (SAM), which is a free techno-economic software modeling tool, for battery storage and solar modeling (Blair et al. 2018). SAM and the FLOw Redirection and Induction in Steady State (FLORIS) model—which is an open-source wind plant optimization and modeling tool—support wind farm modeling (National Renewable Energy Laboratory n.d.[a]). HOPP also includes hydrogen modeling capabilities using an open-source stand-alone electrolyzer model.[11]

The financial component within HOPP uses financial models derived from SAM to determine the profitability of the plant design. The financial component generates the net present value of the plant, based on the plant lifetime and the levelized cost of energy or hydrogen. Additionally, this component within HOPP supports SAM capabilities and a general costing structure for user-specific financial models. The SAM financial model is customizable, but generally takes inputs such as capital costs, operations and maintenance costs, a grid electricity price signal for specific locations, an average inflation rate, discount rates due to shared infrastructure within a hybrid plant, and policy inputs.

By combining the simulation and financial components, HOPP can design a hybrid power plant or hybrid energy system that can give hourly output and dispatch information along with a financial estimate of value. Therefore, HOPP can help renewable energy developers optimize projects to provide better financing terms, lower capital and operational expenses, increased plant performance, and increased energy density per unit of land area, in comparison to single-technology variable renewable energy generators. The architecture, capabilities, and validation of HOPP are presented in more detail in *Control Strategies and Validation in the Hybrid Optimization and Performance Platform (HOPP)*" (Starke, Martin, and Bhaskar forthcoming).

[11] https://github.com/NREL/electrolyzer