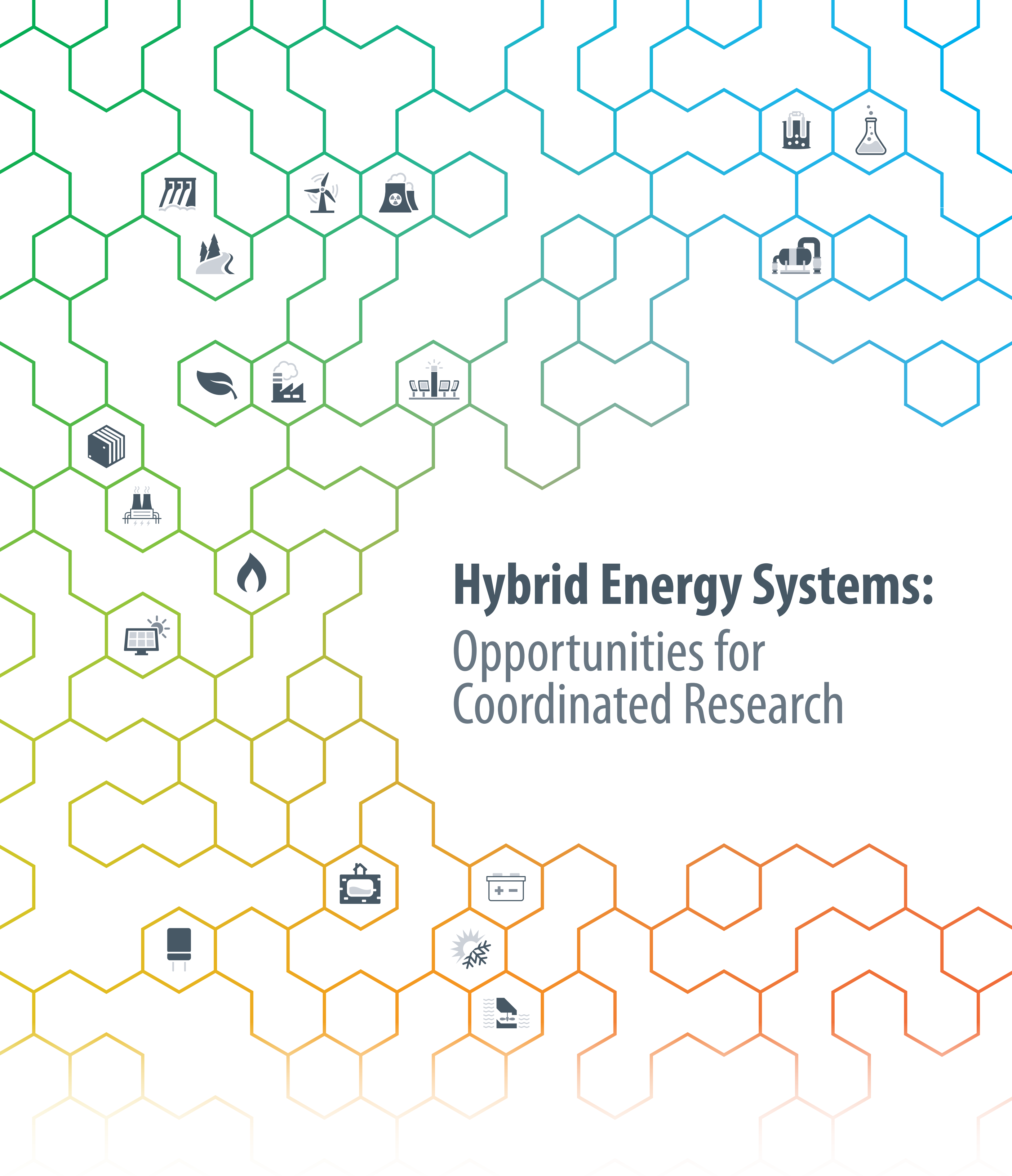

Hybrid Energy Systems:
Opportunities for Coordinated Research

U.S. DEPARTMENT OF
ENERGY

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Disclaimer

Acknowledgements

The *Hybrid Energy Systems: Opportunities for Coordinated Research* report began as a purely voluntary, staff-driven effort to improve coordination across U.S. Department of Energy (DOE) program offices as it relates to hybrid energy systems research. The resulting DOE Hybrids Task Force, which is responsible for this report, consisted of representatives from the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Electricity (OE), the Office of Nuclear Energy (NE), the Office of Fossil Energy (FE), and the Advanced Research Projects Agency–Energy (ARPA-E).

Contributions were also made by a technical team at the DOE National Laboratories, namely individuals from Argonne National Laboratory, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, the National Energy Technology Laboratory, the National Renewable Energy Laboratory, the Pacific Northwest National Laboratory, the SLAC National Laboratory Accelerator, and Sandia National Laboratories. Thank you also to 3rdRail Inc. and the Electric Power Research Institute for their support.

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Executive Summary

To meet the evolving demands of the 21st century, the U.S. power grid is undergoing transformational changes that defy its traditional design of large-scale generation remotely located far from consumers, centralized control structures with minimal feedback, limited energy storage, and passive loads. Over the last decade, the U.S. electric generation mix has changed dramatically, with increased generation from highly-flexible natural gas, rapid deployment and penetration of variable renewable resources, and decreased generation from traditional baseload resources. Other changes that are beginning now and expected to accelerate in the near term include increased deployment of energy storage technologies and greater use of digital and communication technologies in the control of power systems. The introduction of new sources of dispatchability, flexibility, and reliability offers the potential for a more optimized, cost-effective, and modern energy sector from fuel to generation to delivery to load.

One key trend in the evolving U.S. energy sector is the emergence of hybrid energy systems (HES). We define HES in this report as systems involving *multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives*. This definition is consistent with—but broader than—industry definitions.[1] And as defined here, HES are related to, but distinct from, colocated resources, which share some characteristics with HES but have more-limited opportunities for operational synergies.

HES present an opportunity to optimize power plant designs to maximize the services that are useful to and valued by the electric and broader energy systems. They can vary in terms of their subcomponents, linkages (e.g., locational, physical, and operational), and application spaces (e.g., customer-sited or utility-scale). HES can also be configured to provide various electric and nonelectric products (e.g., fuels). For example, HES can have electricity as their only output, with common examples including various generation technologies combined with energy storage. In other cases, HES can consist of industrial processes that utilize generated heat or power to produce a commodity-scale product (e.g., using electrical or thermal energy to produce hydrogen from water or a methane source).

Recent analysis, experimentation, and deployments of HES suggest advantages currently outweigh disadvantages for some technology combinations. They also indicate that hybridization could be an effective strategy for realizing net-economic benefits relative to independent plants by allowing multiple technologies to share costs and infrastructure; enabling the provision of more grid services (or the same grid services at a lower cost); and enhancing system reliability, flexibility, and resilience. Hybridization can also help mitigate

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[1] See, for example:

CAISO, *Hybrid Resources Draft Final Proposal* (California ISO, August 3, 2020), http://www.caiso.com/InitiativeDocuments/DraftFinalProposal-HybridResources.pdf.

Mark Ahlstrom, Andrew Gelston, Jeffrey Plew, and Lorenzo Kristov, *Hybrid Power Plants: Flexible Resources to Simplify Markets and Support Grid Operations* (Energy Systems Integration Group: October 21, 2019), https://www.esig.energy/wp-content/uploads/2019/10/Hybrid-Power-Plants.pdf.

Caitlin Murphy, Anna Schleifer, and Kelly Eurek, “A Taxonomy of Systems that Combine Utility-Scale Renewable Energy and Energy Storage Technologies,” *Renewable and Sustainable Energy Reviews* 139 (April 2021): https://doi.org/10.1016/j.rser.2021.110711.

financial penalties for variable resources (e.g., integration charges and imbalance penalties) and overcome suboptimal technical requirements or limited participation models for the provision of services (e.g., capacity or ancillary services). For example, if a utility or system operator imposes ramp-rate limits on variable renewable resources, or it disallows these resources from participating in ancillary services markets, then hybridizing can help resolve these market design limits. Similarly, a utility or system operator could impose energy requirements on certain market products that might limit the ability of independent energy storage to participate unless it is paired with another resource.[2]

Hybridization also poses challenges and uncertainties. To a large extent, wholesale electricity markets, electric utility regulation, and state energy policies were designed with the expectation that power generating facilities would consist of a single technology type. Furthermore, system operators have historically been able to optimize dispatch to minimize costs and maintain reliable operations across the full portfolio of available resources, rather than having some resources optimize their operations independently. The emergence of competitive HES is thus creating challenges for the design, operation, and regulation of wholesale electricity markets, for state regulation of electric utilities, and for the design and implementation of energy policies. Additionally, current data, methods, scenarios, and analysis tools—ranging from plant-level to capacity expansion to energy economic models—are insufficient for representing the costs, estimating the value, and evaluating system impacts of HES. Optimizing the design and operations of HES also requires development of controls, sensors, telemetry, metering, and other communications equipment to facilitate the coordinated operations of subcomponents with different objectives.

Responding to growing industry interest in HES, the U.S. Department of Energy (DOE) has undertaken research and development (R&D) projects to address challenges and promote innovations in HES. The DOE Hybrids Task Force reviewed DOE's HES R&D portfolio and found that technologies from four DOE program offices—the Office of Energy Efficiency and Renewable Energy (EERE)[3], Office of Fossil Energy (FE)[4], Office of Nuclear Energy (NE), and Office of Electricity (OE)—are the subject of state-of-the-art HES research. Moreover, our review confirmed that DOE has supported the development of HES research capabilities that are designed to explore hybrid-specific questions, span multiple research topics, and evaluate a diverse suite of subcomponent combinations and linkages. Finally, our review revealed that HES research is often housed in an individual office, particularly when it involves a single source of electricity generation linked with an energy storage or conversion technology.

Detailed treatment of the nuances of each generation technology is important and relevant, but many aspects of HES are crosscutting and will be relevant to other generation technologies, including those that are the focus of other DOE program offices. Therefore, a key finding of our review is that there may be opportunities for additional or enhanced collaboration across EERE, FE, NE, and OE, as well as across suboffices that house

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[2] Will Gorman, Andrew Mills, Mark Bolinger, Ryan Wiser, Nikita G. Singhal, Erik Ela, and Eric O'Shaughnessy, "Motivations and Options for Deploying Hybrid Generator-Plus-Battery Projects within the Bulk Power System," *The Electricity Journal* 33, Issue 5 (June 2020): https://doi.org/10.1016/j.tej.2020.106739.

[3] Research activities within EERE are further segmented across the Office of Renewable Power (including the Solar Energy Technologies Office, Wind Energy Technologies Office, Water Power Technologies Office, and Geothermal Technologies Office), the Office of Transportation, and the Office of Energy Efficiency.

[4] Research activities within the Office of Fossil Energy are further segmented across the Office of Clean Coal and Carbon Management (coal to power and/or products and carbon capture) and the Office of Oil and Natural Gas (liquefied natural gas and chemical conversion).

individual generation technology types and other government agencies conducting HES-related research such as the Advanced Research Projects Agency–Energy (ARPA-E).

This report was prepared by DOE and its National Laboratories to establish the state-of-the-art in HES research and highlight challenges that are relevant across HES, regardless of their subcomponents. The report was designed to identify high-priority, near-term opportunities for HES research where multiple DOE program offices could coordinate their efforts to increase impact or reduce duplication. These opportunities do not necessarily reflect new research activities, but rather those that are both high-priority areas for HES and amenable to multi-office collaboration or coordination. The opportunities reported here are categorized into three research areas: markets, policy, and regulation; valuation; and technology development. In addition, two overarching opportunities influence and are influenced by activities in all three research areas.

Executing the opportunities and activities outlined in this report—and any future ones that arise as needs and goals evolve—will be at the discretion of the DOE program offices and will only be possible through ongoing coordination, communication, and collaboration. Existing mechanisms present a framework on which to build, and they illustrate that many forms of collaboration could take place. These could include joint Grid Modernization Laboratory Consortium (GMLC) Lab Calls, funding opportunity announcements (FOAs), workshops, and technical assistance programs. In all cases, any future activities under a given opportunity should build on, and avoid undermining, related interoffice and intraoffice research that is already underway for HES.

Overarching Opportunities

The DOE Hybrids Task Force identified two opportunities as having immediate priority and whose results will help inform opportunities within all three research areas. These opportunities are intended to identify the key current drivers of HES, explore the time frame for current motivations for and anticipated drivers of HES in the future, gain greater visibility into industry efforts related to HES, and disseminate relevant information. Each activity would begin by compiling and synthesizing findings from previous DOE workshops and data resources. Leveraging DOE's past investments in hybrid energy system workshops and data resources would both avoid duplication and help identify the unique aspects of recent commercial activity surrounding HES, which should be the focus of both overarching activities.

Motivations for HES

Host a series of workshops designed to explore the relative importance of the diverse present-day motivations for HES, with a focus on technology combinations that are being deployed, proposed, and considered for interconnection today. Planning and preparation for the workshops would involve reviewing the participants and outcomes of previous related DOE workshops on HES; findings from the workshops would inform deeper analysis around the perceived benefits of HES that are not adequately represented in established valuation tools and methods.

Public Data Resources

Establish regularly updated, publicly available data resources on current and projected technology costs, performance, market value, and market trends for different kinds and configurations of HES. Activities under this opportunity could include compiling data resources from existing work for specific technology combinations, as well as collecting and disseminating new data resources when appropriate.

Markets, Policy, and Regulation Opportunities

The objectives of the markets, policy, and regulation research area are to evaluate regulations, policies, ownership structures, and market products that are emerging or needed to ensure efficient operation of HES. To relate the greater sense of urgency for the markets, policy, and regulation opportunities, they are presented prior to those for valuation and technology development; in other words, the sudden rise in HES is challenging conventional approaches in markets, policy, and regulation. The opportunities outlined here include gaining a better understanding of the evolving development status, rules, and policies specific to HES; proactively responding to the potential impacts of higher penetrations of HES on electricity markets and system operations; improving the analysis of HES within interconnection and transmission planning studies; and providing analytical and technical support to state regulatory commissions and energy offices regarding HES.

Markets Database

Synthesize and disseminate current and evolving rules and policies specific to HES including changes in market participation models, developments in stakeholder proceedings, and changes in interconnection queue procedures.

HES Integration Studies

Analyze the impacts of different kinds and penetration levels of HES on system planning, operations, reliability, costs, resilience, environmental compliance, or fuel provision, as well as state and local policy goals.

HES in Interconnection and Transmission Planning

Review existing approaches to representing HES in interconnection and transmission studies, and examine how HES can defer or avoid transmission and distribution investments.

Technical Assistance

Provide technical assistance to states, tribal entities, legislatures, public utility commissions, and state energy agencies on policy design, utility regulation, and regulatory design issues for HES. This could include assistance in evaluating the role of HES in states' long-term energy policies, evaluating HES in utility planning and procurement, optimal hybrid investment strategies for utilities, regulatory issues around utility ownership and contracting for HES, and rules for HES in state policy mandates.

Valuation Opportunities

The valuation research area focuses on tools, methods, and metrics for quantifying the value that different HES can provide, given hybrid system configuration, energy system, and market characteristics. HES come in a variety of types, are used in a variety of applications, and produce a variety of products. Comprehensive and harmonized valuation methodologies that encapsulate these variations are essential for determining which HES, if any, can best meet the needs of the electric and broader energy system. Opportunities are presented and organized in terms of identifying sources of value, developing consistent metrics and methodologies, and applying tools to estimate HES value over different scales and time horizons.

Sources of Value

Enhance information sharing across recent and ongoing HES research in different DOE offices to achieve harmonized value definitions and categories.

Products and Services Taxonomy: *Establish a harmonized definition for the services and products that HES can provide, building on ongoing technology- specific valuation efforts.*

Documentation of Complementary Characteristics: *Synthesize existing and compile additional data on the capabilities of different technologies which, when combined, enable or enhance the provision of products, services, or new value propositions.*

Cost Synergies: *Leverage and extend recent research to develop a flexible, consistent framework for assessing the potential cost impacts of hybridization.*

Methodologies and Metrics to Measure Value

Establish common methods and metrics for evaluating candidate HES to enable an apples-to-apples comparison of candidate HES.

Resource and Product Complementarity: *Expand ongoing complementarity analyses to new resource combinations, considering both location-dependent and the potential for virtual complementarity; expand analysis of complementarities across electricity and other product markets, including their infrastructure, transport, and storage requirements.*

HES in Valuation Tools*: Coordinate activities for representing and optimizing HES in existing and under-development valuation tools, including price-taker, production simulation, production cost, resource planning (capacity expansion), energy sector, and integrated assessment models.*

Valuation Analysis Framework: *Develop common valuation scenarios, systems, and reporting protocols for consistent treatment and evaluation of HES.*

Estimating Value

Estimate the value that HES can provide through analyses that expand and leverage past and ongoing research for select technology combinations.

Plant-Level vs. System-Level Optimization: *Evaluate how the optimal design and value of HES vary across these different perspectives.*

Transmission Utilization: *Evaluate the extent to which HES can mitigate transmission utilization challenges.*

Retrofit Opportunities: *Expand the range of technology combinations that are examined for retrofit opportunities, considering a wide array of locations, markets, and subcomponents.*

Forecast Errors: *Evaluate the extent to which hybridization mitigates risks, and whether such a mitigation strategy would be cost effective.*

Resilience Benefits: *Coordinate efforts across DOE offices to compile and document the potential resilience benefits of HES.*

Nonenergy Benefits: *Evaluate environmental and other benefits that may arise from hybridization, leveraging recent and ongoing work for select technology combinations.*

It is important to note that the identified valuation opportunities reflect a comprehensive approach to self-consistent valuation, only some parts of which are unique to HES. For example, the proposed Products and Services Taxonomy and Valuation Analysis Framework could assist with the self-consistent valuation of all energy technologies, including both HES and independent technologies. The remaining opportunities are unique to HES, as they represent the underlying drivers for—or the ability to evaluate the potential net benefits of—linking multiple generation, storage, and conversion technologies.

Many of these hybrid-specific opportunities are already the subject of R&D for select technology combinations, so the overarching goals of each one would be to improve transparency, self-consistency, and information sharing across DOE program offices. These goals could be achieved through multiple avenues that vary in terms of their costs and benefits. Compiling a database of methods, tools, and findings for hybrid concepts that have been explored to date would involve less effort, but it would not facilitate an apples-to-apples comparison that might be preferable from a system operator, utility, or customer perspective. By contrast, developing a truly harmonized approach would allow for direct comparison across candidate HES, but the level of effort required may not be justifiable, particularly if the harmonization would reduce the precision with which individual HES could be evaluated. This report does not endorse any specific approach, but instead emphasizes the improved efficiencies that could be achieved across valuation efforts through better coordination in each of these opportunities.

Technology Development Opportunities

The technology development research area has the objectives of (a) accelerating efforts to develop and enable hardware and software that allow multiple energy technologies to be linked and co-optimized, and (b) supporting testing, simulation, and demonstration to validate and de-risk them. Specific technology development opportunities include controls development and testing; plant-level design optimization; developing and testing hybrid energy system components and integration between them; demonstration projects; and optimizing hybridization and conversion strategies. As with the markets and valuation opportunities, the technology development opportunities represent the intersection of high-priority research activities and those that are amenable to enhanced coordination or collaboration across DOE program offices. Therefore, any future research under these opportunities should build on, and avoid duplication of, existing HES research activities within or across DOE offices.

Controls Development and Testing

Expand efforts to develop robust and efficient control solutions for additional technology combinations and service types, and improve coordination for related research activities across DOE offices.

Advanced Computational Methods for Controls: *Leverage advanced computational methods (e.g., AI) to improve the real-time operation of a wide range of HES.*

Optimize Network Utilization: *Coordinate across DOE offices to develop controls that optimize transmission and distribution infrastructure utilization for a wide range of technology combinations.*

Forecasting: *Expand the integration of resource and load forecasts into controls for a broader array of HES through increased coordination across DOE offices and suboffices.*

Relationship with Microgrid Controls: *Coordinate research across controls for microgrids and HES more broadly.*

Plant-Level Design Optimization

Improve coordination across efforts to develop methods and tools for evaluating the optimal sizing, linkages, and operations of HES for a wide array of technology combinations.

Advanced Computational Methods for Design: *Coordinate research activities related to the use of advanced computational methods for optimizing the design of the HES system and subsystems, including informing sizing, financial performance, technical performance, and lifetime estimations to maximize the value proposition of the HES.*

Dynamic Models: *Develop reduction techniques to accurately model and simulate HES in dynamic models.*

Components Development and Testing

Coordinate efforts to develop and test power electronics, devices, communications, heat exchangers, and intermediate loops for application at various time steps, leveraging recent and ongoing capabilities development for independent technologies.

Hardware Development: *Coordinate activities to improve the cost and performance of electrical, thermal, and/or chemical components that enable the efficient integration of multiple technologies to form HES.*

Component Testing: *Support testing and simulation of HES components across new and existing facilities and software platforms, including through emulation focused on power electronics, high-fidelity real-time simulations, hardware-in-the-loop testing, controller and power hardware, and balance of plant systems.*

Demonstrations

Expand and coordinate technology demonstrations that validate technical capabilities, reduce risk, and accelerate adoption of new hardware and software for HES applications, leveraging recent and ongoing efforts for both hybrid and independent energy systems.

End-User Requirements: *Compile existing and gather additional data on end-user requirements related to the performance of customer-sited energy systems, to establish a database of requirements and a pipeline of potential demonstration applications for emerging HES.*

Field Deployments: *Coordinate demonstration and deployment activities for HES and individual components, in order to increase the (a) efficiency with which empirical data on their operation and value are collected and (b) impact associated with derisking such systems.*

Optimal Hybridization and Conversion Strategies

Understand and advance optimal hybridization and conversion strategies.

Tightly Coupled HES: *Continue working across DOE to develop interdependent subsystems that are connected through electrical and properly designed heat and mass transport systems to create highly efficient, low-cost tightly coupled energy system.*

Advanced Power Conversion Technologies: *Develop higher efficiency thermal-to-electric conversion technologies, and better techniques for utilization and recuperation of waste heat.*

Table of Contents

Figures

Tables

Text Boxes

1 Introduction

The term “hybrid” is employed in many disciplines to refer to a system that comprises multiple distinct constituent parts that are combined and integrated to take advantage of each one’s unique characteristics and the synergies between them. In this report, and in the context of the U.S. energy system, we define hybrid energy systems (HES) as:

> *multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives.*

The universe of possibilities for HES that result from this definition—including constituent technologies, technology linkages, applications, and ultimate outputs—is summarized in Figure 1 (page 2).

In response to recent and dramatic changes to the U.S. electric grid, the topic of hybridization is growing in popularity within discussions related to the evolution of the U.S. energy sector. Multiple forms of HES are well established and being used across the energy sector today. Distribution-connected combined heat and power (CHP) plants have been developed to provide both electricity and heat services, both at district scales[5] and in customer-sited applications for select industries.[6] Similarly, customer-sited systems that combine solar photovoltaics (PV) and battery technologies are being deployed for techno-economic and resilience benefits. Finally, the bulk power system has experienced a recent surge in the deployment of utility-scale HES over the last decade (Figure 2, page 3), which likely produce electricity as their only output (see Section 1.1) and are being motivated by a variety of factors (summarized in Table 1).

The U.S. Department of Energy (DOE) is in a unique position to support research that will improve our ability to understand and enable the potential benefits listed in Table 1, be a leader in technological innovation, and inform effective policies and regulations regarding HES. However, doing so efficiently will require increased coordination among the following DOE offices, each of which has distinct—but often complementary—objectives:

- Office of Energy Efficiency and Renewable Energy (EERE)[7]
- Office of Nuclear Energy (NE)
- Office of Fossil Energy (FE)
- Office of Electricity (OE).

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[5] See, for example, “Minnesota Implementation Model: Combined Heat and Power Action Plan,” DOE, accessed February 3, 2021, https://www.energy.gov/eere/slsc/downloads/minnesota-implementation-model-combined-heat-and-power-action-plan.

[6] See, for example, DOE, *Combined Heat and Power (CHP) Technical Potential in the United States* (DOE, March 2016), https://www.energy.gov/sites/prod/files/2016/04/f30/CHP%20Technical%20Potential%20Study%203-31-2016%20Final.pdf.

[7] Research activities within EERE are further segmented across the Office of Renewable Power (including the Solar Energy Technologies Office [PV and CSP], the Wind Energy Technologies Office, the Water Power Technologies Office, and the Geothermal Technologies Office), the Office of Transportation, and the Office of Energy Efficiency.

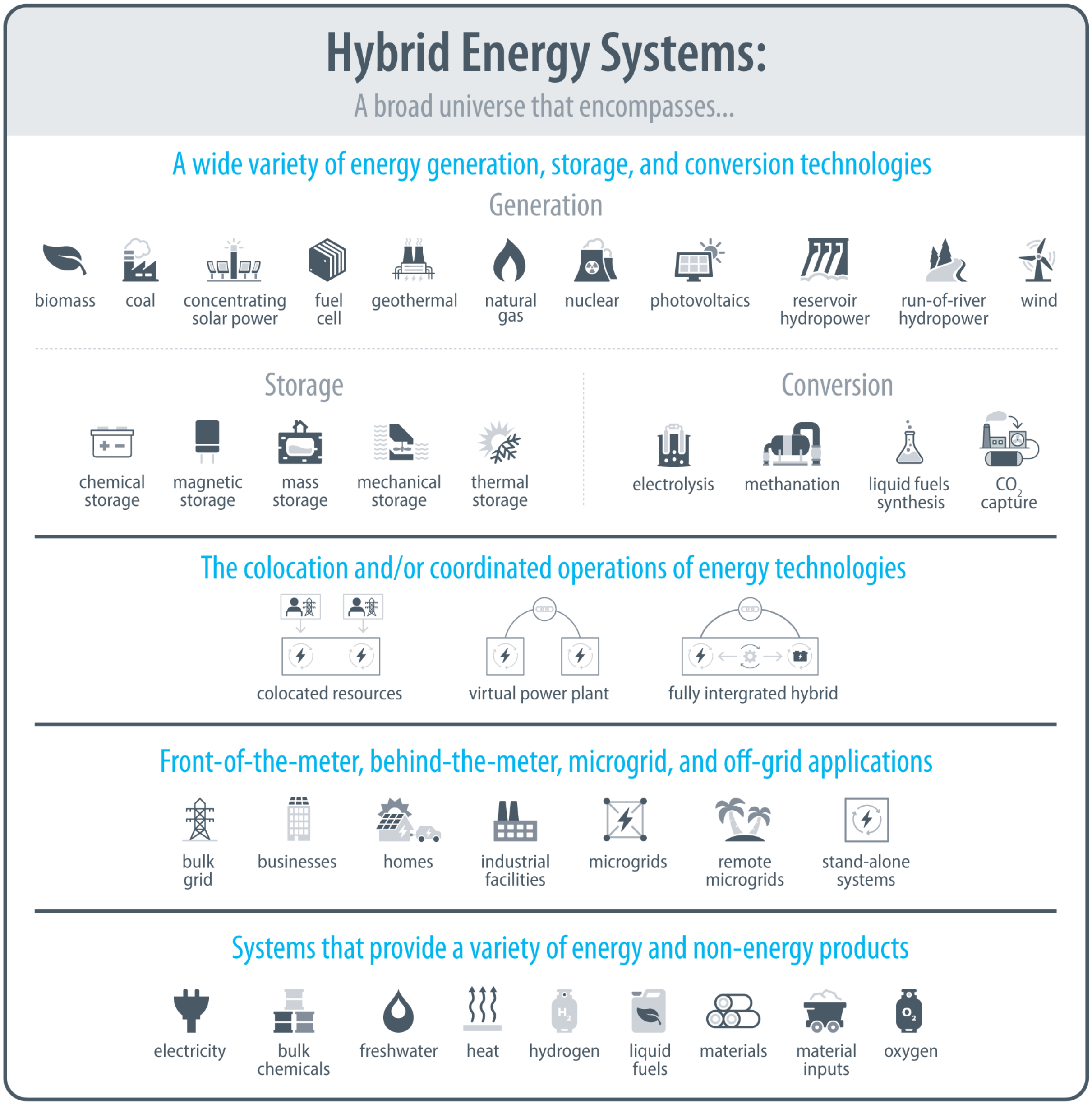
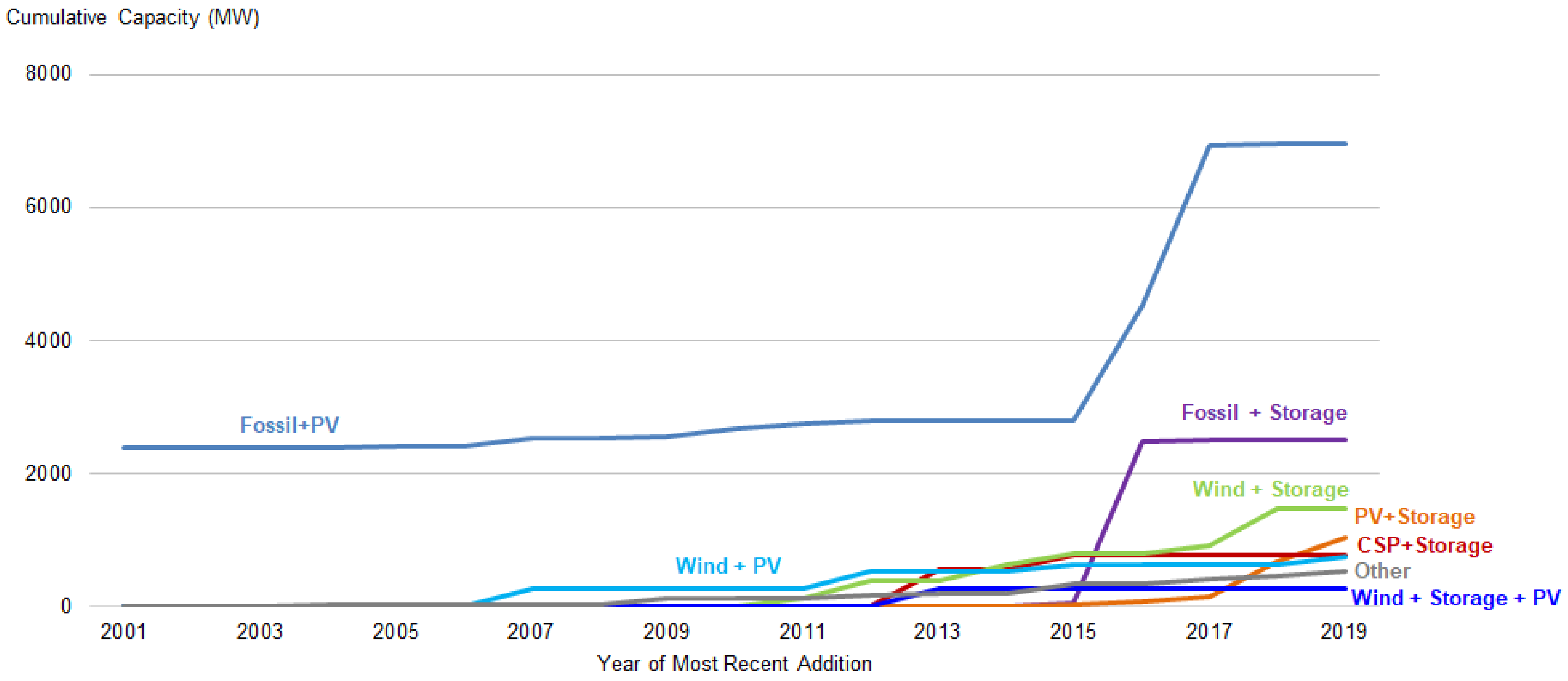


Figure 1. Dimensions that define HES



Other category includes: (1) Fossil+PV+Storage, (2) Fossil+Storage+Wind+PV, (3) Fossil+Wind+Storage, (4) Fossil+Wind+PV, (5) Fossil+Wind, (6) Biomass+PV, (7) Geothermal+PV+CSP, (8) Geothermal+PV, (9) Hydro+Storage

Figure 2. Installed capacity[8] of HES on the U.S. bulk power system over time

HES capacity increases indicate the year in which an HES was formed, based on the year in which either a hybrid plant came online or a second subcomponent was added. Source: Lawrence Berkeley National Laboratory analysis of U.S. Energy Information Administration's EIA-860 data (https://www.eia.gov/electricity/data/eia860/)

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[8] Capacity represents the total capacity of the hybrid plant. Some of these hybrid combinations are dominated by one resource type. For example, the Fossil+PV hybrids generally reflect small amounts of PV colocated with much larger (and previously deployed) fossil units. HES in this figure only cover plants with multiple prime movers; the figure does not include plants that use multiple energy sources in the same prime mover. Therefore, the figure does not include:

- Concentrating solar power (CSP) plants that periodically use natural gas (e.g., "Concentrating Solar Power Projects: Ivanpah Solar Electric Generating System [ISEGS]," NREL, accessed February 3, 2021, https://solarpaces.nrel.gov/ivanpah-solar-electric-generating-system)
- Combined cycle plants that use concentrating solar thermal to preheat the working fluid (e.g., "Concentrating Solar Power Projects: Martin Next Generation Solar Energy Center [MNGSEC]," NREL, accessed February 3, 2021, https://solarpaces.nrel.gov/martin-next-generation-solar-energy-center-0).

Table 1. Potential Factors Driving Hybridization in the Energy Sector

Potential Drivers	Examples
Cost and siting synergies	The potential to increase the efficiency with which land, electrical infrastructure, and physical infrastructure are used translates into both economic and societal benefits. For example, linking multiple technologies could enable the sharing of costs and infrastructure, the latter of which could increase utilization and defer the need for additional infrastructure investments.
Policies and mandates	The federal investment tax credit can offset up to 30% of the capital costs associated with an energy storage device that is coupled with a qualifying renewable energy technology.[9] State-level clean energy standards, renewable portfolio standards, solar carve-outs, and storage mandates directly or indirectly encourage the deployment of HES that can maximize utilization of zero-emitting generation.[10]
Energy storage cost reductions	Storage technologies that are commonly included in proposed HES have experienced recent rapid cost reductions, which have improved the competitiveness of both independent and hybridized deployments of these technologies. Storage technologies are a common component of HES. Among other benefits, they can capture otherwise clipped energy and have the potential to reduce wear and tear from generator cycling.
Transmission benefits	Lengthy interconnection processes and social, environmental, and economic barriers to new transmission projects have also driven entities to consider hybridization as an alternative solution. In particular, existing power plants that typically operate below the full capacity of their interconnection represent an opportunity for hybridization with additional technologies that can capitalize on the available transmission capacity, through either coordinated operations or complementary production profiles. Such an arrangement would be especially appealing if adding a new technology to an existing interconnection agreement resulted in a faster interconnection process.
Market value	Hybridization can mitigate financial penalties for variable resources (e.g., integration charges[11] and imbalance penalties[12]), overcome suboptimal technical requirements or limited participation models for the provision of services (e.g., capacity or ancillary services), and increase value through production of multiple commodities to increase revenue streams. Achieving societal benefits requires linkages between subcomponents that improve system performance relative to those associated with multiple independent projects. Additional studies or experience with HES are needed to determine whether they enable the provision of more grid services (or the same grid services at a lower cost), enhance reliability, or improve flexibility, resilience, or the

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[9] Emma Elgqvist, Kate Anderson, and Edward Settle. *Federal Tax Incentives for Energy Storage Systems* (Golden, CO: NREL, January 2018, NREL/FS-7A40-70384), https://www.nrel.gov/docs/fy18osti/70384.pdf.

[10] Trieu Mai, Wesley Cole, and Daniel Greer, "The Prospective Impacts of 2019 State Energy Policies on the U.S. Electricity System," *Energy Policy* (149), 112013, https://doi.org/10.1016/j.enpol.2020.112013.

[11] Some balancing authorities directly charge wind and solar generators for integration charges. However, others that are operated by electric utilities that also procure or build electric generation add integration charges to projected costs of wind and solar in any integrated resource plans (IRPs) they produce or in competitive solicitations for generation. See, for example, K. Porter, S. Fink, M. Buckley, J. Rogers, and B.-M. Hodge. *A Review of Variable Generation Integration Charges* (Golden, CO: NREL, March 2013, NREL/TP-5500-57583), https://doi.org/10.2172/1069158.

[12] The difference between energy scheduled and actual energy generated is classified as imbalance energy. Balancing area authorities have implemented (Federal Energy Regulatory Commission-approved) energy imbalance service tariffs to discipline market participants and discourage unfavorable operating practices. See, for example, Y. Wan, M. Milligan, and B. Kirby. *Impact of Energy Imbalance Tariff on Wind Energy*. Presented at the AWEA WindPower 2007 Conference, Los Angeles, California, June 3–6, 2007 (Golden, CO: NREL, July 2007, NREL/CP-500-40663), https://www.nrel.gov/docs/fy07osti/40663.pdf.

Potential Drivers	Examples
	environmental footprint of the power system relative to what could be achieved with multiple independent projects.
Flexible commodity production	Certain hybrid configurations can apportion thermal and electrical energy to provide responsive generation to the power grid while also supporting the production of other energy products (e.g., hydrogen, ammonia, water, or liquid transport fuels). The ability to switch between products gives owners more flexibility to optimize their plant operations, obtain greater benefits from existing investments, extend the life of existing assets, and respond to price volatility and future uncertainty.[13]
Investment risk reduction	The future evolution of the energy sector depends on many uncertain factors. Decisions to commit the capital needed to build new assets are based on expectations of this uncertain evolution. Any technology that can adapt to unforeseen changes introduces optionality that will help mitigate investment risks.[14] These adaptions can include modular sizing to allow phased expansion as uncertainties are resolved, adapting dispatch to respond to changing timing of need, or even changing the provision of services to match evolving market needs. This adaptability is not unique to HES, but bringing multiple technologies together may enhance it relative to the individual components and may thereby lower investment risks.
Resilience	Hybrid energy systems' multiple generation and storage subsystems can increase plant-level and system resilience by maintaining power during an event, and providing additional recovery services (e.g., black start) after an event has passed.[15]
Environmental sustainability	Hybridization with renewable energy systems allows for energy arbitrage to displace high emission thermal units. Hybridization with conventional baseload thermal allows for resource operational optimization to avoid off-design operations that result in emissions increases and increased unit operating costs.

Because of their multitechnology nature, HES often comprise technologies that are typically studied separately within their respective DOE offices. Similarly, HES are sometimes investigated by individual offices, based on the technical details or nuances of a specific combination of technologies (or subcomponents). Whereas these technology-specific details are important and relevant, many aspects that are crosscutting and will be relevant to other technologies. HES are already an area of significant interoffice collaboration, but actively seeking additional opportunities to coordinate research and development (R&D) across offices would maximize the value realized from these investments.

In this report, the DOE Hybrids Task Force seeks to highlight critical issues, gaps, and priorities that are relevant for multiple DOE program offices and to identify research activities where the offices can work together to increase impact. This work is focused on understanding what makes a hybrid different from multiple independent technologies, in terms of both the research being performed and the challenges that ongoing and planned research will seek to address. To this end, multiple DOE program offices jointly supported

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[13] See for example, Shannon Bragg-Sitton, Cristian Rabiti, James O'Brien, Terry James Morton, Richard D. Boardman, SuJong Yoon, et al. *Integrated Energy Systems: 2020 Roadmap* (INL, September 2020, INL EXT-20-57708, Revision 1), https://doi.org/10.2172/1670434.

[14] Antonio J. Conejo, Luis Baringo Morales, S. Jalal Kazempour, and Afzal S. Siddiqui. *Investment in Electricity Generation and Transmission* (Cham: Springer International Publishing, 2016), https://doi.org/10.1007/978-3-319-29501-5.

[15] See for example, Douglas Arent, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems, July 24–25, 2018* (Golden, CO: NREL, December 2018, NREL/TP-6A70-72926), https://doi.org/10.2172/1488918.

a synthesis, assessment, and opportunities analysis of research activities that have been dedicated to the exploration and advancement of HES. Under the guidance of these supporting DOE program offices, researchers from multiple DOE National Laboratories performed and supported this analysis, including:

- National Renewable Energy Laboratory (NREL)
- Lawrence Berkeley National Laboratory (LBNL)
- Idaho National Laboratory (INL)
- Argonne National Laboratory (ANL)
- Pacific Northwest National Laboratory (PNNL)
- Oak Ridge National Laboratory (ORNL)
- Sandia National Laboratories (SNL)
- National Energy Technology Laboratory (NETL).

1.1 Classifying HES: Types and Linkages: Types and Linkages

Given the definition adopted in this report, HES encompass a broad universe of generation, storage, and conversion subcomponents (Figure 1, page 2). Combining the constituent subcomponents in HES can be achieved through locational and operational linkages, where the former is defined as siting multiple technologies together (i.e., colocating them), and the latter is defined as operationally linking technologies through an overarching (or joint) control framework and physical linkages. Such systems can be deployed in either front-of-the-meter (e.g., utility-scale plants, aggregated distributed energy resources [DERs], or multicustomer microgrids), behind-the-meter (e.g., customer-sited or single-customer microgrids), or off-grid applications. In this report, the DOE Hybrids Task Force delineates HES based on their ultimate products, with the two primary categories being electricity-only HES and multi-vector HES.

1.1.1 Electricity-Only HES

Electricity-only HES combine multiple electricity generation and energy storage technologies, and their only output is electricity, which is used to provide energy, capacity, essential reliability, and other services within electricity markets. These types of HES are being deployed and are increasingly appearing in independent system operator/regional transmission operator (ISO/RTO) interconnection queues, as well as in utility competitive solicitations. Electricity-only HES account for most of the HES on the power system today (Figure 2, page 3), in the form of battery storage with solar PV, wind, hydropower, or fossil generators; wind with PV; and fossil plants with PV. At the end of 2019, there were more than 110 gigawatts (GW) of HES in 37 interconnection queues across the United States;[16] as of October 2020, over 95% of the capacity in the

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[16] Ryan Wiser, Mark Bolinger, Will Gorman, Joe Rand, Seongeun Jeong, Joachim Seel, Cody Warner, and Ben Paulos. *Hybrid Power Plants: Status of Installed and Proposed Projects*, (LBNL, July 2020), https://eta-publications.lbl.gov/sites/default/files/hybrid_plant_development_2020.pdf.

California Independent System Operator's (CAISO's) interconnection queue were HES;[17] and nearly one-third of the projects bid into Xcel Energy's 2017 all-source competitive solicitation for Colorado were HES.[18]

The subcomponents (or constituent technologies[19]) in electricity-only HES can be linked locationally and/or operationally[20] and can thus be categorized into one of three hybrid types: colocated resources, virtual power plants, and full hybrid systems.

Colocated resources involve two or more energy technologies that are linked locationally (e.g., they share a point of interconnection), but whose operations are largely independent (Figure 3). An owner of colocated resources may make strategic decisions to maximize value of the joint system, but given the lack of shared components and controls, colocated resources would exhibit operational behaviors similar to those of their fully independent alternatives. The constituent technologies in colocated resources are typically treated as independent resources at the point of interconnection (e.g., with multiple identification numbers), so the primary anticipated benefit of hybridization through colocation alone is that the constituent technologies share balance-of-system (BOS) costs and an interconnection.

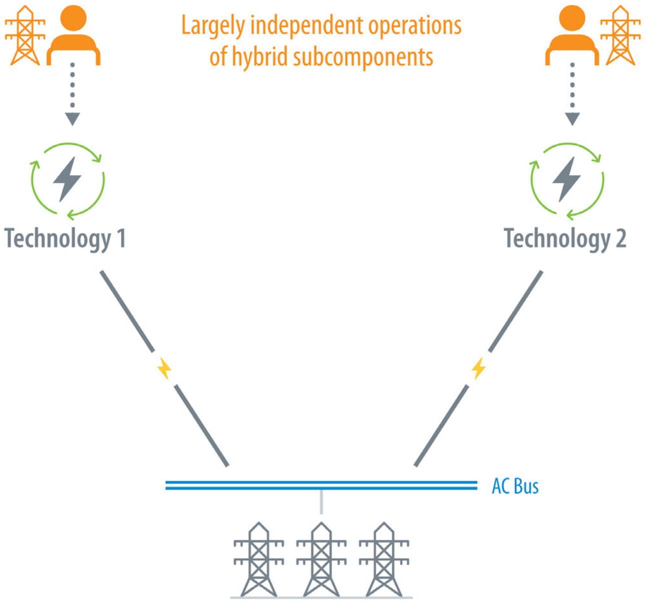

Figure 3. Colocated resources

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[17] CAISO. "California ISO Controlled Grid Generation Queue," accessed October 16, 2020, http://www.caiso.com/planning/Pages/GeneratorInterconnection/Default.aspx.

[18] Xcel Energy, 2017, "2016 Electric Resource Plan: 2017 All Source Solicitation 30-Day Report (Public Version)" Colorado Public Utilities Commission Proceeding No. 16A-0396E. https://assets.documentcloud.org/documents/4340162/Xcel-Solicitation-Report.pdf.

[19] The terms "technologies" and "subcomponents" are used interchangeably in this section. The term subcomponents refers to the data label within the inventory, which captures a hybrid system's constituent technologies within a given DOE-funded project.

[20] Caitlin Murphy, Anna Schleifer, and Kelly Eurek, "A taxonomy of systems that combine utility-scale renewable energy and energy storage technologies," *Renewable and Sustainable Energy Reviews* 139 (April 2021): https://doi.org/10.1016/j.rser.2021.110711.

Virtual power plants involve two or more energy technologies that are sited separately but virtually linked through software, an overarching controls framework, or both (Figure 4). Unlike general grid balancing, virtual power plants involve jointly optimizing the dispatch of multiple energy assets at a level below that of the broader bulk power system operator. General motivations for a purely operational linkage include seeking the ability to leverage complementarities in location-specific resource characteristics, qualify for the provision of services for which each individual plant could not qualify, and avoid integration or imbalance penalties that might be imposed on an individual plant. When connected to the transmission network, a virtual power plant could take the form of aggregating smaller, dispersed assets to enable them to participate in wholesale markets as one larger "hybrid" plant. In a distribution-connected setting, the virtual power plant category could similarly correspond to aggregated DERs.

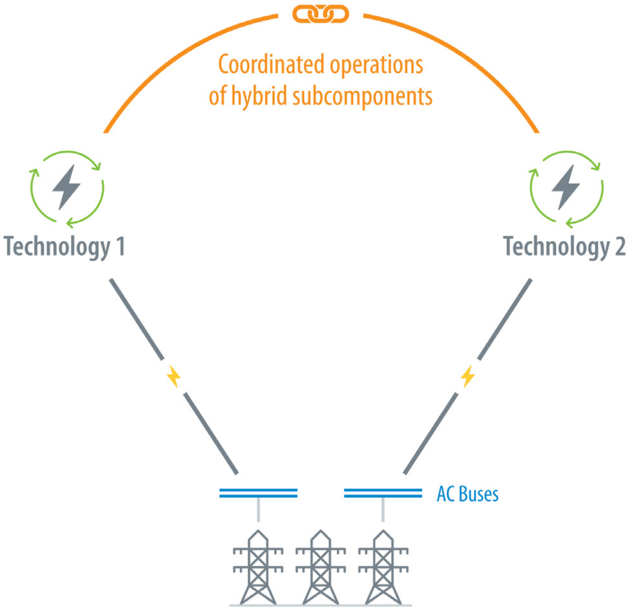

Figure 4. Virtual power plants

Full hybrid systems involve multiple technologies that are both locationally and operationally linked (Figure 5). The design, configuration, and operation of the constituent technologies are fully integrated, such that operational and cost synergies can be achieved by sharing of key components (e.g., a shared inverter between PV panels and a battery system, a shared thermal conversion system between CSP and geothermal systems, or thermal energy storage integrated with a natural gas combined-cycle plant). The constituent technologies in a full hybrid are operated under a single control scheme or strategy, so the entire system can operate more efficiently and be treated as a single resource at the point of interconnection (e.g., with one ID number). In a distribution-connected setting, a full hybrid configuration could take the form of a microgrid (when spanning multiple customers; see Text Box 1) or a single customer-sited deployment of multiple, fully integrated technologies.

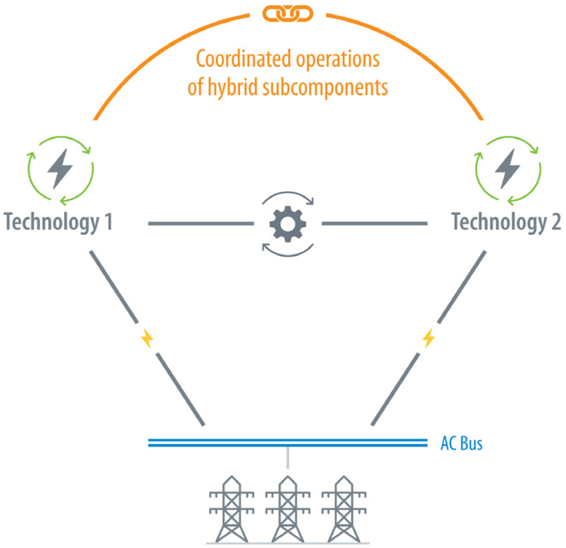

Figure 5. Full hybrid systems

1.1.2 Multi-Vector HES

Multi-vector hybrids similarly comprise multiple generation, storage, and conversion technologies, but their outputs include electricity and at least one other energy or nonenergy product. Examples of coproducts include thermal energy, hydrogen, ammonia, methanol, desalinated water, materials, and liquid fuels. These systems dynamically apportion thermal and electrical energy to provide responsive generation to the power grid while also supporting the production of other products. Though multi-vector HES are in an earlier stage of development than electricity-only systems, the potential benefits have garnered increasing interest in stakeholders from industry, government, academia, and the DOE National Laboratories. Additionally, many of the electricity-only approaches have the potential to expand into multi-vector operations (e.g., using onsite production of hydrogen as a coproduct through electrolysis).

Text Box 1. Hybrid Energy Systems and Microgrids

The topics of hybrid energy systems and electricity microgrids overlap both conceptually and practically: they both address creating electrical domains (or subsystems) that are distinct from the utility grid at large. Whereas HES involve multiple energy technologies that are locationally and/or operationally linked, a microgrid is defined as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries, which acts as a single controllable entity with respect to the grid. Comparing these definitions reveals overlap between microgrids and a subset of HES: a hybrid energy system that can serve local energy consumers when islanded from the larger grid is also a microgrid, whereas HES that only generate power for injection into the grid are not.

The local reliability that can be achieved by microgrids (and the corresponding subset of HES) is very valuable for most applications, and the operational control that hybrids generally have is most of what is needed to create microgrid capability. Given this close connection, it makes sense to create one technology base for such local power coordination, to make it easy for any hybrid to become a microgrid and vice versa. HES need to understand the relative value of different sources and forms of energy to properly balance choices among them. This also applies to microgrids, as they will always have some source of local generation, usually have a battery, and they sometimes have a connection to a utility grid, each with a value. For both hybrids and microgrids, the value of different sources may vary over time.

Unlike the three categories described for electricity-only HES, multi-vector HES exclusively take the form of full hybrids (Figure 5). The design, configuration, and operation of the constituent technologies are fully integrated, such that benefits (financial and social) can be realized by maximizing electricity sales when the grid requires electricity and provisioning energy to the alternative product or products when the value of electricity on the grid is low. A single interconnection provides the grid with a highly flexible electricity source, and the HES economics are improved by increasing the capacity factor of expensive components. In addition, low-cost, clean energy is available for nonelectricity products. Some specific examples of approaches leveraging integrated hybrid energy systems are shown in Figure 6 and include:

- **"FlexPower" Hybrid Plants:**[21] FlexPower plants (Figure 6a, page 12) are being developed as multi-megawatt (MW) scale hybrid power generation systems to produce electricity while providing various types of energy and grid services. Component technologies that can be integrated into a FlexPower plant include multiple generation options (e.g., wind, PV, and hydropower), multiple storage options (e.g., lithium-ion batteries, hydrogen, and pumped-storage hydropower [PSH]), as well as flexible AC transmission systems (FACTS). Projected benefits of this hybrid approach include but are not limited to dispatchability, energy shifting, flexibility, scalability, essential and advanced reliability services, resiliency and robustness, ultrawide dynamic ranges, synchronizing torque, grid forming/black start, and grid-connected and islanded operation. DOE, working with its National Laboratories, is engaged in analytical and experimental validation of the FlexPower concept.
- **Multi-Vector Options Leveraging Concentrating Solar Power:** Concentrating solar power (CSP) offers unique opportunities for hybridization through its leveraging of the high-quality heat generated by a 1,000x or higher concentration of sunlight. As illustrated in Figure 6b this heat can be stored and used to produce electricity (even when the sun is not shining) and other coproducts and services[22]. A key value proposition of CSP is its ability to enable solar electricity on demand through low-cost integration of thermal energy storage coupled with traditional turbine-based heat engines. This combination of readily scalable energy storage and proven turbine technology can provide reliable and flexible renewable electricity production. Moreover, CSP technologies can also be used to collect, store, and distribute the heat for various industrial applications, such as district heating and synthesis of fuels and chemicals (e.g., hydrogen, which could be efficiently produced by thermo-electrochemical processes leveraging both the heat and electricity available at the CSP plant).
- **Nuclear-Renewable Hydrogen Hybrid Systems:** Industry stakeholders, partnering with DOE, universities, and the DOE National Laboratories, are exploring the potential for nuclear-hydrogen hybrid energy systems leveraging hydrogen production technologies such as low-temperature electrolysis and high-temperature steam electrolysis. This multi-vector approach (Figure 6c, page 12) offers coproduction of a valuable chemical commodity (e.g., hydrogen or other hydrogen-based fuels and chemicals) along with grid services through the integration of nuclear generation with variable renewable generation. Recent analysis[23] has focused on the financial opportunities from both the nuclear power plant's perspective and

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[21] The "FlexPower" concept, which is under investigation by DOE's GMLC, is described in detail in Section 5.2.

[22] See, for example, "Concentrating Solar-Thermal Power," DOE, accessed February 5, 2021, https://www.energy.gov/eere/solar/concentrating-solar-thermal-power

[23] See for example, Konor Frick, Paul Talbot, Daniel Wendt, Richard Boardman, Cristian Rabiti, Shannon Bragg-Sitton, Daniel Levie, et al. *Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest* (Idaho Falls: INL, September 2019, INL/LTD-19-55395, Revision 0), https://doi.org/10.2172/1569271.

See also:

from the overall perspective of grid operating costs. Key findings include (a) producing hydrogen can increase profitability of many existing nuclear power plants; (b) using thermal energy from nuclear power plants in steam electrolysis is more valuable than selling electricity under many market scenarios; (c) because hydrogen storage can be expensive, either the hydrogen needs to feed into a market with flexibility or the nuclear power plant needs to be able to maximize hydrogen production at times when power prices are low.

New Approaches to Fossil-Based Energy Leveraging Hybridization: Unique potential benefits of hybridizing traditional fossil energy generation by integration with carbon capture, utilization, and storage (CCUS) technologies, and with energy storage technologies, as well as chemical conversion and thermal management options are being explored in the Coal FIRST (flexible, innovative, resilient, small, transformative)[24] initiative. One of the diverse approaches under consideration integrates an ultra-supercritical (USC) coal-fired boiler with carbon capture in conjunction with thermal energy storage and hydrogen production via electrolysis, as illustrated in Figure 6d. As another example, integrated energy systems are under development that leverage hybrid coal and natural gas boiler/turbine and/or solid-oxide fuel cell technologies as the primary energy source in conjunction with multiple energy storage and coproduction options, including hybrid lithium-ion/redox flow batteries, compressed air energy storage (CAES), electrothermal systems, liquid air or oxygen, and syngas, which could also be used for polygeneration of energy carriers and/or chemicals.

"Department of Energy Announces $40 Million in Funding for 29 Projects to Advance H2@Scale," DOE, August 15, 2019, https://www.energy.gov/articles/department-energy-announces-40-million-funding-29-projects-advance-h2scale.

"U.S. Department of Energy Announces $26.9 Million for Advanced Nuclear Technology," DOE, October 8, 2020, https://www.energy.gov/ne/articles/us-department-energy-announces-269-million-advanced-nuclear-technology.

[24] The Coal FIRST initiative in the U.S. DOE Office of Fossil Energy is developing the coal plant of the future needed to provide secure, stable, reliable power, with near zero emissions ("Coal FIRST," DOE, https://www.energy.gov/fe/coal-first).

See also "U.S. Department of Energy Invests $7 Million for Projects To Advance Coal Power Generation Under Coal FIRST Initiative" (NETL, October 11, 2019), https://www.netl.doe.gov/node/9282.

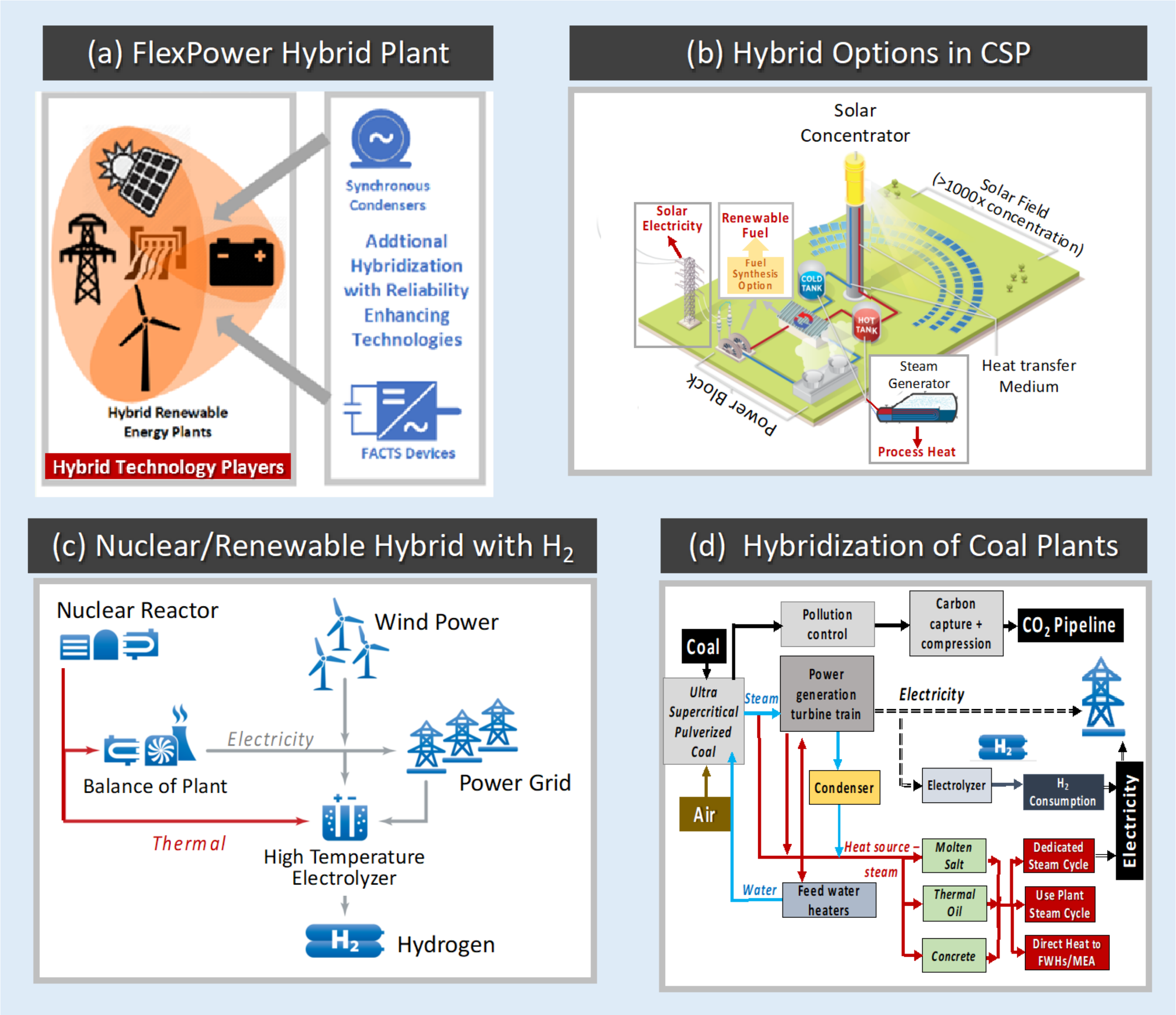

Figure 6. Examples of HES that leverage diverse power generation sources and are integrated with various storage and conversion technologies for production of electricity and value-add coproducts and services[25]

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[25] The graphics in Figure 6 were derived from the following sources:

(a) Original DOE illustration adapted from the GMLC FlexPower project;
(b) Original DOE illustration adapted by EERE's Solar Energy Technologies Office and Hydrogen and Fuel Cell Technologies Office;
(c) Original DOE illustration adapted from Tri-Laboratory R&D activities, such as those reported in https://www.osti.gov/servlets/purl/1569271; and
(d) Original DOE illustration adapted from the GMLC DISPATCHES project on Tightly-Coupled Hybrid Systems.

1.2 Research Areas

Research activities that are both underway and recommended for the advancement of beneficial HES are as categorized below and as summarized in Figure 7:

- Markets, policy, and regulation;
- Valuation; and
- Technology development.

These three research areas are closely interrelated: technology development activities and markets, policy, and regulation both influence the value that can be provided (and captured) by candidate HES. Similarly, valuation research can help inform which technology development activities would be most beneficial, and which market rules and regulations that define participation models for HES would be most helpful. Moreover, these three research areas apply equally to electricity-only and multi-vector HES and, unless otherwise noted, the challenges and opportunities outlined in this report are relevant to both. For example, electricity-only and multi-vector hybrids share a need for controls that can optimize the operations of linked technologies, the complexities associated with optimizing the design of a system with linked technologies, and the methods and approaches for valuing the joint system. However, market and policy factors may be more distinct between these two categories because of the different mechanisms for and degrees of regulation across different segments of the energy (and nonenergy) sectors.

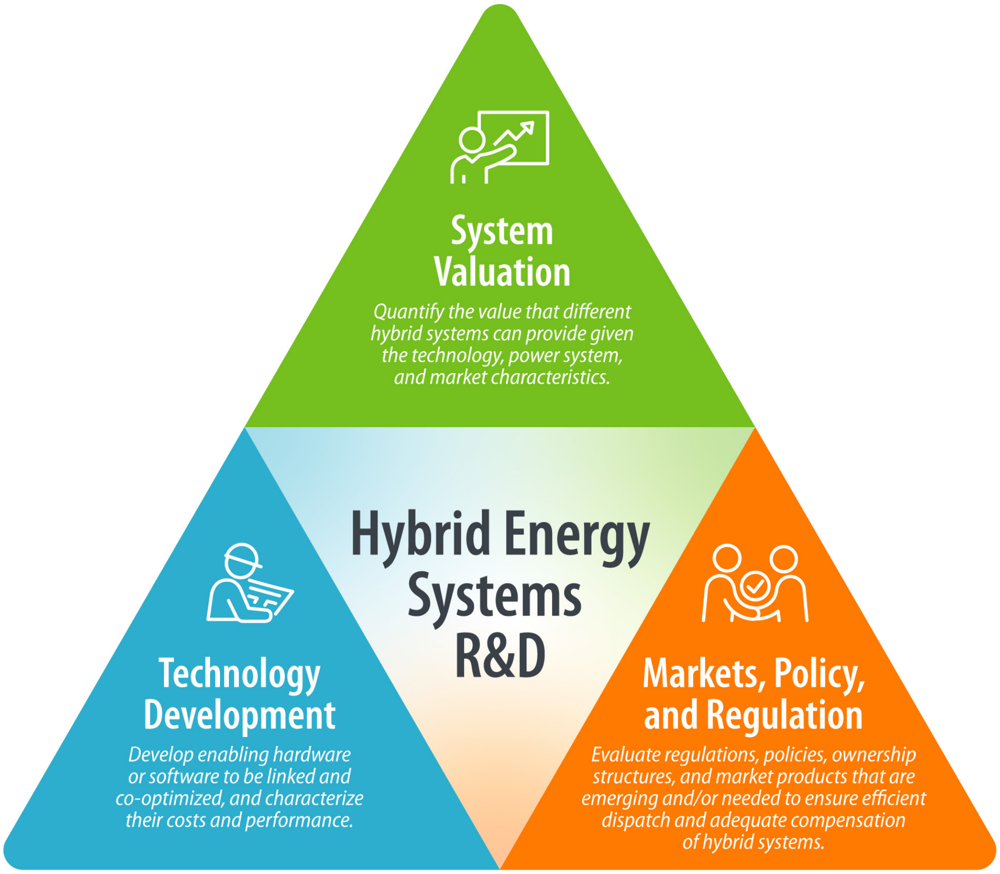

Figure 7. Summary of research areas that define HES R&D

1.3 Report Impacts

This report is designed to answer the question: *What are the near-term opportunities for DOE research activities related to HES that have high priority, would have high impact, and would cut across multiple DOE offices?* In answering this question, a key outcome of this report is to inform DOE R&D activities, with a focus on collaboration opportunities that maximize social, financial, and environmental benefits. To that end, this report identifies R&D opportunities that would facilitate (a) leveraging federal funding more effectively and efficiently, and (b) improving the cost and performance of key foundational and enabling technologies for hybridization. Moreover, the opportunities identified herein are designed to:

- *Support public goals* by providing timely, publicly available information and technical assistance to federal and state regulators, state energy offices, ISOs/RTOs, utilities, and smaller firms that might lack the resources to undertake their own R&D or analysis;
- *Provide incremental value* by exploring issues related to markets, policy, and regulatory challenges that would not otherwise be comprehensively or objectively addressed by stakeholders;
- *Have spillover benefits* by furthering knowledge and analysis techniques relevant to sources of flexibility and grid services beyond those offered by HES;
- *Promote convergence* by building consensus among industry groups, market participants, and other stakeholders on key issues about HES and analytical methods for evaluating them; and
- *Create interoperability* by creating technology suitable for inclusion in technology standards so that products from diverse manufacturers can readily work with each other.

Beyond informing DOE R&D activities, enhancing coordination across DOE could increase the research's value to a wide variety of stakeholders, especially those engaged in efforts to design and implement effective policies and regulations, invest in and deploy HES, develop strategies for designing and operating HES to provide maximum value to the grid and end users. Each of the key audiences for HES research listed in Table 2 could benefit from the public release of information and tools that could be developed through coordinated HES research across DOE offices.

Table 2. Key Audiences for DOE-Funded HES Research

Audience	Key Activities that Could Be Informed by this Report
Technology developers	Optimizing the design and operation of HES
Project developers	Deploying HES in a way that maximizes value
Local officials	Addressing local siting, safety, and resilience issues
Utilities	Procuring services from HES to cost-effectively increase reliability and resilience; conducting resource planning
State and Tribal Governments	Designing and implementing policies and programs; coordinating R&D and commercialization activities led by state energy offices
Public utility commissions (PUCs)	Evaluating whether investments are just and reasonable; overseeing utility planning and procurement
ISOs/RTOs	Designing and operating efficient markets; avoiding artificial barriers to HES market participation
North American Electric Reliability Corporation (NERC)	Regulating bulk-power system users, owners, and operators who have responsibilities to meet requirements of NERC reliability standards
Federal Energy Regulatory Commission (FERC)	Regulating the interstate transmission of energy along with natural gas and hydropower projects; regulating markets for procuring economically efficient, safe, reliable, and secure energy services

1.4 Coordination with Other DOE Initiatives

The challenges that are highlighted in and underpin this report—in particular those related to policy and valuation—are not always unique to HES and are being faced by other sources of flexibility and grid services. Addressing these challenges will therefore require close coordination with other DOE initiatives, including:

- **Energy Storage Grand Challenge:**[26] The Energy Storage Grand Challenge (ESGC) is a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies. Through the ESGC, DOE will deploy its extensive resources and expertise to address the technology development, commercialization, manufacturing, valuation, and workforce challenges to position the United States for global leadership in the energy storage technologies of the future.
- **Grid Modernization Initiative:**[27] The Grid Modernization Initiative (GMI) works across DOE and with public and private partners to develop the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control the grid of the future. As part of GMI, the Grid Modernization Laboratory Consortium (GMLC) was established as a strategic partnership of DOE and its National Laboratories to bring together leading experts, technologies, and resources to collaborate on the goal of modernizing the nation's grid.

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[26] More information: "Energy Storage Grand Challenge," DOE, accessed February 5, 2021, https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

[27] More information: "Grid Modernization Lab Consortium," DOE, accessed February 5, 2021,https://www.energy.gov/grid-modernization-initiative-0/grid-modernization-lab-consortium

- **Applied Energy Tri-Laboratory Consortium:**[28] DOE's three applied energy National Laboratories—INL, NETL, and NREL—formed this joint initiative to integrate and coordinate laboratory expertise and facilities that research integrated energy systems (including the multi-vector hybrid energy systems discussed in this report) and transition technology to industry.

The research opportunities presented in this report should result in activities that complement and tie to these three ongoing initiatives to minimize redundancy and optimize the use of resources.

1.5 Report Organization

The report is organized as follows:

- Section 2 presents state-of-the-art HES research activities, based on the present synthesis and assessment of recent and ongoing HES research.
- Section 3 summarizes key challenges facing HES, based on a survey of industry literature and interviews with key industry stakeholders and researchers.
- Section 4 presents the findings of our opportunities analysis, including key R&D activities that could benefit from coordinated support and guidance by multiple DOE offices.
- Section 5 concludes the report by highlighting potential mechanisms for enhanced collaboration across DOE offices, along with select examples of how such mechanisms have been used to support existing projects and DOE National Laboratory capabilities that are already beginning to advance the state-of-the-art for electricity-only and multi-vector HES.
- Appendix A presents a summary and inventory of research capabilities at DOE National Laboratories that are relevant for HES, with entries provided by individual representatives from each National Laboratory.
- Appendix B presents a summary of HES-related research being performed by the Electric Power Research Institute.
- Appendix C presents a list of markets, policy, and regulation challenges facing HES, and categorizes those issues at a more granular level than what is included in the body of this report.
- Appendix D presents a list of electricity market and broader grid services that could be provided by HES.
- Appendix E presents a list of acronyms and abbreviations included in this report.

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[28] More information: Douglas Arent, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems, July 24–25, 2018* (Golden, CO: NREL, December 2018, NREL/TP-6A70-72926), https://doi.org/10.2172/1488918

2 State-of-the-Art Hybrids Research and Development

This section assesses state-of-the-art research and development (R&D) in order to identify key technical, valuation, and regulatory challenges related to hybrid energy systems (HES). Our summary of state-of-the-art R&D is primarily rooted in an inventory of recent, ongoing, and planned HES research that is supported by DOE, including the research capabilities that it has developed (or is developing) at its National Laboratories. To understand how this inventory of DOE-funded research relates to activities across the broader research community, insights that are gained from it are placed within the broader context of various additional sources of state-of-the-art R&D for HES (Table 3).

Table 3. Sources of Information for State-of-the-Art R&D Activities for HES

Source	Description
Inventory of DOE-funded research related to HES (primary source)	The DOE Hybrids Task Force compiled an inventory of more than 100 HES-related research projects led by the DOE National Laboratories, industry, and universities that have been funded by DOE within the last 5 years.
Inventory of relevant research capabilities at DOE National Laboratories	The DOE National Laboratory participants in this report submitted lists of capabilities at their institutions that can support research related to HES. The resulting inventory provides insights into the capabilities that could be leveraged for HES research; however, (1) the survey likely did not capture all the relevant capabilities and (2) most capabilities were not designed for, but may be amenable to, HES research. The inventory of submitted capabilities is included in Appendix A.
Non-DOE-funded HES research at DOE National Laboratories	Researchers from the DOE National Laboratories self-reported on HES-related research activities that were funded by other public or private sources.
Academic Literature	A repository of journal articles and technical reports (Scopus) was queried to reveal articles about HES that were published between 2013 and 2020.[29] The insights gained from the literature about state-of-the-art HES research provides context (and complements) the DOE-funded research portfolio.[30]
HES-related research being performed by the Electric Power Research Institute	The Electric Power Research institute (EPRI) is engaged in a wide range of HES-related research, which is based on guidance from industry members (including utilities and ISOs) on high-priority R&D topics. This research often complements, or is in collaboration with, that of DOE and its National Laboratories. A technical memo summarizing EPRI's HES R&D activities is presented in Appendix B.

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[29] After querying the Scopus database, a combination of key word searches and text analysis of the resulting abstracts resulted in a list of a little more than 11,000 papers that mention HES in the context of electricity and were published between 2013 and 2020. We then "subsetted" this list to exclude only papers with fewer than 40 citations, a threshold that (a) was chosen to balance obtaining a sufficient sample size while also allowing the manual portion of the selection process to be manageable and (b) likely limits the inclusion of recent articles. Finally, we manually filtered papers to ensure relevance, which resulted in a sample of 278 papers which, in total, have been cited more than 23,000 times.

[30] The approach and criteria of our literature review focused predominantly on HES that produce electricity as their only output. A broader literature review that targets multi-vector hybrids would likely produce additional insights.

Context from these additional sources is provided whenever possible, but the DOE Hybrids Task Force does not claim to have full visibility into ongoing HES research activities, because of the possibility of an incomplete sample of DOE National Laboratory research activities, the diversity of HES R&D activities funded by state energy offices,[31] the proprietary nature of privately-funded research, and the diverse array of HES-related research in the academic literature.

A review of these sources of state-of-the-art HES research reveals several themes:

- Generation technologies from all program offices are the subject of state-of-the-art HES research, most often through transmission-connected colocated resources and full hybrids.
- Energy storage—which spans technologies including batteries, thermal energy storage, and chemical energy storage in the form of hydrogen, formic acid, ammonia, or other chemicals—is the most common subcomponent in actively studied HES. The demonstrated interest in storage-based HES can be explained by energy storage's unique capabilities, recent cost and performance improvements, and ability to provide benefits to the full suite of generation technologies that fall under DOE program offices.
- Research involving HES that comprise PV, wind, and battery technologies is most abundant in DOE-funded, industry-led, and academic research, and it often has the stated motivation of enabling the more efficient integration of variable renewable energy technologies.
- DOE has supported collaborations with industry in the form of demonstration projects, which are designed to de-risk and explore the potential benefits of hybridization; select examples include the demonstration of hybridizing operating fossil fuel-fired power plants (e.g., with thermal energy storage) and nuclear power plants (e.g., with hydrogen production facilities).
- Distribution-connected HES are dominated by systems comprising PV, batteries, wind, and diesel generators, which are often combined for microgrid, remote grid, and resilience applications.
- DOE-funded HES research focuses on technology development and valuation, and only a small fraction of total projects targets markets, policy, and regulation issues facing HES.

The remainder of this section explores insights revealed within each individual research area, including markets, policy, and regulation (Section 2.1); valuation (Section 2.2); and technology development (Section 2.3). The following discussion includes detailed assessments of the extent to which the research topics listed in the tables in Section 2.1–2.3 (Tables 4–6) are being applied across the suite of subcomponents, across the hybrid types (colocated resources, virtual power plants, and full hybrids), and generally versus for specific HES.

2.1 Markets, Policy, and Regulation

Markets, policy, and regulation research topics related to HES extend across topic areas and jurisdictions, from federal regulation and wholesale markets to state utility regulation, state policy, and local regulation (Table 4). HES R&D activities in this research area have focused on wholesale electricity markets. Moreover, the discussion presented in this section is focused on electricity markets and regulation, because (a) the electric sector is highly regulated (relative to other energy and commodity markets) and (b) HES are challenging conventional approaches in markets, policy, and regulation. However, R&D at the DOE National Laboratories

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[31] The National Association of State Energy Offices (NASEO) summarizes programs related to technology innovation at "State Energy Office Roles in Technology Innovation," NASEO, accessed February 5, 2021, https://www.naseo.org/issues/technology-innovation/seo-roles.

has begun to address markets, policy, and regulatory questions about HES. These R&D activities include data collection and analysis, the development and application of modeling tools, and technical assistance to states and cities. HES R&D by the DOE National Laboratories seeks to provide analysis and data to help assess the impact of policies or to help others make decisions about policies, but it does not set or advocate for specific market outcomes or policies.

Table 4. HES Research Topics within the Markets, Policy, and Regulation Research Area

Research Topics	Examples
Wholesale markets	Interconnection, transmission planning, market participation models, market monitoring and mitigation, capacity accreditation and performance requirements, and market impacts
Commodity markets	Estimations of the size and value associated with nonelectricity markets, including existing and potential future markets, some of which will depend on policy (e.g., renewable fuels standards and clean energy standards)
State utility regulation	Interconnection, IRPs, procurement, contracting, resource adequacy, PURPA rules,[32] and utility retail rates
Federal and state policy	Federal tax credits, climate policies, renewable portfolio standards, clean energy standards, clean peak standards, storage carve-outs, and resilience
Local regulation	Safety standards and zoning codes

Examples of recent or ongoing market, policy, and regulation R&D by the DOE National Laboratories include the following.

- Recent work that finds growing commercial interest in renewable HES can be explained in part by a value premium that exceeds recent costs (inclusive of tax incentives that are unavailable to independent storage), though accessing the full value depends on nascent market participation models[33]
- Recent work that finds that the resource adequacy contribution of HES can be impacted by the strategy for coupling storage with a generator;[34] new work under the GMLC ISO/RTO Institutional Support project will examine resource adequacy for HES in much greater depth
- Recent work that calculates the potential for a nuclear power plant in the Midwest to increase its profit margins by hybridizing to produce hydrogen as well as sell electricity to the grid; by producing hydrogen

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[32] The Public Utility Regulatory Policy Act of 1978 (PURPA) requires utilities to purchase electricity from qualifying facilities at prices below the utility's cost of generation. Implementation of PURPA is state jurisdictional.

[33] Ryan Wiser, Mark Bolinger, Will Gorman, Joe Rand, Seongeun Jeong, Joachim Seel, Cody Warner, and Ben Paulos. *Hybrid Power Plants: Status of Installed and Proposed Projects* (LBNL, July 2020), https://eta-publications.lbl.gov/sites/default/files/hybrid_plant_development_2020.pdf.

Will Gorman, Andrew Mills, Mark Bolinger, Ryan Wiser, Nikita G. Singhal, Erik Ela, and Eric O'Shaughnessy, "Motivations and Options for Deploying Hybrid Generator-Plus-Battery Projects within the Bulk Power System," *The Electricity Journal* 33, Issue 5 (June 2020): https://doi.org/10.1016/j.tej.2020.106739.

[34] Andrew D. Mills and Pía Rodriguez. "A Simple and Fast Algorithm for Estimating the Capacity Credit of Solar and Storage." *Energy* 210 (2020): 118587. https://doi.org/10.1016/j.energy.2020.118587.

when the price of electricity is low and maximizing electricity sales when its price is high, the nuclear power plant can realize a net present value of $1.2 billion over a 17-year analysis period.[35]

- Work under the GMLC to support hybrid microgrid systems in rural Alaska under the Alaska Microgrid Partnership[36]
- DOE support to the Navajo Tribal Utility Authority (NTUA) for rural renewable HES
- Other work examining issues in modeling HES in transmission planning and interconnection studies (including limited work in Rhode Island, North Carolina, and Los Angeles[37]) and regulatory issues associated with HES in PURPA (small technical assistance activities supporting work in North Carolina and Idaho).

Appendix A provides an overview of the extensive capacity for HES R&D in the markets, policy, and regulation research area, including modeling, data analysis, technical assistance, and database and standards development. Though such capabilities are well established at the DOE National Laboratories, their application thus far in HES R&D has been limited in terms of its coverage of issues, technologies, and states.

In addition to the DOE National Laboratories, other organizations have also expanded R&D for HES. Responding to growing commercial interest in HES, several ISOs/RTOs have launched stakeholder initiatives to assess and address potential market barriers for HES.[38] CAISO's hybrid resources initiative has already made significant progress, which reflects the urgency of resolving questions about hybrid participation in the CAISO markets. CAISO's initiative will create a participation model for the coordinated operations of solar+storage and wind+storage generation resources, and plans are to implement rule changes in the fall of 2021.[39] FERC has also begun to examine market barriers for HES. In July 2020, FERC convened a technical conference focused on issues associated with potential barriers to hybrid generation and storage resources in three main areas: interconnection, market participation, and capacity accreditation.[40] FERC's interest in these issues for HES builds on related policy developments focused on interconnection practices (FERC Order 845), market participation of storage (FERC Order 841), and market participation of DERs (FERC Order 2222).

EPRI has undertaken member-funded work on capacity accreditation, participation models, and utility evaluation methods for HES. EPRI has also conducted R&D on the evolution of operations and planning with HES. Some of this work is coordinated with DOE-funded projects through the GMLC ISO/RTO institutional

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[35] Konor Frick, Paul Talbot, Daniel Wendt, Richard Boardman, Cristian Rabiti, Shannon Bragg-Sitton, Daniel Levie, Bethany Frew, Mark Ruth, Amgad Elgowainy, *Troy Hawkins. Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest* (Idaho Falls, ID: Idaho National Laboratory, September 2019, INL/EXT-19-55395), https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_18785.pdf

[36] For more information, see "Alaska Microgrid Partnership," GMLC, https://gmlc.doe.gov/projects/1.3.21.

[37] HES activities in Los Angeles represent a non-DOE-funded R&D effort.

[38] For an overview, see ESA, *Status of Hybrid Resource Initiatives in U.S. Organized Wholesale Markets*, (Energy Storage Association, April 10, 2020), https://energystorage.org/wp/wp-content/uploads/2020/04/ESA-Policy-Summary-on-Hybrid-Resources-Across-RTOs-and-ISOs_4_10_20.pdf.

[39] CAISO, *Hybrid Resources Draft Final Proposal* (California ISO, August 3, 2020), http://www.caiso.com/InitiativeDocuments/DraftFinalProposal-HybridResources.pdf.

[40] FERC, "Technical Conference regarding Hybrid Resources (Docket No. AD20-9-000)," (FERC, July 23, 2020), https://www.ferc.gov/news-events/events/technical-conference-regarding-hybrid-resources-docket-no-ad20-9-000-07232020.

support project, to which EPRI is a key contributor. EPRI also participates in the renewable energy HES work with NREL and LBNL, and nuclear HES work with INL.

Several other organizations also have ongoing R&D activities related to markets, policy, and regulation questions raised by HES. For example, the Energy Systems Integration Group (ESIG), a nonprofit educational association, has created a Hybrids and Emerging Flexible Resources Task Force to address technical and market issues associated with HES.[41] The Energy Storage Association (ESA) has reviewed barriers for HES, and ISO/RTO initiatives to address them, in organized markets.[42] State energy offices have also supported R&D for HES, though these have been more focused on distribution-connected HES, such as CHP for district heating.[43] Finally, the National Electric Reliability Corporation (NERC) has undertaken multiple activities that are relevant to HES. Its Inverter-Based Resource Performance Task Force (IRPTF) is developing a guidelines document for battery energy storage and hybrid generation systems, which includes a section on adequate modeling of such systems. NERC has also developed a draft whitepaper on ensuring energy adequacy with energy-constrained resources, which highlights questions about evaluating energy adequacy of battery storage in the context of increased uncertainty from variable resources.[44]

2.2 Valuation

Broadly speaking, active valuation research activities can be described based on what is included in the valuation and how the valuation is performed (Table 5, page 22). For HES, valuation research often targets a single candidate for a system (i.e., a specific set of subcomponents and linkages). Such an approach is sometimes needed to enable representation of the technology synergies that are unique to the hybrid (as opposed to multiple independent) systems. However, more-general valuation approaches—based on tools or methods that apply to many (or perhaps all) hybrid configurations—are also being pursued, and these may be preferable for those seeking to understand the merits of candidate HES relative to other HES and independent systems.

In general, HES valuation research seeks to evaluate the types of services and products that HES can provide and the values associated with them, both of which vary by region and HES make up. Shared costs represent another source of potential value for HES, but only limited research is currently dedicated to understanding the types and magnitudes of cost savings that are possible through hybridization (e.g., shared equipment,

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[41] "HyFlex: Hybrids and Emerging Flexible Resources," accessed February 5, 2021, https://www.esig.energy/hyflex-hybrids-and-emerging-flexible-resources/.

[42] Rob Gramlich, Michael Goggin, and Jason Burwen, *Enabling Versatility: Allowing Hybrid Resources to Deliver Their Full Value to Customers*, (Grid Strategies, Energy Storage Association, September 2019), https://energystorage.org/wp/wp-content/uploads/2019/09/2019.9.16-GridStrategies-ESA-White-Paper-on-Hybrid-Resources.pdf.

ESA, *Status of Hybrid Resource Initiatives in U.S. Organized Wholesale Markets* (Energy Storage Association), April 10, 2020), https://energystorage.org/wp/wp-content/uploads/2020/04/ESA-Policy-Summary-on-Hybrid-Resources-Across-RTOs-and-ISOs_4_10_20.pdf.

[43] See, for example, ICF, *Assessment of Program Options to Support Hybrid Systems with Solar, Storage and Combined Heat and Power: Final Report*, Prepared by ICF for New York State Energy Research and Development Authority (December 2019, https://dataint.s3.amazonaws.com/media/resources/Hybrid%20Solar_Storage_CHP%20Program%20Concepts%20White%20Paper.pdf.

[44] Mark G. Lauby, *Ensuring Energy Adequacy with Energy-Constrained Resources* (North American Electric Reliability, 2020, Whitepaper), https://www.nerc.com/comm/RSTC/AgendaHighlightsandMinutes/RSTC_Meeting_Agenda_Package_Dec_16_2020_ATTENDEE.pdf#search=Energy%2DConstrained%20Resources.

infrastructure, and BOS costs). In other words, HES costs are often considered in DOE-funded research as input assumptions, which are needed to evaluate economic performance metrics (e.g., the levelized cost of electricity or energy and related levelized cost of storage, life-cycle benefits, benefit-cost ratio [BCR], present value, and return on investment). Such limited treatment of HES costs can be problematic if it inhibits an adequate weighing of changes in monetizable value against changes in cost; though adding energy storage to a generation asset would add incremental value in many use cases, it is not always clear whether the added value outweighs the corresponding incremental cost (relative to the generation asset in isolation or independent systems for each subcomponent).

Of the limited DOE-funded research that has been dedicated to understanding HES costs, most recent and ongoing projects have focused on HES that combine renewable energy generation and storage (RE+storage) to form colocated resources or full hybrids. In addition, work under NE, FE, and the Applied Energy Tri-Laboratory Consortium[45] has begun to evaluate the costs associated with nuclear and fossil-based HES.

Table 5. Research Topics within the Valuation Research Area

Research Topics	Examples
What is included in valuation?	
Technology capabilities	Maximum output, duration, ramping, charge time, and minimum turndown
Grid services	Energy, capacity, and essential reliability services
Commodity products	Fuels, chemicals, heat, oxygen, hydrogen
Customer services	Time-of-use management and demand charge reduction
Nonmonetizable benefits	Inertial response, primary frequency response, resilience, and environmental benefits
Costs	Capital expenditures, operating expenses, financing, and tax credits
How is valuation done?	
Resource planning tools	Optimization of the hybrid system design; investments or deployments (within the broader grid mix) to maximize power system benefits
Operational tools	Simulation or optimization of the dispatch of defined HES to maximize power system benefits
Plant-level optimization	Optimization of hybrid system design; simulation/optimization of dispatch to maximize benefits for the hybrid system owner
Economic metrics	Metrics that summarize economic performance based on time-dependent costs and values; many are available.
Model linkage	Linking of existing models for each subcomponent or characteristics

In terms of how valuation is done, it is Important to differentiate research efforts that focus on plant-level optimization and those that focus on system-level optimization. Within our DOE HES project inventory (Appendix A), the most common scope for optimizing hybrid operation was at the plant-level, and it was typically for colocated resources and full hybrid systems. Optimizing the operation of electricity-only HES at the

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[45] See, for example, Douglas Arent, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems, July 24–25, 2018* (Golden, CO: NREL, December 2018, NREL/TP-6A70-72926), https://doi.org/10.2172/1488918.

grid level is less common, which is potentially problematic because the value proposition of HES may be distinctly different depending on whether you are evaluating HES from the perspective of the grid operator or the plant owner. For example, imperfect market rules can lead HES to operate in a way that maximizes revenue without providing incremental (or maintaining its) value to the broader power system.

An emerging area of emphasis involves exploring the extent to which HES can offer system-wide benefits—for example, in terms of increased utilization of the transmission network, improved reliability or resilience, or reduced environmental impact—relative to multiple independent systems for the same subcomponents. Model linkage is a common approach to these explorations, and there are examples of (a) linking plant-level and grid-level models (e.g., thermal models to grid operation and market models), and (b) linking capacity expansion and production cost models, the latter of which are especially important for the dispatch of energy storage subcomponents. Ongoing research at the DOE National Laboratories is also targeting an improved representation of HES in long-term planning and unit commitment models (see Appendix A), which reflects the needs of state regulators.

2.3 Technology Development

Technology development is the research area that is most often addressed in our DOE HES project inventory. This research is primarily applied to colocated resources and full hybrids, which reflects both the hardware-based and software-based research that is needed to develop HES in which the subcomponents are physically linked. Technology development research for virtual power plants is much more limited in frequency, and it is principally dedicated to distribution-connected systems (e.g., aggregated DERs and microgrids) comprising PV+battery, as well as wind and diesel subcomponents in select projects; such research may ultimately be relevant for utility-scale virtual power plants.

The technology development research area spans many topics (Table 6), ranging from hardware and software components to optimized conversion, hybridization, and coupling. DOE-funded research related to (a) optimized energy conversion and (b) hybridization and optimized system coupling (Table 6) spans a diverse array of technology subcomponents, which largely follows from the nature of the research subcategories: all generation technologies must explore the nature of hybridization that will result in cost and performance benefits, relative to independent systems. However, it also indicates the value associated with exploring a variety of technology combinations and couplings, particularly for HES that contain more exotic subcomponents or linkages (see Appendix A).

DOE-funded technology development research often deals with hardware components, with controls being the most frequently studied. Controls research for PV+battery HES is most abundant, while the addition of wind and diesel subcomponents is also common in distribution-connected HES, typically for microgrid and remote deployments. DOE is also funding integration and testing capabilities for a broad range of HES that include fuel cells, electrolyzers, thermal integration with power generators and heat users, and a diverse set of energy storage technologies (e.g., thermal, electrical, and chemical). Furthermore, recent capabilities for multi-vector (or multiproduct) systems include integration of hydrogen and chemicals production with supervisory control based on market signals.

Table 6. Research Topics within the Technology Development Research Area

Research Topics	Examples
Components and Subsystems	
Materials, manufacturing, and supply chain	Unique considerations and requirements for HES and commonly integrated subcomponents
Sensors/telemetry	Communications technologies for HES, including cybersecurity
Power electronics	Inverters, switchgear, transformer, and skid
Plant-Level Process Design and System Integration	
Optimized system coupling	Optimal linkages between hybrid system subcomponents
Optimized energy conversion and hybridization	Exploration of optimal strategies for maximizing efficiency, productivity, and value through conversion synergies
Hardware-in-the-loop	Real-time laboratory testing of components and/or systems under simulated use conditions
Controls	Theory, hardware, and optimization algorithms for subcomponents
Energy management system	Monitoring and software for energy supply and demand
Resource and demand forecasting	Incorporation of multiple forecasts for energy demand and resource availability into operational controls for HES
Integration with External Systems	
Electric Grid Integration	Management of electricity purchases and delivery with grid system operators
Natural gas network	Management of natural gas purchases and delivery with pipeline system owners and operators and with end-use customers
Validation, demonstration, and standards development	De-risking the components of and complete HES through real-world projects, which move DOE-funded research into the public arena and often involve industry partnerships

Beyond controls, DOE-funded research seeks to advance sensors and telemetry, cybersecurity, and in-the-loop testing; these aspects of DOE's HES R&D portfolio are particularly important, because a review of the academic literature indicates they are underrepresented there. This observation suggests DOE is addressing key gaps in the HES technology development research space. At the same time, the academic literature contains subcomponent combinations that are not well-represented in our DOE HES project inventory. For example, the academic literature revealed an emphasis on solving the challenges of heat on PV systems by pairing them with a thermal sink, which puts the generated heat to use. Batteries paired with a supercapacitor bank to produce a hybrid system with both high instantaneous and sustained discharge was also a common theme in the academic literature.

A final notable characteristic of DOE-funded and industry-supported research is its emphasis on technology transfer projects, which are often rooted in successfully transferring DOE-funded projects to the public arena. A key part of this work involves successful demonstration and implementation projects for HES in partnership with industry. Most DOE-funded demonstration projects involve cost-sharing and multistakeholder partnerships—comprising research institutions, utilities or electric operatives, and state or local government agencies—that help de-risk HES deployment and get industry buy-in.

Most non-DOE publicly funded HES research (reported by the DOE National Laboratories to the Hybrids Task Force) would be classified as either a technology transfer or a distribution-connected project, most of which include some form of microgrid performance assessment. These projects are again heavily focused on PV+battery systems, which are often deployed for resilience purposes at government facilities spanning various branches of the federal government. The deployed HES are often designed for a specific load profile, which most often corresponds to commercial building loads. Accordingly, the strong emphasis on PV+battery HES should be interpreted through the lens of cost-effectiveness for this specific use case, as there are likely other applications for which PV+battery systems may not be able to meet the needs of a given site (e.g., load profiles, limited tolerance for interruptions, reliability, and resilience).

Finally, EPRI's technology development activities for HES reveal similar trends overall, with several studies focusing on RE+storage and fossil fuel+storage hybrid types. EPRI research has also complemented DOE-funded demonstration projects through its Integrated Grid Pilot Projects, which involved some demonstration of HES including PV+storage.

3 Key Challenges Facing HES

Key challenges serve as the foundation for potential research opportunities, which should target the greatest barriers to HES advancement. The key challenges presented here are informed by a variety of factors:

- Research topics that are currently underrepresented across DOE's research portfolio and the broader academic literature (see Section 2);
- Lab-led interviews with stakeholders to identify key challenges that the energy sector currently faces but which fall outside stakeholders' targeted research activities; and
- Opinions of DOE National Laboratory researchers who are active in HES R&D.

To structure discussion about the key challenges, they are organized based on the larger research areas (markets, policy, and regulation; valuation; and technology development) and mapped to the different hybrid types (colocated resources, virtual power plants, and full hybrids).

3.1 Key Markets, Policy, and Regulations Challenges

To a large extent, wholesale electricity markets, electric utility regulation, and state energy policies were designed with the expectations that power generating facilities would only consist of a single technology type and system operators would optimize dispatch to minimize costs and maintain reliable operations across the full portfolio of available resources rather than having some resources optimize their operations independently.[46] The emergence of competitive HES (Figure 8)—which may be colocated in different electrical and resource configurations and operated as a single unit—is thus creating challenges for the design, operation, and regulation of wholesale electricity markets for both state regulation of electric utilities and the design and implementation of energy policies.

HES present challenges in terms of understanding their deployment under existing electricity market rules, policies, and regulations. Key challenges also exist in terms of understanding how their provision of services that are currently not currently monetized—energy storage, reliability/resilience, and environmental—could evolve with changes in electricity market designs (e.g., capacity market designs), changes in end-use technologies that affect the balance between electricity and fuel production, reliability/resilience needs (e.g., state resilience plans), and changes in environmental regulation (e.g., cap and trade systems). Better understanding and anticipation of the deployment of HES requires forward-looking analysis that examines the potential evolution of HES value over time.

The key markets, policy, and regulation challenges presented by HES vary by perspective, with the most important difference being between federally regulated ISO/RTO markets (Table 7, page 28) and state-regulated resource permitting, utility rate, and emissions and investment policies (Table 8, page 29). These challenges span a range of markets, policy, and regulatory processes, from long-term utility and ISO/RTO planning to the enforcement of state energy policies.[47] Finally, Table 7 and Table 8 represent the key

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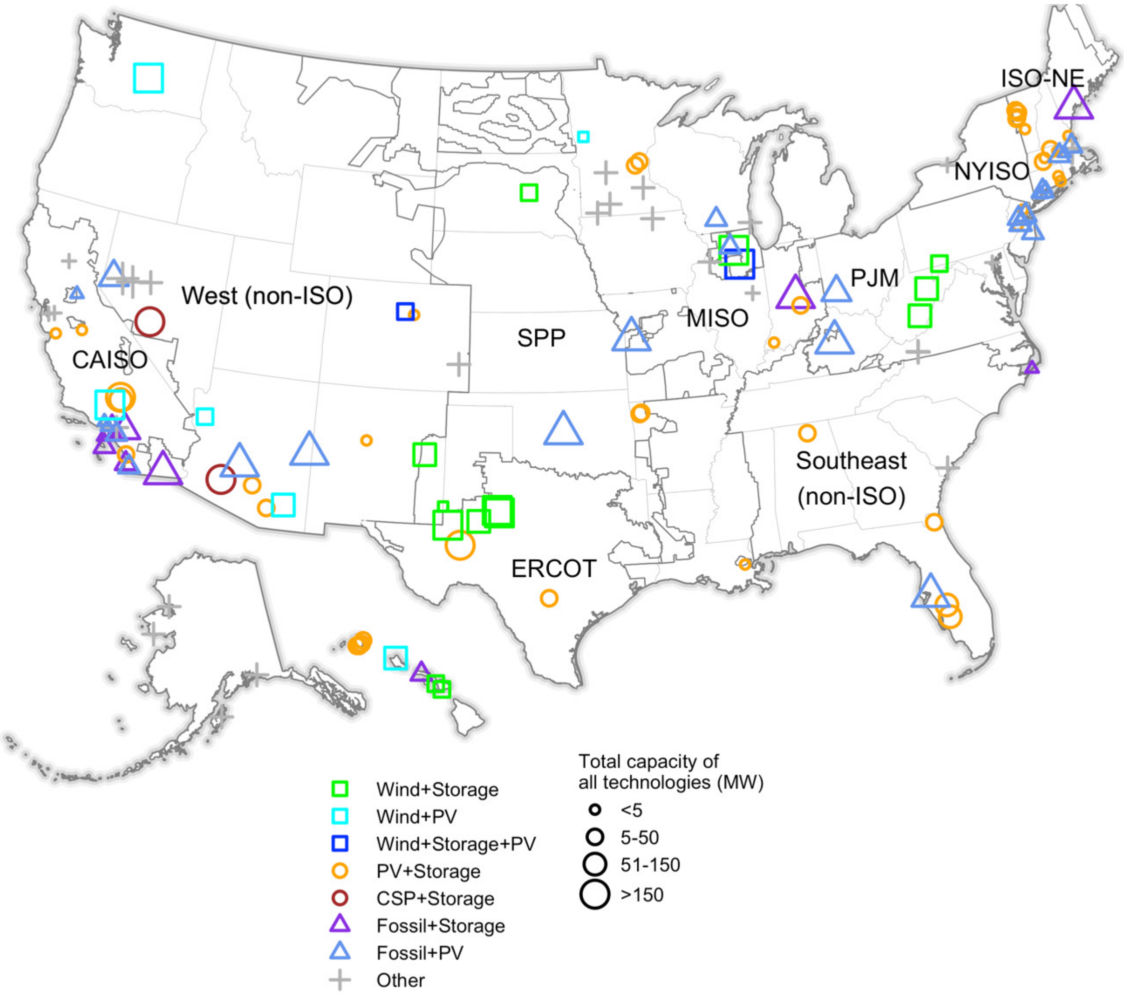
[46] Dual-fuel units that can burn natural gas or oil have long been in use in parts of the United States, but these are examples of a single technology with multiple fuels rather than multiple technologies within the same facility.

[47] For more on these challenges, see:

challenges facing hybrid systems within the markets, policy, and regulation research area; a more complete list—which presents a range of issues and the categorization of those issues at a more granular level—is included in Appendix C.



Source: LBNL analysis of EIA-860 data[48]

Figure 8. Map of all deployed electricity-only HES through 2019

CAISO, 2019, *Hybrid Resources Issue Paper*, (California ISO, July 18, 2019), http://www.caiso.com/InitiativeDocuments/IssuePaper-HybridResources.pdf

MISO, "Issue Tracking Details: Hybrid Resource Participation Model," (Midcontinent Independent System Operator, last modified December 10, 2020), https://www.misoenergy.org/stakeholder-engagement/issue-tracking/hybrid-resource-participation-model/

Rob Gramlich, Michael Goggin, and Jason Burwen, *Enabling Versatility: Allowing Hybrid Resources to Deliver Their Full Value to Customers* (Grid Strategies, Energy Storage Association, September 2019), https://energystorage.org/wp/wp-content/uploads/2019/09/2019.9.16-GridStrategies-ESA-White-Paper-on-Hybrid-Resources.pdf.

[48] The data presented here is based on original analysis for this report, but it was developed using a method that is similar to the one used by Ryan Wiser, Mark Bolinger, Will Gorman, Joe Rand, Seongeun Jeong, Joachim Seel, Cody Warner, and Ben Paulos. *Hybrid Power Plants: Status of Installed and Proposed Projects*, (LBNL, July 2020), https://eta-publications.lbl.gov/sites/default/files/hybrid_plant_development_2020.pdf.

Table 7. Key Challenges for HES within Federal Regulation and ISO/RTO Markets

Challenge	Description	Hybrid Type[49]
Lack of understanding of market trends and drivers for HES	Few HES are part of the U.S. power grid today, making it difficult to know what configurations of HES to expect in the future and what kinds of market tools HES will need to operate effectively. To make changes in market designs and rules that enable HES to provide its full value to market participants, federal regulators and ISOs/RTOs will need to better understand and anticipate the market forces and incentives that drive hybrid project development. Drivers of commercial interest in HES, and how these might change with changes in policies, market designs, and environmental regulation, are not yet well understood. Public domain information and analysis of the drivers of HES is currently limited.	Colocated resources, virtual power plants, full hybrids
Insufficient methods for modeling HES in transmission planning and interconnection studies	In transmission planning and interconnection studies, ISOs/RTOs and utilities simulate the performance of the grid based on specific assumptions about the operation of individual resources; however, the actual operation of HES may deviate from those assumptions, particularly if market participants co-optimize hybrid operations. Incorrect assessment of HES can lead to longer interconnection times and unnecessary transmission investment costs. Methods for modeling the market behavior and electrical characteristics of HES in different coupling configurations are not yet well-developed, nor are they validated against actual HES performance.	Virtual power plants, full hybrids
Underdeveloped methods for HES capacity accreditation	The capacity credit of a hybrid resource may be different from the sum of the capacity credits that would be awarded to individual resources (e.g., if a shared inverter limits total output relative to multiple independent systems); how HES are operated may also affect their capacity credit (and value). Capacity accreditation methods, analytical frameworks, and modeling tools for HES are not yet well-developed. More generally, capacity accreditation practices are in flux in many regions.	Virtual power plants, full hybrids
Lack of participation models for HES (forecast/bid parameters, related ISO/RTO scheduling processes)	HES often include multiple participation models (e.g., for the CAISO, a PV+storage facility includes an eligible intermittent resource [EIR] and non-generator resource [NGR], which are subject to different participation rules). Creating new participation models for HES might lead to an unwieldy proliferation of models, but existing participation models do not allow market participants to capture the value of HES. Another option being explored is having hybrid systems use existing participation models for conventional dispatchable generators. As part of these decisions, ISOs/RTOs must find a balance between allowing hybrid owners to optimize their own resources and ensuring system reliability. Additionally, ISOs/RTOs have not yet resolved issues associated with the treatment of HES with different coupling configurations in participation models. Finally, flexible participation models may be particularly important for multi-vector hybrids as their participation in ISO/RTO markets will need to reflect the alternative opportunities or obligations they have in non-electricity markets. Cogeneration facilities that export to the grid and sell power in wholesale markets provide an example pathway for multi-vector hybrids.[50]	Virtual power plants, full hybrids
Lack of understanding of impacts of HES on price formation and uplift charges	HES could significantly change market participants' bidding strategies and market price formation. For example, storage pairing with (a) thermal units could reduce startup and no-load costs, and (b) wind and solar could change production relative to independent storage or independent wind and solar. These changes could impact price volatility, the timing of peak prices, and the frequency of negative pricing. How HES might affect bidding strategies is not yet clear and depends, in part, on availability of various participation models. The impact of HES on price formation has implications for market design.	Virtual power plants, full hybrids

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[49] For all rows in this section, "full hybrids" refers to both electricity-only and multi-vector hybrids.

[50] See for example, https://www.energy.gov/eere/amo/downloads/new-release-us-doe-analysis-combined-heat-and-power-chp-technical-potential.

Table 8. Key Challenges for HES within Resource Permitting, Utilities, and State Policies

Challenge	Description	Hybrid Type
Lack of well-developed methods for evaluating HES in utility resource planning and acquisition	In their integrated resource plans (IRPs) and competitive solicitations, utilities often evaluate HES as separate resources. As with other technologies providing flexibility (e.g., independent storage), utilities may have insufficient temporal and spatial granularity to capture the benefits of HES when considering things like PURPA avoided cost. Improving utility evaluation methods could lead to more optimal investments in HES.	Colocated resources, virtual power plants, full hybrids
Lack of understanding of potential opportunities and regulatory challenges of utility business models for HES	HES raise several important questions for state regulators and energy offices, from economic intuition about cost-effectiveness to whether utilities should own or contract with HES. For example, state PUCs will need to oversee utility evaluation of HES in IRPs, but many commissions lack information and intuition about the benefits and costs of HES. State PUCs, energy offices, and tribal entities need technical assistance that builds the analytical capabilities of staff to integrate HES into utility regulation and the design of utility programs. Some regulatory processes may not allow for consideration of additional value outside of the utility's core sector (e.g., hydrogen production for use in non-electric sectors), which is especially important for multi-vector hybrids.	Colocated resources, virtual power plants, full hybrids
Lack of well-developed approaches to regulating HES participation in state policy mandates	HES may create definitional and boundary challenges for state policy mandates. For instance, PV paired with battery storage may not be fully eligible to meet renewable portfolio standards (RPS) if the battery can charge from the grid. States are at different stages of considering HES in the design of state policy mandates, in terms of eligibility, accounting, and tracking. The participation of multi-vector HES in state policy mandates spanning multiple sectors (e.g., economy-wide decarbonization) will also be increasingly important as the stringency of those mandates increase over time.	Colocated resources, virtual power plants, full hybrids
Lack of understanding the role of HES in meeting state policy goals	The role of HES in meeting states' long-term energy policy goals (e.g., 100% renewable or clean energy goals) and environmental goals (e.g., air quality improvements or land conservation) is unclear. Research is needed to better understand and align the environmental performance of HES to move toward these goals. In turn, this improved understanding must be effectively communicated to state regulators and state energy offices to ensure they understand how different HES can help meet their energy goals and how to design more effective policies and regulations for both electricity-only and multi-vector HES.	Colocated resources, virtual power plants, full hybrids

3.2 Key Valuation Challenges

The key valuation challenges facing HES (Table 9, page 31) were derived from our assessments of state-of-the-art R&D and industry perspectives. The challenges can be categorized based on two overarching themes. First, our understanding of how hybridization impacts the joint system's technology costs and values is insufficient; overcoming this challenge requires improving our ability to compare the costs and values of HES against those associated with multiple independent projects. Second, efforts to value HES are currently inhibited by our inability to evaluate the benefits they can provide to the bulk power and broader energy systems; this challenge is primarily rooted in the lack of adequate representations of HES in system-level models and tools.

Many of the challenges in Table 9 reflect understudied areas for HES, including HES costs and understanding the benefits they provide. In particular, the potential for cost-savings is an important source of value for all HES, which can involve shared siting, permitting, and transmission interconnection (spur-line) costs through colocation, or shared component costs when systems involve a physical coupling. Though HES costs are often considered in DOE-funded research projects, they typically (a) include costs as exogenous assumptions (rather than researching the potential for, or optimizing, cost savings), (b) are performed for a specific HES (in terms of technology subcomponents and sizing) without a complete understanding of the potential for economies of scale, and (c) cannot readily represent additional technology combinations. This limited treatment of HES costs can be problematic if it inhibits an adequate weighing of changes in monetizable value against changes in cost; though adding energy storage to a generation asset would add incremental value in many use cases, it is not always clear whether that is enough to outweigh the corresponding incremental cost (relative to the generation asset in isolation or independent systems for each subcomponent). Finally, HES costs research typically involves looking at a snapshot in time, so it is limited in its ability to project HES cost trajectories over time, including costs for HES subcomponents and the magnitude of potential shared costs between them.

Understanding the plant-level benefits for HES is a prominent area of HES valuation research, but our current understanding of the value that HES can provide to the energy system and society more broadly is highly limited (Table 9). The key challenge associated with understanding these potential benefits is primarily rooted in the fact that our bulk power and energy system-level valuation tools, methods, and supporting data are currently insufficient for representing the cost and value synergies of HES.

Other entries in Table 9 are currently the focus of state-of-the-art HES research, but they were identified as key challenges by industry stakeholders. For example, economic metrics are being evaluated in a wide array of publicly supported, industry supported, and academic HES research, but different metrics and methodologies for comparison are used. As a result, when looking across an array of technically sound research results for the value of HES, there is significant confusion about the cost-effectiveness of hybridization. Though this challenge is not unique to HES, it is exacerbated by the diverse array of relevant metrics and comparisons when multiple energy technologies are combined into a single plant.

Finally, beyond the near-term deployment of commercial HES, there is a need to understand the long-term potential of HES, which will ultimately require optimizing the design and operations of HES. This optimization is made challenging by the expansive design parameter space—including technology combinations and the nature of linkages among them—and evolving control architectures for HES. Even for a fixed set of subcomponents, comparing the net-economic value of different configurations requires a detailed understanding of the design-dependent costs and values (e.g., services and products the HES can provide). Parameterizing the full design parameter space is challenging, and exploring it is computationally intensive because of the many technology combinations and linkages.

Table 9. Key Valuation Challenges for HES

Challenge	Description	Hybrid Type
Inconsistency in the evaluation of HES cost synergies	The potential cost savings associated with hybridization (e.g., through shared BOS, infrastructure, or equipment costs) are not well understood and likely vary depending on HES design (e.g., the relative sizing of and nature of linkages among subcomponents). The limited research in this area typically takes a technology-specific approach and primarily focuses on commercial technologies. A flexible (and consistent) representation of the potential cost impacts of hybridization is needed to evaluate the cost-effectiveness of current and future HES, including current and projected estimates for capital investment, operational, and shared costs.	Colocated resources, virtual power plants, full hybrids
Incomplete understanding of the system benefits provided by HES	The benefits HES can provide to the energy system depend on the technology characteristics and the rules associated with energy services and products. Constantly evolving market rules and policies make it challenging to keep track of and plan for the value streams that HES can capture, including incentives (e.g., California's Self-Generation Incentive Program) and services and products that cannot be monetized today and are challenging to value (e.g., resilience and environmental performance). Research to date has focused on the economic performance of HES from the plant owner's perspective, with more limited consideration of their impacts on energy system value. Understanding the system-level impacts of HES requires exploring the full design parameter space—including technology combinations, linkages between them, and different operational paradigms—which is computationally intensive.	Colocated resources, virtual power plants, full hybrids
Lack of standardized methods for evaluating economic performance	Established economic metrics can be applied to HES, but findings about the cost-effectiveness of hybridization are muddled by both insufficient metrics and differing baselines for the comparison. Commonly employed levelized cost metrics are insufficient for capturing any incremental value (beyond volumetric energy production) that is achieved through hybridization. Even when applying metrics that capture both incremental costs and values, evaluating the economic performance of HES is challenging because of the various baselines against which they are compared. Understanding the conditions under which HES provide net-economic and societal value is currently challenged by an inconsistency in the metrics and baselines against which HES economic performance is evaluated.	Colocated resources, virtual power plants, full hybrids
Lack of sufficient methods for performing HES design optimization	The technology components and specifications that are brought together to optimize HES can make it challenging to compare the net-economic value of different design options. The technical capabilities and costs (see the top row of this table) of HES are configuration-dependent (i.e., the different sizes of individual subcomponents and the nature of their linkages). Recent work has begun to address these challenges for select technology combinations and linkages, but a lack of adequate data and flexible modeling capabilities inhibits researchers' ability to consistently evaluate optimal designs for current and future HES, considering the full design parameter space, different ownership structures, and cost-competitiveness of HES within the context of broader energy system costs (e.g., in resource planning tools).	Colocated resources, virtual power plants, full hybrids
Complexities associated with HES operations optimization	Related to the optimal *design* is the optimal *operation* of HES; this challenge similarly depends on the subcomponents, sizing, and linkages that define HES design, but it is also very sensitive to the operational paradigm. Different control architectures and response times will determine which services and products the HES can provide, and our current understanding of the operational expenses incurred as a result of providing additional services is very limited. Moreover, comparing different technology options requires an understanding of the trade-offs associated with technical values of colocation versus virtual coupling, and how operational approaches might impact capacity value or capacity accreditation, which is currently lacking.	Virtual power plants, full hybrids

Furthermore, understanding trade-offs associated with technical values of colocation versus virtual coupling, how value might change with respect to different ownership structures, and how operational approaches might impact capacity value or capacity accreditation are all important considerations when evaluating different HES, but they are challenging to implement. Finally, it is important to consider the dynamic aspects of HES value across multiple products and operating schemes, which can result in value changes not only throughout a day, but also seasonally and over longer time horizons as the power sector, energy sector, and monetizable products and services evolve. Thus, these challenges bridge planning and operational practices, and while they are not unique to HES, they are exacerbated by the need to consider multiple energy technologies and (in some cases) markets and products.

3.3 Key Technology Development Challenges

This section presents key near-term technology development challenges facing both current (or emerging) and future HES (Table 10). One of the most prominent technology development challenges facing current and emerging HES is technology solutions that ensure full market participation and compensation for HES. For example, enabling the provision of more or additional services and products requires the advancement of HES controls, which are designed to operate HES as an economic, dispatchable, and flexible source of energy. Similarly, research related to telemetry, metering, and other communications equipment is needed to facilitate the secure and coordinated operations of multiple subcomponents in response to grid and market signals. Also, multi-vector HES could involve nonelectric integrations using heat, hydrogen, or chemicals, and thus those technologies, resilient integration capabilities (e.g., heat carriers and corrosion tolerant piping to carry them), and controls for coupling need to be developed or adapted from current technologies. The successful deployment of such equipment depends on sufficient testing and validation, the establishment of (and compliance with) technology standards, and appropriate cybersecurity measures.

For current and emerging HES, there is also a need to address the risks associated with first-of-a-kind systems. Select HES have benefitted from rapid technology cost reductions in recent years, which have enabled cost-effective hybridization even after accounting for the increased equipment, complexity, and risk. For emerging or precommercial HES, a key challenge lies in this balance between cost and complexity—and, in turn, risk—which means the benefits of hybridization need to significantly outweigh the added risk for private organizations to invest in them.

A final class of technology development challenges requires near-term action in order to facilitate the advancement of future HES. For example, a key challenge for future advancements in HES is a lack of technology characterization to understand what types of R&D can expand HES abilities, the services and products they can provide, and the applications for which they can produce net-economic benefits. This challenge is exacerbated by the wide range of subcomponents and linkages that should be considered, the different requirements of end uses that could benefit from the adoption of HES, and the evolution of market services and products (and their value). Another key challenge lies in identifying and addressing limitations with individual subcomponents that could influence the future cost and performance of HES, which may be especially relevant for technologies that are commonly included in HES. Finally, while near-term (first-of-a-kind) HES deployments can accommodate custom designs, long-term success requires the scalability through consistent system architectures that integrate with standard protocols to enable interoperability of commodity subcomponents.

Table 10. Key Technology Development Challenges Facing HES

Challenge	Description	Hybrid Type
Limitations in the services and products enabled by tech-specific HES controls	Realizing the operational synergies that are exploited in HES requires plant-level controls that coordinate the operations of multiple subcomponents to maximize total system value. Valid control theory, models, and demonstrations of controller architectures for large-scale deployment of utility-scale HES are needed to optimally control and operate HES to provide a broad array of services and products. This topic is the subject of research for select HES and services, but there is a need to expand such research to additional technology combinations, linkages (including virtual hybridization), services, and products.	Virtual power plants, full hybrids
Ensuring rapid and secure communications with multiple components	Coordinating the operations of multiple subcomponents requires the rapid transfer of information between (a) subcomponents and (b) HES and the grid. Given the multiple nodes and pathways, latencies in this equipment must be minimized to ensure rapid responses to grid signals and changes in resource availability. HES will not necessarily introduce new cybersecurity threats, but combining multiple subcomponents results in (a) an increased attack surface, (b) concerns about interoperability of legacy equipment with new equipment, and (c) the potential use of third-party components that lack secured supply chains.	Virtual power plants, full hybrids
Need for additional testing and validation of enabling hardware	Individual hardware components that enable integration (e.g., power electronics, inverter technologies, and heat exchangers) undergo extensive testing and validation at established DOE National Laboratory and industry test beds. However, the testing requirements may not be directly transferable for HES, which can involve hardware shared by different HES subcomponents, a purely virtual linkage of HES subcomponents, and multiple forms of energy conversion.	Virtual power plants, full hybrids
Insufficient technical requirements	Current generation, storage, and conversion technologies are subject to differing technical requirements (related to, e.g., hardware or software, metering, sensors, control strategies) when operated as an independent asset. To create a hybrid of these assets, technical requirements for multiple technologies must be understood and deconflicted to allow interoperability.	Virtual power plants, full hybrids
Risks associated with first-of-a-kind systems	The power industry is highly regulated and risk averse. Overcoming the risks of first-of-a-kind, complex HES will require multiple demonstrations of the new technologies at scale—including both full HES projects and individual components (e.g., hardware and controls)—to provide an improved understanding of HES performance. Private financing for such demonstrations is very limited.	Virtual power plants, full hybrids
Incomplete understanding of grid and end user technical requirements	There is a lack of foundational data and knowledge about how the technical characteristics of proposed HES map to the requirements for providing services and products, which depend on (a) market rules and regulations for transmission-connected HES and (b) end-use requirements (e.g., load profiles, sensitivity to momentary interruptions, and backup power requirements for customer-sited electricity-only HES, and product quality, storability, and impacts of varying availability on users of the second product for multi-vector HES). This foundational information could help inform technology development activities for HES.	Colocated resources, virtual power plants, full hybrids
Limitations with individual subcomponents	The limitations of individual subcomponents can impact the performance and cost of HES. For example, addressing the flammability and temperature stability issues with lithium-ion batteries could prove to be pivotal for the success of select HES. Similarly, forecasting challenges associated with variable resources can be (a) exacerbated in HES that contain multiple variable resources and (b) problematic for optimally dispatching coupled energy storage.	Colocated resources, full hybrids
Challenges with scalability	Distribution-connected HES are often custom-designed for specific applications, which limits their potential for improved economic performance through scalability. There is a need for standardized designs and system architectures that enable the interoperability of “commodity” (rather than custom) subcomponents and controls frameworks.	Full hybrids

4 Opportunities for Coordinated HES Research

In this section, we present opportunities for near-term cross-office coordination. The opportunities presented in this section were identified by first identifying R&D opportunities to address the key challenges facing HES (Section 3), and then down-selecting to those opportunities that are amenable to cross-office coordination or collaboration. In particular, we have highlighted cross-cutting opportunities that, if tackled by individual offices, would likely involve duplicate efforts and redundancy.

Some of the identified opportunities represent areas that are ripe for new research, which could be designed to address common challenges facing constituent technologies that are the focus of a given DOE program office or suboffice. However, many of the opportunities represent areas of active research across DOE; in these cases, the identified opportunity lies in building on, leveraging, and increasing coordination across offices' ongoing research activities for specific technology combinations. This increased coordination could simply take the form of information sharing across offices to avoid duplication of effort or expanding research activities to additional technology combinations. When appropriate, it could involve increased coordination for follow-on research activities to maximize impact by simultaneously addressing challenges that are shared across DOE program offices.

For all opportunities, the role of DOE reflects its established approach to energy systems R&D, which includes (but is not limited to):

- **Providing information and analysis in the public domain:** collecting, reviewing, analyzing, and reporting information that is currently only accessible through paid subscriptions
- **Supporting the development of innovative approaches to emerging market and regulatory challenges:** funding research that facilitates innovative solutions to emerging challenges in electricity market design and federal and state regulation
- **Developing new methods, analytical frameworks, and modeling tools:** funding research that develops new analysis methods and modeling tools (as needed) and improves the representation of HES in existing tools
- **Supporting technical assistance:** funding and providing technical assistance to state regulatory commissions, state energy offices, utilities, and ISOs
- **Supporting the development of standards for emerging HES components and controls:** leveraging DOE National Laboratory expertise in the development of technology standards
- **Supporting early-stage technology development R&D:** funding research that develops, tests, and demonstrates the technology subcomponents, hardware, midware, and software that can facilitate beneficial hybridization

With these roles in mind, we begin this section by presenting overarching opportunities, which influence and are influenced by markets, valuation, and technology development activities. Next, we walk through opportunities that are organized, in part, to reflect the relative timelines over which the challenges being addressed become increasingly urgent. For example, market-based opportunities are presented first, as regulators are already facing challenges associated with studying and making decisions about HES that have requested interconnection on both the distribution and transmission networks. Second, we present opportunities for advancing HES valuation research, the challenges for which are closely integrated with both markets and technology development opportunities; in other words, these valuation challenges must be addressed in the near term to inform both (a) the integration of commercial HES onto the grid today and in the coming years, and (b) technology development activities over the coming years and decades to enable the greatest value to the power system and society. Third, we present technology development opportunities that span multiple timelines: some opportunities represent near-term R&D activities to address challenges for current and emerging HES, while others represent near-term actions that are needed to facilitate the long-term success of a broader set of future HES.

4.1 Overarching Opportunities

The following opportunities were identified as having immediate priority and whose results will help inform opportunities within all three research areas. These activities seek to identify the key drivers of HES today, explore the time frame for current motivations and anticipated drivers for HES, gain greater visibility into industry efforts related to HES, and disseminate relevant information.

4.1.1 Motivations for HES

Industry interest in and activity regarding HES is apparent in interconnection queues and project pipelines across the United States. However, it can be challenging to reconcile the current and anticipated industry interest with recent research focused on the value HES can capture from energy and capacity markets (accounting for near-term tax credits for select technologies), which often suggests multiple independent systems offer greater net-economic benefits than HES. This apparent disconnect could be explained by the diverse motivations for HES that fall outside the largest value streams, such as market risk mitigation, ancillary services revenues, revenue diversification, permitting and siting delays for new projects, provision of local reliability and resilience (e.g., for microgrid-based hybrid applications), and achievement of computational tractability in system operation software.

To reconcile industry interest and ongoing valuation studies, DOE could host a multistakeholder workshop to identify the key current drivers of HES, explore the time frame for anticipated drivers of HES, gain greater visibility into industry efforts related to HES, and gauge industry interest (or lack thereof) in virtual power plants. Planning for such a workshop should begin by reviewing previous HES workshops hosted by DOE and its National Laboratories.[51] Moreover, the work should be designed to directly solicit and collect specific insights from industry, utility planners who evaluate HES in processes like integrated resource planning, and other

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[51] For example, see:

Shannon Bragg-Sitton, Richard Boardman, Mark Ruth, Owen Zinaman, and Charles Forsberg. *Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report* (Idaho Falls, ID: Idaho National Laboratory, INL/EXT-14-32857-Rev.1; NREL/TP-6A20-62778), https://doi.org/10.2172/1170315.

Shannon M. Bragg-Sitton, Richard Boardman, Mark Ruth, and Peter B. Lyons. *Workshop Report: International Workshop to Explore Synergies between Nuclear and Renewable Energy Sources as a Key Component in Developing Pathways to Decarbonization of the Energy Sector* (Idaho Falls, ID: Idaho National Laboratory, August 2016, INL/EXT-16-39701 Rev. 1), https://doi.org/10.2172/1364488

Douglas Arent, Peter Balash, Richard Boardman, Shannon Bragg-Sitton, Jill Engel-Cox, David Miller, and Mark Ruth. *Summary Report of the Tri-Lab Workshop on R&D Pathways for Future Energy Systems, July 24–25, 2018* (Golden, CO: NREL, December 2018, NREL/TP-6A70-72926), https://doi.org/10.2172/1488918.

stakeholders. Planning for such a workshop should begin by reviewing previous HES workshops that have been hosted by DOE and its National Laboratories, targeting attendees and topics that address pressing challenges related to HES that are currently being developed, proposed, or considered for interconnection in the near term. Ensuring that a wide range of viewpoints are considered requires involvement from multiple groups, including utilities, regulators, developers, large industrial customers, and corporate purchasers.

The findings from this workshop could serve as a benchmark of current and anticipated motivations for hybridization. To build on this benchmark, a useful next step would be to identify and engage in deeper case studies related to the aspects of these motivations, or sources of value, which are not currently adequately represented in valuation tools. Such case studies should seek to characterize and quantify these potentially unexpected sources of value to inform model development and analysis activities for valuing commercial and emerging HES. Moreover, a primary goal of them would be to inform DOE, researchers, policymakers, and system planners about the conditions under which various motivations interact and influence the level (and pace) of HES deployment that might be expected. Finally, the outcomes of such case studies should guide improvements in "standard" valuation techniques, highlight important motivations to other stakeholders, and inspire broader conversations about whether unexpected sources of value are transitory elements that might be the outcome of an inefficient policy or are more robust features that are expected to be persistent.

4.1.2 Public Data Resources

Uncertainty related to the lack of rigorous, timely information on HES costs, performance, and capabilities is a barrier to their efficient deployment. This opportunity would reduce uncertainty about HES by providing regularly updated, publicly available data resources on current and projected technology costs, market value, and market trends for HES. Utilities and state regulators could use this information to benchmark cost and technology assumptions used in resource planning. Developers could use the information to develop investment strategies and benchmark costs. Information on market trends could also inform other aspects of DOE R&D strategy that cut across individual technology offices, by providing regularly updated insights on the kinds of hybrid technologies and configurations (e.g., AC-coupled, DC-coupled) with the greatest market interest.

The projects under this opportunity would leverage ongoing work at the DOE National Laboratories, integrate HES into existing DOE-funded databases and report series,[52] and further the development of methodologies for assessing the costs and benefits of, and business models for, HES. Incremental funding would support data collection on hybrid costs and market trends and the development of industry-standard methods for benchmarking hybrid costs, cost savings, and market value. Moreover, targeted research activities could help clarify the additional costs that are induced by fully integrating multiple subcomponents, the extent to which soft costs are truly shared in electricity-only HES, and potential benefits provided by controlled energy provisioning in multi-vector HES. In addition, research activities could quantify how those shared costs vary both (a) between greenfield and retrofit projects, and (b) as the capacities of each subcomponent change. The research activities could also quantify how the optimal configuration changes with varying external drivers

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[52] Existing NREL models and data sets (e.g., LandBOSSE, HybridBOSSE, and the PV+storage cost benchmarks) can be used to assess component-level cost-sharing potential for wind, PV, and batteries. In addition, existing NETL, INL, PNNL, SNL, and NREL data sets and models (e.g., Bituminous Baseline Reports, Institute for the Design of Advanced Energy Systems [IDAES], Risk Analysis Virtual ENvironment [RAVEN], Holistic Energy Resource Optimization Network [HERON], and REopt) can be used to assess cost and performance of integrating nuclear, coal, gas, and biomass-fired thermal generators as well as nonelectric applications (e.g., low temperature electrolysis and solid oxide electrolyzer cell [SOEC]) technologies with a range of energy storage technologies including thermal, mechanical, and hydrogen.

(e.g., electricity and commodity prices). Finally, additional research is needed to expand existing, or develop new, capabilities to represent the potential for cost savings associated with the hybridization of a broader set of subcomponents, including thermal and hydropower technologies.

Hybrid technology cost information could be integrated into resources such as into EIA's Annual Energy Outlook,[53] NREL's Annual Technology Baseline (ATB),[54] and NETL's Baseline Report Series.[55] In addition, information on hybrid benefits and market trends—including installed costs, power purchase agreement (PPA) prices, estimated market value, and impacts on other factors such as emissions—could be integrated into existing DOE report series (e.g., by the dominant resource) or a new regular report series on HES.

4.2 Markets, Policy, and Regulation Opportunities

Consistent with the rest of this report, the near-term R&D opportunities related to markets, policy, and regulation focus on electricity markets and regulation, because (a) the electric sector is highly regulated (relative to other energy and commodity markets) and (b) HES are challenging conventional approaches in markets, policy, and regulation. The opportunities outlined here include gaining a better understanding of the evolving development status, motivations, and rules for HES (Section 4.2.1); proactively responding to the potential impacts of higher penetrations of HES on electricity markets and system operations (Section 4.2.2); providing analytical and technical support to state regulatory commissions and energy offices on HES (Section 4.2.3); and improving the analysis of hybrid resources within interconnection and transmission planning studies and examining the implications of HES for interconnection processes (Section 4.2.4).

4.2.1 Establish a Markets Database

As wholesale market rules and policies specific to HES emerge across states and ISO/RTOs, there is a need to understand, synthesize, and disseminate the rules that define hybrid participation models and how they differ. Policy proposals vary in terms of how HES interconnect with the grid, participate in wholesale markets, and are treated in terms of capacity accreditation. Definitions of HES and technical design requirements also vary by market. These policies may provide different incentives or disincentives for hybridization.

This opportunity would create a public database—rooted in data collection and monitoring—of formal tariff and business requirements, developments in stakeholder proceedings, rulemakings, and policy incentives related to HES. The database would provide an in-depth review of the current and evolving changes in the design of markets to accommodate new HES and would facilitate and encourage information sharing across stakeholders while remaining policy neutral. This database can build on ESA's hybrid status document[56] and

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[53] EIA, *Annual Energy Outlook* 2021 (U.S. Energy Information Administration, 2021), https://www.eia.gov/outlooks/aeo/.

[54] NREL, *Annual Technology Baseline* (National Renewable Energy Laboratory), https://atb.nrel.gov.

[55] NETL, "Baseline Studies Overview," https://netl.doe.gov/node/7512.

[56] ESA, *Status of Hybrid Resource Initiatives in U.S. Organized Wholesale Markets* (Energy Storage Association), April 10, 2020), https://energystorage.org/wp/wp-content/uploads/2020/04/ESA-Policy-Summary-on-Hybrid-Resources-Across-RTOs-and-ISOs_4_10_20.pdf.

EPRI's annual cataloguing of market rules and policies that includes information specific to storage and HES.[57] This catalogue is currently funded by EPRI members, but a publicly available version may have broader appeal.

A DOE-funded and supported database would track the status of a wide range of issues. These include diverging definitions of what constitutes an HES (i.e., technology and sizing specifications), changes in interconnection queue procedures for HES (for new requests for access and storage additions to existing generators in queue), forecasting services provided for HES, metering requirements (e.g., for RPS eligibility), and changes in market participation models (e.g., proposals of new market resource types, treatment of HES as a single or multiple colocated resources for markets, operations, and settlement).

Clarity on heterogeneity in hybrid treatment—and the motivations that have informed these decisions—will benefit technology R&D, project developers, and states and ISO/RTOs at earlier stages in their conversations about HES. By specifying existing technical requirements across regions in the United States, a publicly available database would open data-driven discussions on whether certain frameworks incentivize or disincentivize the participation of HES. Moreover, such a resource would allow developers to better understand which markets are more favorable to HES, the technical expectations in these regions, and the opportunities for reducing the regulatory uncertainty they now face. Lastly, states and ISO/RTOs could use a DOE-supported database to compare regulatory frameworks for HES across the United States, develop best practices, and engage with one another and other stakeholders while drafting policy on the treatment of HES.

4.2.2 HES Integration Studies

Rapid growth in hybrid resources could affect the overall energy system and electricity markets and reliability in ways that are not yet well understood. These impacts are likely to be different depending on the types of HES and the level of penetration they achieve. Making proactive changes in electric market design and system operations that enable more-effective hybrid integration could unlock new market services and ways of operating the electricity system that reduce system costs and increase system reliability. Likewise, multi-criteria optimization across the full energy system is important to understand potential impacts across society.

Uncertainty about the system impacts of hybrid resources is comparable to that of wind and solar generation in the late 2000s and early 2010s. Integration studies helped provide ISOs/RTOs, regulators, and utilities and other market participants with greater visibility and intuition of the impacts of higher penetrations of wind and solar generation on system planning, operations, reliability, costs, emissions, and other metrics for environmental system performance.

The HES integration studies in this opportunity would analyze the impact of different kinds and penetrations of hybrid resources on ISO/RTO transmission planning, resource adequacy planning, markets, and system operations, as well as state and local policy goals. These studies would examine the evolution of the power system as a whole, and they would include scenarios with different kinds and penetrations of HES as well as scenarios that examine different requirements for services that are not fully monetizable, such as resilience, environmental compliance, and fuel provision. Like renewable integration studies, HES integration studies would help system operators proactively identify and address key challenges for integrating higher penetrations of HES to ensure system reliability and resiliency can be maintained (or improved) through effective integration of these new resources into operations and planning.

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[57] EPRI, *Wholesale Electricity Market Design Initiatives in the United States: Survey and Research Needs* (Electric Power Research Institute, November 07, 2016), https://www.epri.com/research/products/000000003002009273.

HES grid integration studies would require the development of new modeling approaches and methods to better incorporate the potential values of HES that are not well-captured in existing models or are not fully monetized. These values might include reduced uncertainty and risk for resource owners, enhanced resource performance, enhanced environmental performance and value, and provision of enhanced reliability and resilience. Early research to develop hybrid resource models for use in reliability and economic studies would inform the development of viable HES participation models for wholesale markets. The tools, insights, and methods developed through these studies would be foundational to more-focused technical assistance to ISOs/RTOs, regulators, and utilities and other market participants. Given the critical role of these entities, they should be involved in the design and review of the HES integration studies. Because multi-vector hybrid energy systems can provide additional flexibility to balance supply and demand across multiple markets, additional approaches to formulate and optimize them simultaneously with the grid and overall energy system are needed. These approaches would need to evaluate the dynamic internal interactions, dynamic interactions with the grid, interactions with the overall energy system over longer periods, and broader interactions with the environment. They would also need to enable multicriteria optimization to address not only economic costs and benefits but also those on the sustainability, reliability, and security.[58]

4.2.3 HES in Interconnection and Transmission Planning

Existing interconnection and transmission studies and processes may not accurately capture the operations of HES, leading to unnecessary investments in transmission infrastructure, higher than necessary interconnection costs, longer than needed interconnection times for HES, and potential reliability issues. Additionally, pairing generation resources with storage—or vice versa—may defer or avoid electricity transmission and distribution (T&D) investments by relieving contingency constraints in the transmission system and relieving thermal or voltage limits in the distribution system. These values may not be accurately captured in T&D planning and procurement of “non-wires alternatives” (resources that can defer or avoid T&D network investments).[59]

This opportunity would consist of two components, the first of which would review existing approaches to assessing and treating HES in bulk power system interconnection and transmission studies, identify gaps, and recommend improvements for models and study processes to better account for hybrid operating characteristics. Through more rational treatment of HES during transmission planning and interconnection, the review could enable the more-efficient deployment of HES, ensuring system reliability is maintained with higher

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[58] Douglas J. Arent, Shannon M. Bragg-Sitton, David C. Miller, Thomas J. Tarka, Jill A. Engel-Cox, Richard D. Boardman, Peter C. Balash, et al. “Multi-Input, Multi-Output Hybrid Energy Systems,” *Joule* 5, Issue 1 (January 20, 2021): 47–58. https://doi.org/10.1016/j.joule.2020.11.004

[59] See, for example:

National Council on Electricity Policy, *Updating the Electric Grid: An Introduction to Non-Transmission Alternatives for Policymakers*. Prepared by the National Council on Electricity Policy (September 2009), https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Updating_the_Electric_Grid_Sept09.pdf.

Snuller Price, Jack Moore, Gabe Kwok, and Jonathan Kadish. *I-5 Corridor Reinforcement Phase 2 Non-Wires Analysis: Feasibility for Line Deferral*. Prepared for Bonneville Power Administration by Energy and Environmental Economics, Inc. (December 19, 2011). https://www.bpa.gov/Projects/Initiatives/NonWires/I-5_Phase2_Non-Wires_Analysis_Feasibility_Study_December2011.pdf.

Richard Cowart, “Recommendations on Non-Wires Alternatives,” (Electricity Advisory Committee, October 17, 2012), https://www.energy.gov/sites/prod/files/EAC Paper - Recommendations on Non-Wires Solutions - Final-25-Oct-2012.pdf.

penetration of HES. Projects under this first component would consist primarily of two classes of scoping-level studies that would:

- Review existing practices and emerging strategies for assessing HES in transmission planning and interconnection studies, identify gaps, and recommend improvements: Considering transmission planning and interconnection together is important for capturing the relationships between them. In addition, these scoping-level studies would examine the extent to which the electrical characteristics (voltage, current, reactive power capability) of different kinds and configurations of HES are accurately captured in transmission planning and interconnection studies and where key gaps might exist.
- Evaluate the impact of, and different strategies for, reducing the interconnection costs of HES, comparing the benefits and potential risks of different strategies to resource owners through a select number of modeled use cases: These studies would also explore the larger implications of allowing resources to more rapidly interconnect to the transmission system, subject to operating limits. More widespread use of operating limits on interconnecting resources, in exchange for faster interconnection and lower interconnection costs, might imply fundamental changes to the interconnection process and to transmission planning.

The second component in this opportunity would focus on the role of HES in electricity T&D investments. Although non-wires alternatives for transmission involves both ISOs/RTOs and state regulation, states have expressed interest in this topic, and this opportunity would focus on a state perspective. This scoping study would use case study analysis to examine the extent to which pairing resources can defer or avoid T&D investments. The study would examine regulatory, technical, and economic considerations for storage-paired resources to provide non-wires services.

Finally, though this opportunity focuses on electricity T&D, a parallel opportunity exists for the supply chains and interconnections associated with multi-vector HES, such as pipelines. For example, multi-vector HES that use carbon dioxide (CO_2) to make products could reduce the need for CO_2 pipelines for carbon capture and storage, or they could otherwise interact with the planning for such systems.

4.2.4 Technical Assistance

In most states, legislatures, PUCs, and state energy offices are still in the early stages of understanding whether and how HES could contribute to state policy goals, how utilities should evaluate the economics of HES in their IRPs and competitive solicitations, how utilities should contract with HES, and how HES should be treated in renewable portfolio standards, clean energy standards, and clean peak standards. This opportunity would provide broad technical assistance to states on policy design, utility regulation, and regulatory design issues for HES. It would help states design policy and regulation that enables efficient deployment of HES.

The projects under this opportunity would include analytical studies on the role of HES in states' long-term energy policies, evaluation of HES in utility planning and procurement, optimal hybrid investment strategies for utilities, regulatory issues associated with utility ownership and contracting for HES, and rules for HES in state policy mandates. Projects would also include technical assistance covering policy, regulatory, and economic issues associated with HES that draw on expertise from the DOE National Laboratories, EPRI, and consultants. For instance, technical assistance could take the form of a series of regional workshops that first provide a high-level introduction to HES (concepts, definitions, issues) and then provide technical training on more specific topics related to HES (interconnection, resource planning, markets, contracting, operations).

Of the potential projects under this opportunity, two of the highest-priority projects are related to the challenges of accurate assessment of HES in utility planning. The first project is an analytical study identifying potential gaps in existing practices, tools, and methods for evaluating HES in utility resource plans. The second project, which is likely complementary with the first, is a collaboration with a utility, or utilities to improve evaluation methods for HES.

4.3 Valuation Opportunities

HES come in a variety of types, are used in a variety of applications, and produce a variety of products. Given its close relationship with both technology development and markets-based research (Figure 9), valuation opportunities are inherently related to those presented in Sections 4.2 and 4.4. Valuation research is needed to explore whether a given technology development effort would be cost-effective (now or in the future), and it is necessary to understand the impact of various markets, policy, and regulatory decisions. This interconnectedness is especially relevant for HES, whose net-economic value must be justified relative to independent components and other competing energy technologies.

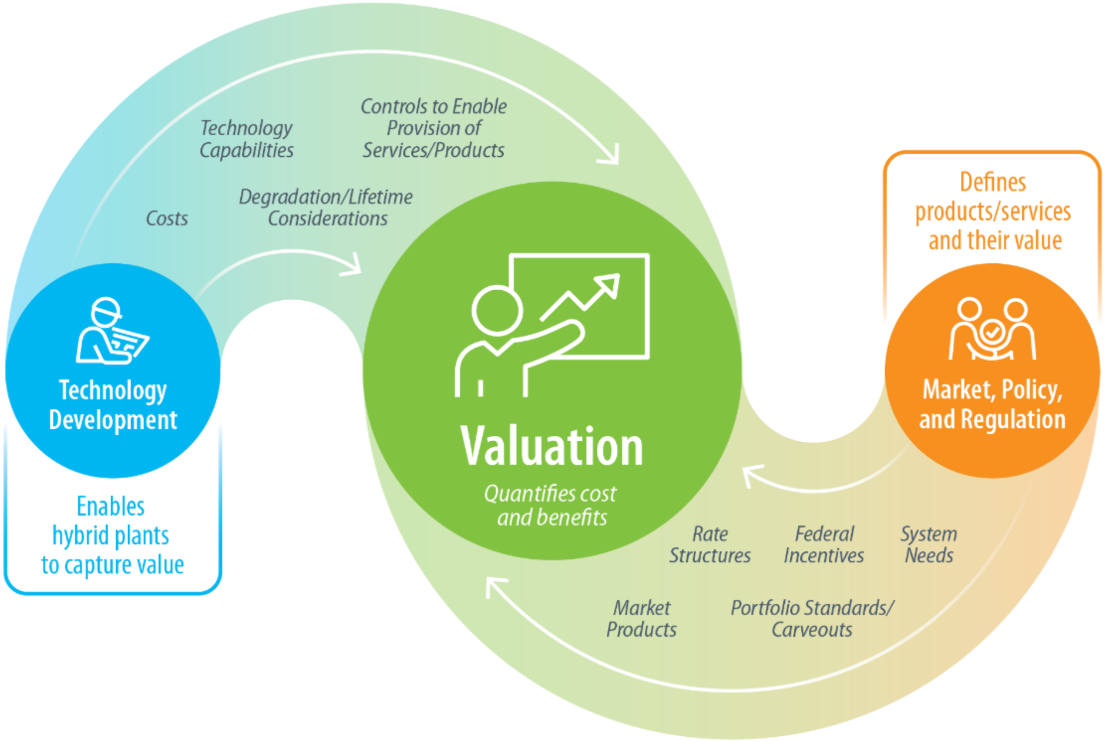

Figure 9. Select examples of how valuation activities inherently depend on inputs and information from the technology development and market, policy, and regulation research areas

HES come in a variety of types, are used in a variety of applications, and produce a variety of products. A comprehensive valuation methodology that encapsulates these options is essential for determining which HES, if any, can best meet the range of needs that are present across the energy system. This section summarizes the key R&D opportunities that are needed to consistently estimate value across HES technology combinations and configurations, in terms of sources of value, metrics and methodologies for quantifying those sources of value, and analyses to support the estimation of value over a given time horizon.

4.3.1 Sources of Value

The first step in a comprehensive valuation framework—for both HES and independent technologies—is to identify and characterize their sources of value, along with the technical characteristics that are required to realize them. These sources of value will often take the form of services or products (Section 4.3.1.1) or cost savings (Section 4.3.1.3). However, they should also capture the potential synergies that can be realized through hybridization, often as a result of combining subcomponents with complementarity characteristics (Section 4.3.1.2).

4.3.1.1 Services and Products Taxonomy

Because the motivations for pursuing HES are diverse and involve goals of capturing a diverse array of sources of value, comparing the overall benefits provided by different HES can be challenging. Early-stage R&D related to emerging HES may not always target the full set of services and products that can be provided, such that the value proposition of the proposed HES could be artificially depressed. A fundamental research need is establishing a harmonized definition for the services and products that HES can provide.

The large-scale project under this opportunity would involve developing a taxonomy of the services and products from which HES (and independent technologies more broadly) can derive and provide value. A valuable source of information for such a taxonomy would be the recent, ongoing, and planned HES valuation activities, which are currently performed on an office-specific (or project-specific) basis. Compiling the sources of value that are pursued across these projects would provide a strong foundation for the overarching services taxonomy. However, harmonization of similar sources of value would be needed to avoid repetition and double-counting. The taxonomy should categorize sources of value across multiple dimensions, including:

- Electricity services and energy and nonenergy products
- Services that are currently monetizable versus those that do not currently receive compensation because they are difficult to monetize or considered a free resource
- The beneficiaries of each value source (e.g., HES owner, grid operator, and society)
- Value streams that are a function of market rules and policy design versus those that are persistent across markets
- Value streams that are expected to persist or grow over time versus those that are expected be short-lived (e.g., near-term policies and shallow ancillary services markets[60]).

The last point is especially important for determining which HES research will be high value in the long-term to avoid emphasizing short-lived value streams that lead to suboptimal hybrid system design, operation, and deployment. The documented sources of value should be technology agnostic, because both technology capabilities and technical requirements for value streams will evolve over time.

4.3.1.2 Documenting Complementary Characteristics

Common throughout proposed HES is the idea of combining technologies whose characteristics (or capabilities) complement one another's, such that the joint system has superior cost and/or value performance relative to its independent counterparts. One example lies in the operational timescales of the subcomponents: battery energy storage systems are so prominent in HES R&D, in part, because their rapid

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[60] See Zhi Zhou, Todd Levin, and Guenter Conzelmann, *Survey of U.S. Ancillary Services Markets* (Argonne National Laboratory, June 2016, ANL/ESD-16/1 Rev1), https://publications.anl.gov/anlpubs/2016/09/130102.pdf.

response times complement—and therefore help avoid costs for—both variable and baseload resources (e.g., through reduced variability and ramping, respectively). Another form of complementarity lies in technology linkages where heat is involved (e.g., thermal generators), such that hybridization can help ensure the thermal cycles operate at maximum efficiencies, enabling more cost-efficient operation and productive use of heat byproducts. Finally, the spatial energy density of a subcomponent can inform the extent to which hybridization would be beneficial in terms of taking advantage of underutilized areas associated with existing power plants and rights-of-way.

The diverse array of complementary characteristics speaks to the many ways in which HES can be configured to provide incremental revenue, system value, and societal benefit. However, they are often treated independently of one another, such that the research community lacks a database or centralized source of information about the many types of complementary characteristics. The projects under this opportunity would involve compiling complementary characteristics that are well understood, as well as documenting emerging forms of complementarity that can be leveraged in precommercial HES.

The resulting database would include:

- The *types* of complementary characteristics, both physical and operational
- A mapping of the operational timescales associated with the services and products being pursued through hybridization
- The expected impact of exploiting a given form of complementarity, providing additional services or products versus more of the same versus the same at lower costs
- The functional relations among them (e.g., to enable development of appropriate physical models to represent the HES under various use cases and operational conditions).

It will also be important to acknowledge whether the complementary characteristics induce beneficial or detrimental impacts on the performance of each subcomponent. The question of whether to hybridize is ultimately decided by the total performance of the system, but documenting when complementarities produce benefits for one subcomponent and not the other will provide insights into whether an independent deployment of one of the technologies could produce similar benefits.

The impact of this effort would be an enhanced ability to identify, evaluate, and tune promising future HES. For example, one outcome of this project would be a better understanding of the types of energy storage that are most beneficial for unlocking a desired outcome of hybridization—batteries may be ideal for arbitrage, whereas ultracapacitors may be more effective for facilitating the provision of ancillary services, and long-duration storage would be needed for seasonal shifting. Moreover, documentation of complementary characteristics would help streamline future research for various subcomponent combinations and would potentially identify combinations that are of interest across DOE program offices.

4.3.1.3 Cost and Other Economic Synergies

With electricity-only hybridization comes the potential for capital and operating cost savings, because of shared BOS costs, infrastructure, and/or equipment. However, additional research is needed to understand the magnitude of these potential cost savings, accounting for any costs incurred as a result of the increasing complexity associated with coupling generation, storage, and conversion technologies. Moreover, there are opportunities to both (a) refine cost estimation methods for RE+storage, nuclear-based, and fossil-based HES, and (b) expand (and standardize) such methods for HES comprising other subcomponent combinations. For example, research related to establishing and evaluating economic metrics for PV+battery projects is more abundant than other projects, and it may be transferrable to other similar HES. In addition, analysis in this area could improve our understanding of the *future* cost impacts, based on the relative shares and expected trajectories of the various cost components (e.g., capital expenditures, BOS costs, and operational costs), technology combinations, and shared costs.

Multi-vector HES involve integrated systems that provision energy between multiple markets. Thus, they may have increased capital cost over one or the other independent systems but may also have the potential for cost savings when compared to two independent systems. Multi-vector HES also (a) can increase capital utilization for some components (e.g., a nuclear HES that sells both electricity and hydrogen would avoid generation reductions that could happen if it sold electricity-only into a market that has hours with very low or negative process) but (b) decrease capital utilization for other components (e.g., an electrolyzer in the nuclear-hydrogen HES would likely operate with a lower capacity factor). Thus, valuation studies are needed to understand the trade-offs between those capital utilization options.

4.3.2 Methodologies and Metrics to Measure Value

Once there is agreement on HES' potential sources of value, work can be performed to assess the value stacking and quantitatively compare the value propositions among (a) HES and multiple (comparable) independent systems, and (b) candidates for HES comprising different subcomponents and linkages. These metrics and methodologies should be standardized and consistent—regardless of the subcomponents or linkages—in order to enable the intercomparison of potential hybridization solutions. However, such standardization will need to be flexible to account for regional characteristics and markets that may make certain HES more valuable in certain circumstances. The metrics and methodologies should use accepted and established financial metrics (e.g., BCR)—based on the outcomes of the sources of value area of work—and guidelines for valuation processes more generally.[61] However, certain unique considerations for HES serve as the foundation for the opportunities presented here: assessing resource complementarity for subcomponent combinations (Section 4.3.2.1), representing HES in existing valuation tools (Section 4.3.2.2), and establishing a common valuation analysis framework for HES (Section 4.3.2.3).

4.3.2.1 Assessing Resource Complementarity

Temporal complementarity represents the potential for the production profiles of different HES subcomponents to complement one another, in terms of the time at which energy is produced (for variable resources) and the time*scales* over which subcomponents operate. Minute-scale complementarity could assist with obeying ramp rate limitations, hourly and daily complementarity can reduce forecast uncertainty at the plant level, and seasonal complementarity (monthly or yearly) can increase transmission utilization and the capacity value of hybrid resources. Depending on the subcomponents, temporal complementarity is a function of location, in terms of both the location-dependent complementarity for a given set of variable subcomponents and the potential for complementarity through virtual hybridization. A related form of resource complementarity could involve the spatial coincidence of resources that are geographically restricted (hydropower, geothermal) or cannot be cost-effectively transported over large distances (biomass).

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[61] For example, see GMLC project 1.2.4: "Grid Services and Valuation Framework Development," GMLC; accessed February 9, 2021, https://gmlc.doe.gov/projects/1.2.4.

Data and models to assess the temporal complementarity of weather-dependent variable resources are currently limited to wind and solar resources,[62] based on historical data. Data and models for resources with greater site-specificity (hydropower, geothermal, biomass) are highly limited. Moreover, the application of methods for assessing complementarity is fairly nascent and typically involves complementarity over a limited subset of timescales.

The first set of projects under this opportunity would involve detailed analysis and methods development for designing HES to maximize value based on the optimal timescale of temporal complementarity—accounting for localized interconnection constraints, transmission congestion, the time-varying value of electricity, and cost savings—for both greenfield and retrofit projects. Research about the ideal set of metrics (e.g., Pearson, Kendall rank, Spearman, or Point-Biserial correlation, and capacity factor) to capture and quantify complementarity is also needed. The final set of projects would seek to facilitate complementarity analyses with other resources, through the development of new and use of existing data sets (e.g., temporally resolved precipitation, geospatial data on water availability and surface water flows, and competing intersectoral constraints on water usage for hydropower) and capabilities (e.g., models that can capture the multiple timescales over which temporal complementarity can occur). Altogether, the impact of this full set of projects would be an enhanced ability to explore optimized plant-level design and system value that could be provided with HES that combine a variety of technologies or subcomponents.

4.3.2.2 Representing HES in Valuation Tools

DOE has supported the development of a broad suite of valuation tools across the DOE National Laboratory complex, including price-taker, production simulation, production cost, and resource planning (or capacity expansion) models. In most of these valuation tools, the unique characteristics of generation assets—such as renewable resource profiles for variable renewables and heat rates and capacity factors for fuel-based units—are individually modeled. Therefore, representing HES introduces significant challenges in terms of the large number of plant-types that would need to be added to represent the full range of combinations and synergies among hybridized subcomponents. Modeling HES therefore may warrant innovation to generalize how technologies are represented in a variety of valuation tools.

To facilitate state-of-the-art representations of HES in existing valuation tools, DOE could support the review of existing approaches to modeling HES in interconnection and transmission studies. The goal of this review would be to establish recommendations for improving models and study processes to better account for HES' operating characteristics in multiple applications, including large-scale planning studies and tools that are accessible for industry to help with individual plant interconnection studies. Such an exercise would begin by surveying existing and in-progress hybrid representations, including resource planning tools from DOE and its National Laboratories, universities, the U.S. Environmental Protection Agency (EPA), EIA, EPRI, utilities, consultancies and international organizations (e.g., the International Renewable Energy Agency, or IRENA). The

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[62] For example, see:

"NSRDB: National Solar Radiation Database," NREL, accessed February 9, 2021, https://nsrdb.nrel.gov.

"Wind Integration National Dataset Toolkit," NREL, accessed February 9, 2021, https://www.nrel.gov/grid/wind-toolkit.html.

"System Advisor Model (SAM)," NREL, accessed February 9, 2021, https://sam.nrel.gov.

"reV: The Renewable Energy Potential Model," NREL, accessed February 9, 2021, https://www.nrel.gov/gis/renewable-energy-potential.html.

survey should first identify which resource planning tools currently model or plan to model HES, and then explore each tool's:

- Method for modeling hybridized technology subcomponents
- Connections between hybridized subcomponents
- For multi-vector HES, the ability to address markets for additional products
- Any hybrid valuation that is inherent in the model (i.e., capacity value relative to independent or capital cost relative to independent)
- Ability to easily adopt additional hybrid configurations
- Ability to address economic, sustainability, reliability, and security impacts
- Major assumptions surrounding hybridization.

DOE could also consider performing a similar survey of HES representation in a variety of tools to better understand the conditions under which different valuation tools are appropriate for hybrid system valuation (e.g., based on the value streams that are of interest, subcomponent combinations, markets, and other factors).

Building on these initial surveys, DOE could conduct a multimodel comparison to understand considerations, best practices, and research gaps for representing HES in capacity planning models (similar to previous exercises that have been performed for variable renewables, independent battery storage, and nuclear technologies). A goal of the model comparison should be to encourage flexible methodologies that ensure future HES can be readily represented—rather than requiring extensive model development as different subcomponent combinations approach cost-effectiveness.

4.3.2.3 Valuation Analysis Framework

Existing research about the cost-effectiveness of HES is riddled with apparent contradictions. For example, some RE+storage research compares economic metrics for HES against the independent renewable energy system, which suggests hybridization is cost-effective; however, evaluating the same metric for RE+storage against independent renewable energy and storage systems may indicate that multiple independent systems have greater net-economic benefits than the hybrid system. And even if the RE+storage is found to have improved economic performance over multiple independent systems, it may still not be as cost-effective as competing energy assets, which can only be evaluated through a system-level analysis.

The goal of this opportunity would be for DOE to support research that maximizes self-consistency, transparency, and clarity among HES valuation efforts through a common set of valuation scenarios, the establishment of common "systems" in which to evaluate HES economic performance, and common reporting protocols. Though this opportunity was developed with HES in mind, it is likely relevant for independent energy technologies as well.

Valuation scenarios: DOE could support the establishment of a common set of valuation scenarios, the goal of which would be to provide a practical benchmarking exercise through the common treatment and evaluation of existing, proposed, and future HES. Such a framework would avoid the apparent disconnects between studies that focus on firm capacity versus those that focus on ancillary services or load following, as well as conflicts across studies with disparate assumptions about market products and conditions.

System definitions: DOE could also support the establishment of definitions for what constitutes "the system" in which the HES is to be integrated and valued. Common reference systems—such as a set of distribution systems (e.g., the IEEE 123 node systems), simplified bulk power systems with some environmental conditions (e.g., water dependencies, climate conditions, natural resource availability and access or proximity to pipeline systems that can transport fuel inputs and product outputs), and thermal and commodity (e.g., natural gas) reference systems—would help ensure an apples-to-apples comparison across candidate HES. However, it is important to note that valuation activities within these simplified theoretical systems (a) should not be interpreted as predictors of actual HES operations or system value, and (b) may not be relevant for assessing improved performance and added value streams for existing generation or infrastructure assets.

Common reporting protocols: DOE could support the development of common reporting protocols that can be tested (e.g., by having an independent organization redo the analysis to see whether it yields similar outcomes). Of particular importance is ensuring transparency (and consistency) in the comparisons being made. The cost and performance of candidate HES can be compared with those for:

- A single independent system, based on one of the subcomponents
- Multiple independent systems, based on all subcomponents
- Different sizing and configurations for the same HES subcomponents
- Competing assets on the bulk power system.

These different comparisons are all needed to capture the perspectives that are relevant for HES, but the use of one comparison or another can lead to conflicting conclusions, in terms of whether hybridization is thought to be cost-effective. DOE could help support a more cohesive look at the cost-effectiveness of hybridization by recommending a common set of valuation metrics and comparisons that capture the net-economic benefits of HES relative to relevant baselines.

The impact of establishing a common set of valuation scenarios, reference systems, and reporting protocols would be the facilitation of an apples-to-apples comparison across HES that is practical and straightforward to implement. However, this set of activities must not discredit the various motivations for hybrid system development and deployment. Notably, there will need to be differentiation based on (a) HES with distinct motivations (e.g., fossil and nuclear baseload plants versus weather-based variable resources) and (b) the identified value proposition of HES (e.g., in wholesale electricity markets, for vertically integrated utilities, for behind the meter use, for providing essential reliability services, or for generating nonelectricity coproducts). The implementation of this services taxonomy should take the form of a common set of industry-vetted valuation scenarios, which could help benchmark services that are likely to be included in making the business case for candidate HES. However, it is worth noting the impact is most likely to be achievable for electricity-only HES, because of the diversity and current gaps in analysis capabilities for multi-vector HES.

4.3.2.4 Estimating Value

Once the potential sources of value and measurement approaches are established, the next step is to use a variety of tools to estimate the value of various HES, in different regions, under different system conditions, and at different points in time (e.g., daily, seasonally, and from the present to the future). The tools required will depend on the target audience. For example, capacity expansion modeling is needed to understand system value, but targeted tools that are accessible to developers and asset owners are also needed to help them consider the value of deploying HES. Of utmost importance for the credibility of any cost-benefit analysis is the transparency of all assumptions and scenario definitions, reference system specification, and any other projections relevant for the outcome of cost estimates and valuation. This opportunity primarily encompasses a variety of analysis projects that would help identify the greatest benefits that HES can provide from a system perspective, accounting for system costs, reliability, resilience, and other potential benefits.

For each subsection below, it is likely that similar analysis has been performed for a given technology combination, likely through research supported by a single DOE program office or one of its suboffices; therefore, the goal of each of these analysis efforts would be to either expand related recent and ongoing research to additional technology combinations, particularly for those that span multiple offices or suboffices.

4.3.2.5 Plant-Level versus Grid-Level Optimization

DOE could support modeling and analysis to understand how hybrid valuation varies, if at all, between plant-level and grid-level optimization. Optimizing the design and operations of HES for plant-level benefits typically focuses on maximizing revenue while minimizing cost. By contrast, optimizing HES operations for grid-level benefit may focus on maximizing provision of a specific set of services that are perceived to be the highest-value utilization of a specific HES configuration. This activity would involve performing comparative value analysis to understand the alignment of, and differences between, these perspectives. The analysis should consider various market rules, grid build-out scenarios, ownership structures, and policies to understand the degree of alignment or divergences between plant-level and grid-level optimization.

4.3.2.6 Transmission Utilization

DOE could support modeling and analysis to evaluate the extent to which HES can mitigate transmission utilization challenges, including both underutilization and congestion. This opportunity was introduced in Section 4.2.4, which proposed performing a baseline assessment of current practices related to the treatment of HES in interconnection and transmission studies. The present opportunity is broader in nature, considering not only non-wires alternatives that can mitigate transmission utilization challenges, but also strategies for designing HES that can increase flows on underutilized transmission segments. In addition, projects under this opportunity would focus on the related *value,* or the magnitude of transmission investments (for both upgrades or new lines) that could be avoided through the design and operation of HES to optimize transmission utilization.

Performing these valuation projects would likely depend on related technology development activities (Sections 4.4.1.2 and 4.4.4.2) that are necessary precursors to quantifying the performance—and, in turn, valuing—of HES in terms of mitigating transmission utilization challenges. Finally, this discussion has focused on electric grid transmission infrastructure challenges, but parallels can be drawn with the infrastructures and policies related to the transmission or energy and nonenergy products (e.g., hydrogen, chemicals, liquid fuels, water, and CO_2) associated with multi-vector HES.

4.3.2.7 Retrofit Opportunities

DOE could support analysis to understand the potential for hybridization through retrofit opportunities across a wide array of locations, interconnection queues, and subcomponents. Select examples of research projects include (a) evaluating the extent to which it could be cost-effective to deploy additional generation technologies on the land between wind turbines (accounting for interconnection costs and challenges), (b) understanding how to prioritize “repowering” opportunities to extend the useful life of wind, solar, hydropower, nuclear, fossil, and other assets as markets evolve (accounting for market sensitivities), and (c) developing tools to help owners of existing assets select appropriate hybridization strategies where there are benefits both to the energy system and owner.

4.3.2.8 Mitigating Forecast Errors

DOE could support research to evaluate the extent to which hybridization mitigates risks associated with forecast errors, and whether such a mitigation strategy is cost-effective. Hybridization can mitigate the variability of weather-dependent resources through the colocation and coordinated operation of a dispatchable technology. However, analysis is needed to evaluate whether hybridization is a robust solution for this challenge, in other words whether (a) the additional complexity of hybridization is justified based on the value (or avoided cost) that it achieves and (b) alternative approaches would achieve similar benefits at a lower cost. Separate analysis would be needed for transmission-connected and distribution-connected systems—which are subject to different pricing and rate structures—but both should be evaluated with reliability and resilience metrics.

4.3.2.9 Resilience Benefits

DOE could support the compilation and documentation of the ways in which HES interact with energy system resilience, considering multiple subcomponents and application spaces. Resilience valuation is an active field of research, but it currently lacks well-defined and validated metrics and evaluation frameworks. Despite these uncertainties, projects under this opportunity could evaluate the relative resilience benefits of HES and comparable independent systems, from a system performance perspective. Such an analysis would help inform whether resilience could be an important source of value for HES in the future for customer-sited, microgrid, or transmission-connected systems.

4.3.2.10 Environmental and Other benefits

DOE could support research to quantify and value the environmental and other benefits that could be realized by HES. Many of the commonly stated motivations for hybridization have the potential to mitigate environmental risks. For example, increased efficiency, avoided ramping, and maximizing clean energy utilization could all reduce the emissions of greenhouse gas emissions and pollutants, the latter of which could improve air quality. Moreover, the joint operation of HES could be designed to (a) avoid migrations by birds or marine mammals, or (b) minimize water withdrawals or consumption from the energy sector. Hybridization with renewable energy systems allows for energy arbitrage to displace high emission thermal units; hybridization with conventional baseload thermal units allows for resource operational optimization to avoid off-design operations that result in emissions and operating costs increases. The projects under this opportunity would develop new and exercise new and existing tools to quantify (and value) the degree to which HES would impact the environmental performance of the energy system.

4.4 Technology Development Opportunities

HES require the integration of different variable and conventional generation, energy storage, and conversion technologies (and in some cases loads) into energy and power management systems at different time scales. Various methods of interfacing HES components with each other and with the energy system (e.g., the grid) make this a significant challenge, because of a variety of possible design complexities and their impacts on communications and control architectures. In this section we present technology development R&D opportunities for HES, which include controls development and testing (Section 4.4.1), plant-level design optimization (Section 4.4.2), developing and testing HES components (Section 4.4.3), demonstration projects (Section 4.4.4), and optimal hybridization and conversion strategies (Section 4.4.5). The inclusion of a given opportunity is not meant to imply that ongoing research is not being dedicated to these areas, but rather to indicate opportunities for increased coordination and collaboration across DOE program offices and their suboffices.

4.4.1 Controls Development and Testing

A key challenge for the wide-scale industrialization of HES lies in the complexity associated with developing and testing robust and efficient control solutions for each technology combination. Certain power management strategies (at millisecond-second-minute-hourly scales) are required to enable stable operation of HES, thus ensuring, for example, voltage and frequency regulation, and enabling various other functions such as energy and capacity services, provision of reserves, and congestion management.[63] HES controls research should include the ability of subcomponents to operate in both grid following and grid forming modes (i.e., inverter-coupled energy storage), as well as the ability to co-optimize the provision (and dispatch) of energy and ancillary services. The complexity of hybrid controls grows exponentially as other diverse energy storage and conversion technologies (e.g., electrochemical, molecular, thermal, and mechanical technologies) are being considered as candidates for further hybridization with renewable generation because of both (a) the interactions with the grid and (b) thermal inertia and other impacts introduced by the other conversion technologies.

The primary goals of projects within this opportunity are to expand (a) the technology combinations for which advanced controls are being developed and tested, and (b) the suite of services and products (or sources of value more broadly) that are being enabled by those controls. Such R&D will likely be component-specific, and attention should be paid to how the needs vary for the different types of HES. For example, the controls and requirement to consider response time is inherently different based on the type of technology and the siting of the subcomponents. For full electricity-only hybrid systems, for example, the control-focused research for HES must be divided into two different but interdependent layers: a fast control layer (e.g., 10–100 Hz control speed) that will send setpoints and receive feedback from individual HES subcomponents and an optimization layer that determines the setpoints to HES subcomponents at the start of each market interval (e.g., 5-minute, day-ahead) based on constraints and resource forecast. Additional considerations may need to be made for virtual power plant applications, where response times will also need to reflect the dispersed nature of the subcomponents. Full multi-vector hybrid systems could potentially add another control layer at the control frequency of the thermal or chemical integration and that layer would have to interact with the others.

The remainder of this opportunity presents select examples of R&D activities that fall under the controls development and testing umbrella, in order to emphasize research questions that are unique to HES, including aspects of controls research that leverages advanced computational methods (Section 4.4.1.1), optimizes T&D network utilization (Section 4.4.1.2), incorporates resource forecasts (Section 4.4.1.3), and leverages and informs advances in microgrid controllers (Section 4.4.1.4). It focuses on development and testing needs for full electricity-only hybrid systems, but analogous needs are likely for multi-vector hybrid systems.

4.4.1.1 Leveraging Advanced Computational Methods

Integrating a wide array of subcomponents into a robust, cost-effective, and adaptive architecture while managing the competing life, performance, and value constraints during normal operations is a considerable undertaking. The use of advanced computational methods (e.g., artificial intelligence [AI] and machine learning) can help manage this challenge by consolidating and filtering the large amount of data generated by HES to facilitate ease of processing for the site owner or utility and the automation of some lower-level functions. Currently, the application of advanced computational methods to HES is limited by the lack of data needed for these methods to be beneficial. Overcoming this data gap and continuing to develop advanced computational methods for HES have the potential to advance HES controls.

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[63] For a more complete list of services that could be provided by HES, see Appendix D.

The projects under this opportunity would involve using advanced computational methods (e.g., AI) to improve both the development and real time operation of controls for HES, including applications related to cyberphysical controls and smart grids. One specific example of a project lies in implementing an AI framework to create robust decision processes in the design of control algorithms for storage-based HES, considering a variety of market factors. Such a project would begin with a survey of modules and software that asset owners use to develop offers. Next, through the consolidation of electrochemical system performance across myriad deployments, scenarios, scales, and years, AI characterization could improve the performance and cost of HES through the creation of optimal cycling protocols.[64] Monitoring and data collection on HES in real time could further be back-integrated into HES controls, which would adapt over time to continuously improve system management. In addition, AI could assist with the development of offers to participate in the provision of different services while accounting for degradation.

The success of projects under this opportunity would have many long-term impacts, including (a) continuous improvement of system knowledge and ability to control multiple scenarios with increasing robustness at low risk and cost, (b) development of improved evaluation and monitoring protocols for new energy storage chemistries, and (c) improved system management strategies yielding improved performance with low cost and low risk. Additionally, higher-performing HES will be more flexible in their utilization profiles, thus allowing for the possibilities of addressing both routine and event-driven needs, with reduced risk and lower cost. The final outcome of this project would be a study that quantitatively compares cost and performance outcomes for traditional performance estimates and AI-detailed control data.

4.4.1.2 Optimizing Transmission and Distribution Network Utilization

The utilization of transmission and distribution (T&D) networks is time-dependent: lines are often used near or at-capacity during peak periods, and they are underutilized during off-peak hours and seasons (where peak can refer to maximum production or load). Both extremes introduce opportunities, in the form of non-wires alternatives (see Section 4.2) and increasing utilization during off-peak times (Figure 10). A potential benefit of HES is that they can serve both these functions, depending on the subcomponents and the nature of linkage between them. The following discussion focuses on opportunities within the electricity system, but similar themes and research activities would likely be relevant for the transmission (or transport) of chemicals, liquid fuels, and other products of multi-vector HES.

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[64] This opportunity could build on DOE's current investment in deep knowledge about energy storage.

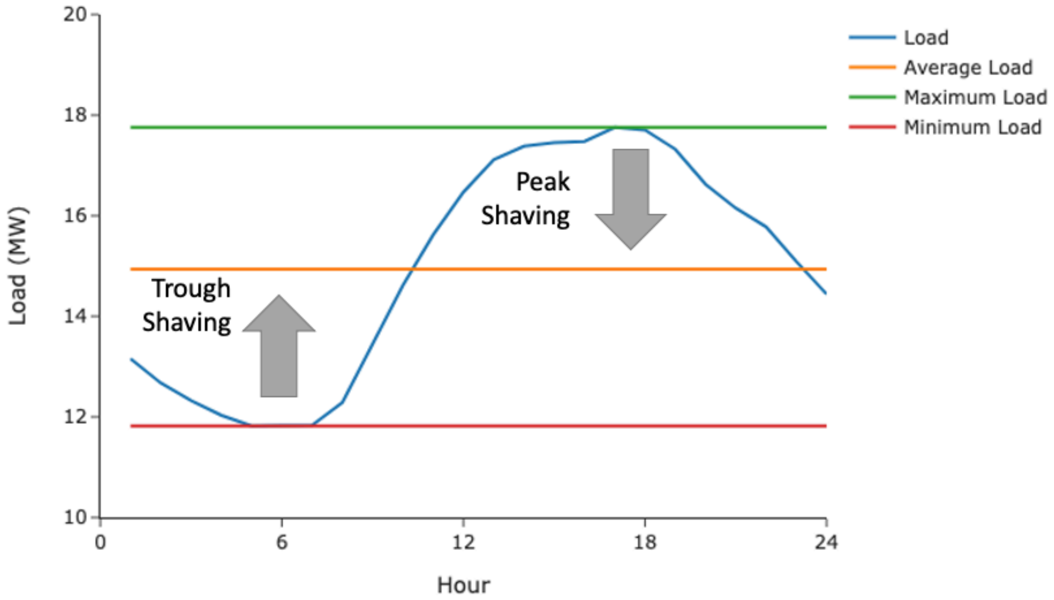

Figure 10. Peak shaving and trough shaving (or valley filling) potential of HES

Recent research has been devoted to the optimal dispatch and placement of HES to optimize T&D infrastructure utilization.[65] This research has typically focused on HES that include a storage component, which enables the system to provide both peak and trough shaving by either producing or consuming electrons (Figure 10), based on price signals. However, HES without a storage component can also increase the utilization of the T&D networks (e.g., when multiple variable resources with inverse production profiles are linked together, with the explicit goal of producing electricity at different times of the day or year).

Though this opportunity is clearly related to the previously mentioned markets and valuation aspects of non-wires alternatives, realizing the potential T&D utilization benefits of HES is rooted in technology development activities. For example, DOE could support additional research dedicated to developing controls that include an objective of maximizing network utilization, which is especially important for (and can leverage related research for independent) storage-based systems. Dedicated research would be needed for both transmission-connected and distribution-connected HES, because of the different requirements and operational signals for each. Such research activities should also include a demonstration component to prove the effectiveness and value of such an approach from the perspective of the system operator.

4.4.1.3 Incorporating Resource Forecasting

For a wide range of HES, a need within controls development research is understanding how to incorporate resource forecasting into the control model. One driver for this needed development was introduced in Section 4.4.1.2: for HES that are deployed in areas with network congestion, controls should be developed to provision

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[65] Panagiotis Andrianesis, Michael Caramanis, Ralph D. Masiello, Richard D. Tabors, and Shay Bahramirad. 2020. “Locational Marginal Value of Distributed Energy Resources as Non-Wires Alternatives.” *IEEE Transactions on Smart Grid* 11 (1): 270–80. https://doi.org/10.1109/TSG.2019.2921205.

Ioannis Lampropoulos, Tarek Alskaif, Jelle Blom, and Wilfried van Sark. 2019. “A Framework for the Provision of Flexibility Services at the Transmission and Distribution Levels through Aggregator Companies.” *Sustainable Energy* 17 (March 2019:): 100187. https://doi.org/10.1016/j.segan.2018.100187.

energy generation away from electricity sales during periods of peak production (or congestion), thus avoiding the curtailment of generation that is due to an inability to transport that power to customer loads.

For HES that include electricity storage, a second driver is ensuring the storage asset is fully charged and available when the grid calls for maximum power, especially if the energy source is variable renewable energy (VRE) and it is unavailable. Realizing this second application would require dedicated research to improve forecasting of both resource production and grid status (or signals); therefore, it represents the intersection of ongoing research related to controls for independent VRE and storage systems. Projects under this opportunity would integrate the findings from these separate R&D efforts, with a goal of understanding (a) how to integrate resource and grid forecasts into controls for HES, and (b) the optimal combination of capabilities from these separate R&D efforts to avoid an overengineered solution with declining returns as precision increases. Related research could further consider demand forecasts, as they relate to (and inform the value-optimal operations of) distribution-connected HES and microgrids.

4.4.1.4 Relationship with Microgrid Controls

Microgrids represent a subset of distribution-connected HES (Text Box 1), which introduces the opportunity for coordinated research across controls for microgrids and HES more broadly. Projects under this opportunity would be bidirectional. In one direction, recent and forthcoming advances for HES could be adapted and applied to microgrids, in order to implement flexible and modular control models for microgrids that enable the connecting and disconnecting of systems at will. In the other direction, recent experiences in establishing standards for microgrid controllers (IEEE 2030.7) could help address the challenge that no standards have been established for HES controls. In particular, DOE-funded activities could enable DOE National Laboratory experts to assist with a proposal to adapt the microgrid controller standard to enable it to serve as an HES controller standard. Similarly, those experts could consider the compliance of HES controls to existing standards for battery energy storage, inverter-based resource, and DER controls, and they could evaluate whether those standards are sufficient for electricity-only HES.

4.4.2 Plant-Level Design Optimization for HES

Designing HES is a complex process involving an immense design parameter space. Optimizing the sizing, linkages, and operations of HES subcomponents to maximize the joint system's overall performance is data and computationally intensive. In addition, optimizing the design of HES is currently challenged by a lack of representation of HES in dynamic models that quantify plant-level performance and interactions with the electricity grid.

4.4.2.1 Leveraging Advanced Computational Methods for HES Design

To overcome the challenges associated with HES design optimization, DOE could support research to understand and apply advanced computational methods to this complex problem. In addition to the advanced computational methods described in Section 4.4.1.1, machine learning-based techniques may be especially powerful for optimizing the design of complex HES. In particular, machine learning-based methods have a demonstrated ability to detect and extract important correlations, interpret important predicting variables (e.g., market price fluctuations and resource availability), capture nonlinear and outlier behavior (e.g., market behavior and the complex, path-dependent degradation of battery technologies), define relationships between different timescales (e.g., 5-minute and daily), and handle parameter uncertainties. All these capabilities could be applied to inform an optimal design in terms of sizing components, minimizing performance degradation, and extending system lifetime through the co-optimization of operations with HES design criteria. Other advanced computational methods may accomplish similar goals, perhaps with better performance.

An example of a project in which advanced computational methods could provide significant advancements lies in developing methods to optimize the design of HES that contain energy storage, including batteries and other electrochemical subcomponents. The value generated by a battery depends on its lifetime energy throughout, which is dictated by complex path-dependent degradation. Therefore, the optimal design of storage-based HES depends on managing the battery degradation in complex and dynamic scenarios. Current laboratory testing requires approximately 2–2½ years and significant resources to evaluate the performance degradation and overall battery life for an individual cycling protocol. This approach limits the number of cycling protocols that can be experimentally tested, relies on estimation for other operating cycles or uses, and might not accurately capture or predict the battery degradation under real-world operating conditions. Initial DOE laboratory results suggest AI methods could reduce the testing time to 2–3 weeks, simulating 1,500–2,000 cycles, which would allow for the rapid evaluation of lifetimes and potentially help reduce the testing time needed for future battery chemistries. Through this approach, advanced computational methods could be very impactful in terms of enabling the selection of the best storage chemistry for a specific HES, informing the sizing of the other subcomponents to align with the optimal battery cycling or utilization profiles, and increasing the accuracy of performance degradation and lifetime estimations for storage-based HES.

4.4.2.2 Representing HES in Dynamic Models

Presently in North America, an aggregated modeling approach is followed to represent the behavior of energy technologies, including inertial-based resources, inverter-based resources, and hybrid plants. Because of the additional unique elements in a hybrid plant, efficient dynamic model reduction techniques are required to keep simulations and data management computationally tractable, particularly for power flow models. When determining the dispatch level and capacity of hybrid plants, the various stacked benefits and services that can be provided must be considered; it is equally important to be able to develop robust controllers to enable delivery of services while ensuring stable and reliable operation of the hybrid plant. With an increase in hybrid plants, along with their characteristic behavior, ensuring coordination of power delivery (both active and reactive) is important to maintaining stability of the power network. Coordination becomes more crucial when, within a single hybrid plant, inverters of different vendors may have different control modes. Being able to accurately model and simulate the behavior of hybrid plants in planning studies should go hand-in-hand with the development of robust controller algorithms.

Projects in this opportunity would (a) develop model reduction techniques to efficiently represent an entire hybrid plant, (b) develop processes for running large sets of interconnection studies in a parallel manner to optimally interconnect hybrid plants in a way that ensures dynamically stable operation, and (c) elucidate differences in hybrid plant models across various software vendors. These activities could enable utilities, original equipment vendors, and independent research organizations improve methods and processes for planning and operating HES on the bulk power system.

4.4.3 Developing and Testing Components

At its core, efficient hybridization is rooted in hardware components that can enable coupling (or linkages) that reduce costs and/or increase value. Moreover, HES R&D centers of the future will need to provide at-scale multi-technology power electronics, power/energy devices and communications at various timesteps to emulate various real-world operational and cybersecurity events.

4.4.3.1 Hardware development to enable efficient and cost-effective coupling

For fully integrated HES, the potential for shared equipment represents an important source of value (via cost savings and/or operational synergies). However, this can only be achieved if a single piece of equipment can meet the requirements of all relevant sub-components, without compromising the value that can be provided by the joint system. For example, advanced power electronics have been identified as a critical need to (a) condition, optimize, and enable generation and storage of electricity from increasing variable renewable energy sources (e.g., PV and wind turbines) and associated battery storage technologies, and (b) integrate inertial based generators with inverter-based generators, to facilitate more effective thermal integration, load response, and HES efficiency. A shared inverter that serves both the PV and battery sub-components in fully-integrated PV+battery HES has the potential to reduce capital costs for the joint project, relative to multiple standalone projects. However, research has shown that the avoided costs could be largely (or entirely offset) if the shared inverter is designed for the requirements of the PV sub-component (uni-directional) but not the battery sub-component (which can generate more value with a bi-directional inverter). Furthermore, HES that include nuclear or fossil will require integration of its inertial generator with inverter-based technologies. Another example is thermal integration within a multi-vector HES in which heat can be dynamically apportioned among multiple processes. The resulting dynamic provisioning of thermal energy are subject to inertia and can result in thermal stress. Control methods linked to buffering technologies could improve the likelihood of such multi-vector systems to be successful.

Projects under these opportunities would involve technology development to improve the cost and performance of hardware components that enable the efficient integration of multiple components to form HES. The first step would involve surveying subject matter experts for all interested DOE program offices, to identify key enabling technologies for hybridization, indexed by their technology readiness levels. This list could then serve as the foundation for potential collaborative Technology Development research across DOE offices, which would likely be rooted in key technologies that are relevant for select HES (as opposed to universally relevant across the full universe of HES). Finally, research under these opportunities should include an emphasis on scalability and supporting the development of technology standards, to ensure that any hardware developed via DOE-funded research can be readily integrated into pre-commercial and commercial HES.

4.4.3.2 Component testing through at-scale emulation

Given the wide spectrum of HES configurations, it is important to identify the required testing capabilities, and whether existing National Laboratory facilities are sufficient for meeting those requirements. To date, many (physical and cyber) test facilities and research platforms that have been established across DOE's National Laboratories. Some are dedicated to hybrid-specific research (see Section 5), but most are generally designed for testing and simulation across facilities and software platforms, including through emulation focused on power electronics (such as inverter technology), high-fidelity real-time simulations, electric and thermal hardware-in-the-loop testing (HIL), controller and power hardware, and balance of plant systems.

There are multiple projects that could help advance DOE's ability to test HES components through at-scale emulation. First, existing and under-development platforms should be evaluated to understand whether they can accommodate hybrid-relevant sub-components, such as diverse power/energy devices, shared hardware, conversion technologies, sensors/telemetry, and communications infrastructure at various timesteps, to better emulate real-world hybrid system operations and reduce latency. Second, DOE should support the coordination of test facility and software platform interoperability between the labs, which could be especially relevant for the physical testing of Virtual Power Plant sub-components. That effort should include identification of data requirements to emulate thermal integration and the subsequent test facilities and software platforms.

Finally, DOE should ensure that dedicated cybersecurity research platforms and efforts are able to accommodate the new hardware/midware/software that is specifically developed to support the integration of two or more hybrid components. The cybersecurity vulnerabilities of HES are largely shared with those of the underlying sub-components, such that HES will not necessarily introduce new cybersecurity threats. However, combining multiple sub-components together results in (a) an increased attack surface (due to multiple communication-connected devices), (b) concerns over the interoperability of legacy equipment with new equipment, and (c) the potential use of third-party components that do not have verified or secured supply chains. Therefore, cybersecurity testing for HES primarily requires coordination with ongoing cybersecurity research, but it may also require new testing capabilities to represent how the combined communications aspects of HES are distinct from their standalone counterparts. As in Section 4.4.3.1, projects under this opportunity should ensure alignment with standard processes for the development of technology standards.

4.4.4 Need for Demonstrations

Technology demonstrations that prove technical capabilities and, in turn, reduce risk are seen as a key opportunity for getting buy-in from industry and accelerating the adoption of new HES. DOE could help reduce the risks associated with HES development and deployment by (a) exploring end user requirements for HES to inform HES technology development and align emerging HES with appropriate end-use applications, and (b) supporting project demonstrations and deployments with industry and state energy offices to help emerging HES gain acceptance.

4.4.4.1 Mapping End User Requirements to HES Capabilities for Demonstrations

HES have begun to gain acceptance for select end-use applications whose technical requirements align with the technical capabilities of commercial HES. For example, commercial building-type loads represent a growing market for select HES that could help reduce utility bills *and* improve their local reliability and resilience (e.g., PV+battery or CHP). In addition, industrial end users are increasingly interested in multi-vector HES that can generate electricity bill savings and generate other useful products such as heat, fuels, and chemicals. In the future, more end users could benefit from customer-sited HES, and additional HES could be developed based on improved cost and performance for their subcomponents and advancements in the components that facilitate hybridization. Though the advancement of HES can (and will) occur independent of specific end-use applications, a better understanding of the technical requirements of various end users can be a valuable input for informing future technology development efforts for emerging HES.

Projects under this opportunity would involve mapping end-user requirements to HES capabilities. The demands of end-use customers are highly diverse: some end-use applications have limited tolerance for momentary interruptions; others have stringent resilience requirements, which dictate security thresholds and hours of backup duration that can be provided; and still others have load profiles that are misaligned with resource availability. Some of these requirements can be addressed through the design and configurations for candidate HES, and some may be better met by nonhybrid systems. To facilitate making this determination, DOE could support the documentation of the technical requirements of end-use customers, along with the technical capabilities of various candidate HES. A key activity under this opportunity would be compiling the results of related recent and ongoing research within individual DOE program offices and their suboffices to leverage the work that is already underway.

The impacts of this opportunity include informing HES technology development to ensure emerging systems do not approach but miss requirements associated with controls, communications equipment, for example. In addition, a better understanding of the technical requirements of various end users would help develop a robust pipeline for demonstrations as new HES emerge (and the capabilities of existing HES evolve), and it would help prescreen the applications that are best-suited for demonstrating those HES. Finally, a database of end-user requirements could help support the scalability of emerging HES, by targeting technology development activities that are universally applicable.

4.4.4.2 De-risking and Field Deployment/Demonstration for a Wide Array of HES

Uncertainties and risks associated with HES reflect the unanswered questions (from market regulators and potential adopters) about the underlying HES technologies and the value HES provide to the grid. Field deployments and demonstrations can help de-risk these technologies by providing empirical data on their operation, but they can also be tricky.

To reduce costs, demonstrations often require integration of a technology into an existing plant, but modifications to an operating unit introduces new risk to the existing plant. Overcoming regulatory and permitting issues can also be a concern associated with modifying an existing plant with new technologies. Alternatively, starting from scratch with a new-build demonstration is difficult with most of these concepts as they are being advanced by cash-poor start-ups (which often require the utility or another entity to finance the capital), and their permitting process can take years. The majority of current demonstration project funding goes to transmission-connected PV+battery, coal+thermal storage, and nuclear+hydrogen HES, but these are not the only HES that could be of value to the grid.

Expanding demonstration efforts to a broader array of HES would provide more evidence to grid operators, the electricity industry, and potential investors of the different value and use cases for various HES. To ensure efficiency and avoid duplication of effort, this opportunity could be executed by matching specific risks associated with individual demonstrations to the DOE National Laboratories that are well-equipped to address these risks (directly or through capability development that builds on existing expertise). In addition to utility and other industry partners, states and state energy offices could play a key role in supporting demonstration projects.

4.4.5 Optimal Hybridization and Conversion Strategies

R&D related to future HES requires understanding and advancing optimal hybridization and conversion strategies, which is rooted in technology development research activities.

4.4.5.1 Tightly Coupled HES

Tightly coupled hybrid energy systems refer to physically connected technologies having various time constants. These systems can increase the economic value of dedicated energy resources and independent systems through more-efficient use of variable and underutilized energy sources. They can also provide a range of services to the grid, including power on demand and power phase, frequency, and voltage maintenance, as well as multiple other energy products or energy-intensive products such as chemicals, thermal energy for industrial processing or district heating, and water treatment.

Creating a highly efficient, low-cost tightly coupled energy system will require the development of interdependent subsystems that are connected through electrical and properly designed heat and mass transport systems. Tightly-coupled systems must also be resilient to inherent or unplanned system perturbations. They require system-wide monitoring, state awareness, and application of supervisory or fully automated control systems that anticipate and adjust energy flows and unit operations in accordance with energy availability and market signals. Many of the advanced technologies that could be part of future HES have been described in the previous opportunities, and they include:

- Thermal, chemical, and electrical energy delivery and storage systems
- Advanced power generation technologies, including hybrid systems that reduce exergy destruction (i.e., the loss of available work as heat, waste products, or electrical grounding)

- Advanced heat transport and heat exchangers
- Smart control systems
- Cybersecure communications and control
- Advanced fuel production and processing
- Stable water systems and natural water cycles
- CO_2 capture and utilization.

4.4.5.2 Advanced Next-Generation Power Conversion Technologies

Advanced next-generation power conversion technologies are required for thermal power generators such as fossil-fuel, nuclear, and geothermal power plants. Opportunities exist for higher efficiency thermal-to-electric conversion technologies and for utilization and recuperation of waste heat. Examples of next-generation thermal-to-electric conversion technologies include supercritical CO_2 (sCO_2) closed-loop Brayton cycles, which DOE has invested heavily in over the last several years to commercialize the technology for a range of power generation technologies, including fossil fuels, nuclear, and CSP. This technology development opportunity has the potential to increase efficiencies (a) from on the order of 40% for conventional steam Rankine cycles to (b) over 50% for sCO_2 closed-loop Brayton cycles. In turn, this improved efficiency could reduce the levelized cost of electricity production by 10% or more, according to DOE Solar Energy Technologies Office projections for CSP.[66]

Other opportunities include new heat-exchanger technologies and materials to more-efficiently convert heat to and from thermal storage systems that can provide large-scale (gigawatt-hours), long-duration (tens to hundreds of hours) energy storage for the grid. Commercial molten-salt thermal storage systems have already been demonstrated to provide gigawatt-hours of storage for CSP plants, and interest in using thermal storage to increase the flexibility and dispatchability of conventional baseload power plants is increasing.

Finally, an opportunity exists to use waste heat from the power cycle for process heating or other applications such as desalination and water treatment. Continued DOE R&D investment in these advanced thermal power conversion and storage technologies *and* subsequent pilot-scale demonstrations of integrated systems will be critical to their commercial success.

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[66] Mark Mehos, Craig Turchi, Jennie Jorgenson, Paul Denholm, Clifford Ho, and Kenneth Armijo. 2016. *On the Path to SunShot: Advancing Concentrating Solar Power Technology, Performance, and Dispatchability*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-65688. http://www.nrel.gov/docs/fy16osti/65688.pdf.

5 Conclusions

Recent growth in deployment of HES projects suggests they have potential advantages over independent systems, but challenges and uncertainties remain and must be addressed, as presented in Section 3. Multiple DOE program offices are already responding to these challenges through various R&D activities, but the review of DOE's HES portfolio presented in Section 2 reveals opportunities for additional collaboration across offices to increase impact, share lessons learned, avoid redundancies, and maximize federal spending.

To highlight topics that could require collaboration and coordination across offices, DOE and National Laboratory personnel came together to identify high-priority, near-term research opportunities (Section 4). The opportunities are assumed to be relevant for the near term, but specifying funding years and sequencing for them was outside the scope of this effort. Similarly, this report—which is intended to identify high-priority, near-term HES research opportunities on which DOE program offices could collaborate—does not bind or constrain DOE program offices to any specific activities. Rather, it serves as a first step in identifying common priorities and setting a foundation for follow-on discussions. Executing the opportunities and activities outlined in the report—and any future ones that arise as needs and goals evolve—would be at the discretion of the participating program offices and would only be possible through ongoing coordination, communication, and collaboration. This section presents a set of recommendations for enabling these partnerships.

5.1 Collaboration Mechanisms

Each of the research opportunities presented in this report were identified as high priority by at least two or more participating offices and are therefore envisioned to be carried out in a collaborative way. Existing mechanisms present a framework from which to build on, and they illustrate the many forms in collaboration could take place, including:

- **Grid Modernization Laboratory Consortium (GMLC) Lab Calls:** Many of the Grid Modernization Initiative (GMI) projects are jointly funded and managed by several of the five DOE applied offices: FE, NE, OE, EERE, and Cybersecurity, Energy Security, and Emergency Response (CESER). These projects are designed to leverage the capabilities and expertise of multiple offices because the challenges being addressed overlap technical domains. Most GMI projects involve the combined effort of several DOE National Laboratories and external partners, ensuring the nation's best resources are focused on specific challenges and building a foundation for future collaboration within the DOE National Laboratory complex.
- **Funding Opportunity Announcements (FOAs):** Every year, DOE program offices solicit research proposals from colleges and universities, nonprofit and for-profit research organizations, DOE National Laboratories, small businesses, and other federal research organizations. Joint funding solicitations could provide a foundation that ensures adjacent efforts by individual applied offices complement and further advance progress in addressing these challenges.
- **Workshops:** DOE program offices can work together to facilitate and conduct targeted engagements on high-priority topic areas related to HES that address the current and expected needs of decision makers, including state PUCs, energy offices, reliability organizations and market operators, electric utilities, communities, consumer advocates, and other federal agencies.
- **Technical Assistance:** DOE could collaborate on competitive solicitations to provide technical assistance to states, regions, and tribes by directly funding the DOE National Laboratories to develop tools and data

sets to facilitate effective stakeholder analysis and other activities. Technical assistance topics could arise from information learned through the joint workshops.

- **Peer Review:** In addition to cofunding industry solicitations or National Laboratory projects, leveraging expertise for peer review of concept papers, applications, journal publications, methodologies and assumptions, and technical reports across multidisciplinary offices can also be valuable.

5.2 Exemplary Efforts

The following projects represent examples of existing partnerships in HES research across offices that set a precedent for carrying out the opportunities presented in this report.

DISPATCHES (jointly funded by NE, FE, and the DOE Hydrogen and Fuel Cell Technologies Office [HFTO]): The GMLC "Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems" project is creating DISPATCHES, the Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems, which will enable the design and optimization of HES. The platform will support hybridizing existing generation facilities (e.g., nuclear and coal plants) as well as greenfield hybrid designs that incorporate advanced technologies (e.g., advanced modular nuclear reactors and Coal FIRST technologies), and it will enable the consideration of multiple technology options with different time constants. The design of the HES will be optimized for operation within the bulk power system via energy market signals (day ahead, real-time, and ancillary services) obtained from a production cost model. The goal of DISPATCHES is to identify flexible, dynamic designs that are responsive to grid market signals resulting in highly efficient, cost-effective hybrid energy systems that can act as a "black box" to the grid to provide increased flexibility and resiliency. This goal will be achieved by building on existing capabilities and dynamic models developed in support of the DOE mission across several offices. DISPATCHES will be demonstrated through the assessment of several representative hybrid system concepts that are of clear interest to utility and industrial partners as well as the sponsoring DOE program offices. The case studies include (a) existing and new coal (i.e., Coal FIRST technologies) coupled with energy storage options (i.e., thermal energy storage and hydrogen), (b) an existing nuclear facility coupled with hydrogen production and use, and (c) renewables coupled with dispatchable (i.e., natural gas) power options. The resulting multiscale optimization platform could be extended to include other complex energy system challenges, including coupling with natural gas supply chains and markets. DISPATCHES will be released under an open-source license to enable broad use by utilities and technology developers.

DISPATCHES
Design Integration and Synthesis
Platform to Advance Tightly
Coupled Hybrid Energy Systems

FlexPower (GMLC project, jointly funded by OE and EERE):[67] This project adopted a pioneering analysis, validation, and demonstration concept (the "FlexPower concept") to show how technology hybridization can leverage utility-scale single-technology generation's value of being a simple variable-energy resource, like wind and solar, or a predictable but constrained renewable energy source, such as hydropower, to a resource that provides dispatchability (similar to conventional power plants), flexibility, a full range of reliability services (comparable to or better than conventional plants) and improved resiliency. The project team, consisting of researchers from NREL, INL, SNL, GE Global Research, and First Solar, will develop a multimegawatt (MW) FlexPower plant validation platform at NREL to demonstrate the main benefits of hybrid PV-wind-storage-hydropower plants. The project will produce publicly available results on the FlexPower controller architecture,

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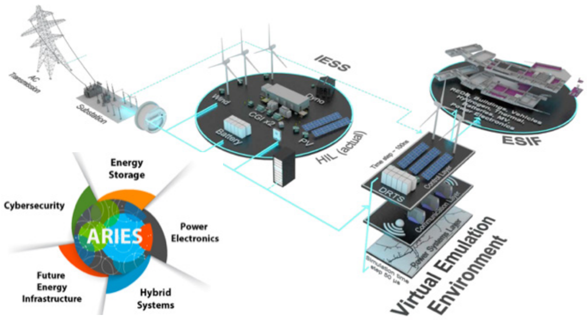
[67] The DOE Wind Energy Technologies Office, Water Power Technologies Office, and Hydrogen and Fuel Cell Technologies Office support the FlexPower project.

publicly available control codes developed by the DOE National Laboratories for various industrial control platforms (e.g., the Schweitzer Engineering Laboratories—Real-Time Automation Controller [SEL/RTAC] and National Instruments' LabVIEW), hybridization potential assessment maps and databases, and results of regional impact studies. The data will be disseminated via publications, targeted regional webinars, and conference presentations, including at industry workshops, ESIG, IEEE, and international venues.

5.3 National Laboratory Capabilities

DOE has supported the development of multiple state-of-the-art HES research capabilities across the DOE National Laboratory complex that are designed to explore hybrid-specific questions, span multiple research areas, and evaluate a diverse suite of existing and potential subcomponent combinations and linkages. These capabilities represent examples of targeted HES efforts that benefit multiple DOE program offices—and benefit from multioffice support and investment. In executing the opportunities outlined in this report, participating offices should leverage these existing capabilities.



The **Advanced Research on Integrated Energy Systems (ARIES)**[68] research platform is designed to de-risk, optimize, and secure current energy systems and to provide insight into the design and operation of future energy systems. ARIES encompasses a Hybrid Energy Real-Time Time Hub (HERTH) that includes emulation of energy system, communication, and control layers at-scale up to 20 MW and virtually to real-world gigawatt-level sizes. It will address the fundamental challenges of (a) variability in the physical size of new energy technologies being added to energy system, (b) the control of millions to tens of millions of interconnected devices, and (c) the integration of diverse technologies that have not previously worked together. The ARIES platform is housed at NREL.

The **Institute for the Design of Advanced Energy Systems (IDAES)** was formed in 2016 to develop new computational capabilities to optimize the design and operation of complex, interacting energy technologies and systems. The IDAES Integrated Platform[69] includes core equation-based modeling and optimization components and specialized AI and uncertainty quantification (UQ) capabilities that enable rigorous analysis of multiscale, dynamic processes and operating scenarios to improve efficiency of existing systems and develop next-generation energy systems. IDAES is led by NETL in collaboration with SNL, LBNL, Carnegie Mellon University, West Virginia University, and the University of Notre Dame.

The **Argonne Collaborative Center for Energy Storage Science (ACCESS)** is a powerful collective of scientists and engineers from across ANL who solve energy storage problems through multidisciplinary research at every link of the energy storage chain from analysis of raw materials to system end of life and recycling. Physical capabilities include testing facilities for batteries, fuel cells and electrolyzers, thermal storage, and grid integration. Computational and modeling capabilities include high-performance computing with a focus on AI/machine learning for hybrid systems and advanced combustion modeling, agent-based models of system

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[68] See "ARIES: Advanced Research on Integrated Energy Systems," NREL, accessed February 9, 2021, https://www.nrel.gov/aries/.

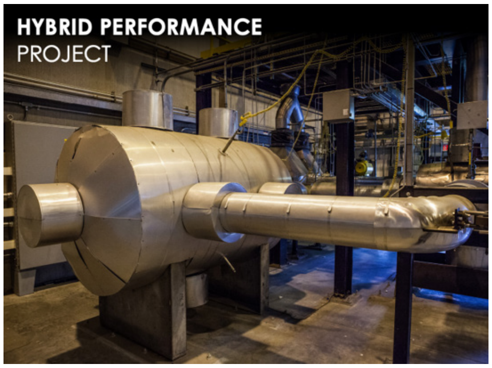
[69] See "IDAES/idaes-pse," accessed February 9, 2021, https://github.com/IDAES/idaes-pse.

manufacturing chains and energy markets, coupled models of electric and natural gas grids, and the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) life cycle analysis tool.

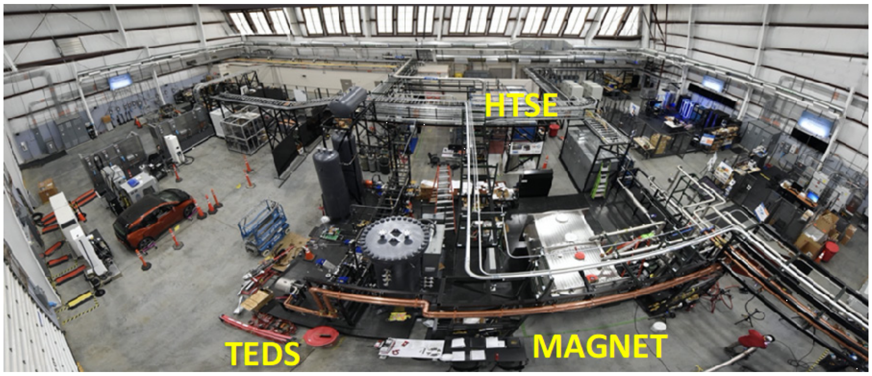
The **Grid Storage Launchpad Facility** at PNNL will use independent testing and validation of grid energy storage to develop and promulgate rigorous grid performance standards and requirements—spanning the entire energy storage R&D development cycle, from basic materials synthesis to advanced prototyping. One of the primary focuses of the facility is to bring together DOE, multidisciplinary researchers, and industry to lower the barriers to innovation and deployment of grid-scale storage technologies.


Grid Storage Launchpad Facility

The **Hybrid Performance (HyPer) Facility**[1] at NETL is designed to develop control strategies for the reliable operation of HES. The facility employs a cyberphysical approach that integrates real time simulation with physical hardware to evaluate the dynamics of fully integrated systems, allowing control strategies to be developed and tested for system start up, load transition and shut down to reduce risks associated with commercial deployment. The test facility is designed to enable tight thermal and electrical coupling of inertial (gas turbine and internal combustion engine [ICE] generators) and inverter-based technologies (solid oxide fuel cell/solid oxide electrolyzer cell [SOFC/SOEC] technologies) to increase efficiency and reduce emissions. NETL has an active collaboration with INL in the area of HES. The HyPer facility was recently connected through ES-Net with the INL real time grid simulation platform.



The Dynamic Energy Transport and Integration Laboratory (DETAIL)[70] at INL has established and is expanding an experimental capability to demonstrate coordinated, controlled, and efficient transient distribution of heat and electricity for power generation, storage, and industrial uses. DETAIL includes a combination of connected assets that can be reconfigured to research specific topics related to technology grid-integration and hybridization. This initial configuration incorporates the INL Thermal Energy Distribution System (TEDS), which includes thermal energy storage; a Microreactor Agile Nonnuclear Experimental Testbed (MAGNET); and a high temperature steam electrolysis (HTSE) system that can be tested using a grid emulator and energy storage devices, including fast charging vehicles.



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[70] Shannon Bragg-Sitton and Richard Boardman. *Integrated Energy Systems for Hydrogen and Chemicals Production*. Presented at Hydrogen and Fuel Cell Energy Annual Merit Review (DOE, May 2020). https://www.hydrogen.energy.gov/pdfs/review20/ne01_bragg-sitton_boardman_2020_o.pdf.

The **INL Framework for Optimization of ResourCes and Economic (FORCE)** is a flexible modeling ecosystem consisting of a suite of computational tools for techno-economic assessment (TEA) and optimization of integrated energy systems that includes opensource components. Capabilities include dynamic modeling of plants (HYBRID model repository[71]), Tool for Economic AnaLysis (TEAL[72]) for assessment of complex cash flows, and Holistic Energy Resource Optimization Network (HERON[73]) for modeling of the energy market. This suite of tools uses the INL-developed Risk Analysis Virtual Environment (RAVEN[74]) software for optimization. The HYBRID repository is a collection of models and workflows used to assess the technical and economic feasibility of different HES. The repository provides a library of high fidelity Modelica models developed using the Dymola compiler that includes models of nuclear reactors, gas turbines, hydrogen production facilities, energy storage technology, and other integrated energy system technologies.

The **Distributed Energy Technologies Laboratory (DETL)** at SNL conducts research to integrate emerging energy technologies into new and existing electricity infrastructures and accommodate the nation's increasing demands for clean, secure, and reliable energy. DETL provides power electronics testing capabilities including island and campus grids, remote operations, and scaled portions of utility feeders and the transmission infrastructure. It includes a 480-V, three-phase microgrid, with interconnections to the utility grid and to various DERs, including PV inverters, microturbines, fuel cells, reciprocating engine-generators, and electrical energy storage systems. DETL provides expertise and testing capability to perform grid-connected performance evaluations (e.g., efficiency, distortion, power factor, response to abnormal grid conditions), off-grid (stand-alone) performance evaluations (e.g., transient response, compatibility with various load types, voltage and frequency regulations), specialized tests (e.g., radio-frequency emissions, "non-islanding inverter," interactions of multiple sources on a common microgrid, surge tolerance).

The **Electricity Infrastructure Operations Center** (EIOC)[75] at PNNL brings together industry software, real-time grid data (Offsite link) and advanced computation into a functional control room. This unique integrated energy operations capability was shaped with input from utilities and researchers across the Northwest. The results and new technologies developed here will be transferable across the industry and address the national need to better manage and control the grid.

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[71] HYBRID is a Collection of high fidelity, dynamic models for IES design, analysis, and optimization, and it is available opensource at https://github.com/idaholab/hybrid.
[72] TEAL is available opensource at https://github.com/idaholab/teal.
[73] HERON is available opensource at https://github.com/idaholab/heron.
[74] RAVEN is available opensource at https://github.com/idaholab/raven.
[75] PNNL's EIOC information is available at "Electricity Infrastructure Operations Center," PNNL, accessed August 25, 2020, https://eioc.pnnl.gov/.

Appendix A. National Laboratory Capabilities Relevant for HES

This appendix details the list of DOE National Laboratory capabilities related to HES. These capabilities are summarized below and presented in Table 11 (for markets-based capabilities, page 65), Table 12 (for valuation capabilities, page 70), and Table 13 (for technology development capabilities, page 75).

A.1 Markets-Based Research and Support Capabilities at DOE National Laboratories

The DOE National Laboratories have extensive capabilities related to electricity markets-based research, including models that are designed for or support markets-based research, technical assistance efforts, database development, and standards development. Markets-based modeling capabilities exist across the DOE National Laboratories, including agent-based electricity market models (e.g., the Electricity Markets and Investment Suite [EMIS] at NREL) and tools to support markets research for nuclear power plants at INL. The DOE National Laboratories also have a variety of established valuation tools that can support electricity markets research, by evaluating the extent to which different market rules impact plant-level and system costs. For example, ANL, NREL, NETL, and PNNL have capabilities in using commercial grade production cost simulation tools, such as PLEXOS, GridView, and PROMOD, to perform the hourly or subhourly security constrained unit commitment and economic dispatch of generators in the bulk power grid. NETL has also improved the existing environmental effluent representation in its implementation of these models to better capture the emissions impacts of dispatch and technology R&D. Additionally, NETL has paired its implementation of these models with macroeconomic, employment, capacity expansion, natural gas infrastructure, power system financial, and power systems analysis models, providing the capability to study the energy system across multiple time domains and regions. Finally, ORNL has developed electricity dispatch models to help quantify environmental costs and benefits and find solutions that improve environmental performance and increase the value of electricity generated.

HES can also be deployed in distribution systems. Understanding the operations of such HES in wholesale markets requires cosimulation of distribution systems and wholesale market simulation tools. PNNL has been using cosimulation tools developed under GMLC Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) project to carry out such analyses by coupling of distribution systems tools (GridLAB-D) and agent-based wholesale market modeling tools (Agent-Based Modeling of Electricity Systems, or AMES).

Despite these well-established and advanced markets-based modeling capabilities, the representation of hybrid systems within existing tools is in the early stages. The most commonly represented HES take the form of renewable energy-plus-storage (RE+storage) hybrids. Though they were not developed for this specific purpose, the representation of RE+storage hybrids in agent-based and system-level tools has helped support markets-based technical assistance to state, utility, regulatory, and policy stakeholders. The combination of capabilities and technical assistance allow for markets-based analyses for hybrid systems in both regulated and restructured markets, and they exist at multiple DOE National Laboratories, including PNNL, ANL, LBNL, NREL, INL, and NETL.

Finally, the DOE National Laboratories also maintain policy databases for energy storage (PNNL) and renewable energy (LBNL and NREL) technologies, which provide a foundation for regular reporting and analysis on technology development and technology costs. In addition, the DOE National Laboratories engage in the development of standards, which are intimately related to the acceptance and participation models of emerging HES.

Table 11. Markets-Based Research Capabilities Submitted by DOE National Laboratories

Capability	Description
Argonne National Laboratory	
Modeling and analysis	ANL has extensive technology modeling and simulation capabilities that can be applied for the hybrid energy systems as well. We have developed several computer models that can be applied for the modeling of HES in power systems and electricity markets. In addition to optimizing the operation of HES for power system needs, we can also perform market analyses and optimize HES operation in electricity markets to maximize their contributions of energy and ancillary services. We have experience in techno-economic studies and valuation of various technologies in both traditionally regulated and restructured market environments. We also have experience in lifecycle analysis of many energy technologies. We use novel techniques and methodological approaches (e.g., agent-based modeling and AI/ML) for the modeling of various HES technologies and their operations.
National Renewable Energy Laboratory	
Energy Markets and Investment Suite (EMIS)	EMIS is a capacity expansion model for evaluating the impact of market design and investor heterogeneity on investment decisions and reliability that can (a) represent individual investor firms with heterogenous beliefs about the future and risk representations, (b) explore how different market designs perform under uncertainty and imperfect information, (c) allow nonoptimal investment (i.e., overinvestment or underinvestment) by firms with imperfect information, and (d) Leverage and integrate with the Scalable Integrated Infrastructure Planning (SIIP) modeling framework that include NREL's next generation of integrated modeling tools
Regional Energy Deployment System (ReEDS)	ReEDS is a bottom-up electric sector capacity expansion model for the contiguous United States that finds the least cost construction and operation of generation, storage, and transmission assets through 2050.
PLEXOS Market Simulation Software	PLEXOS is a commercial electricity production simulation model used by NREL researchers to test various power market designs in terms of flexibility incentives for generation and demand response resources as well as revenue sufficiency.
Scalable Integrated Infrastructure Planning Power Systems (SIIP::Power)	SIIP::Power provides a flexible framework for defining and solving power systems analysis problems, including a variety standard unit commitment and economic dispatch formulations. As a result of research completed under this study, SIIP::Power can now model a value of lost load that varies over the duration of a power interruption and by node. SIIP::Power uses this information to select which buses to serve at each time-step when there is not enough energy to serve all loads in order to minimize total system cost (including both outage and generation costs). Exercising the production cost modeling framework in SIIP::Power with this duration-dependent value of lost load results in operational differences, such that the total level of lost load (in megawatt-hours) is similar, but the overall system costs and the maximum hours of outage experienced by any bus on the network are reduced.

Capability	Description
Renewable Energy Optimization (REopt)	REopt is a techno-economic decision support model used to optimize energy systems for buildings, campuses, communities, and microgrids. Based on research completed under this study, the tool can now incorporate the avoided cost of a power interruption into the lifecycle cost calculation for backup power systems. Initial results indicate that accounting for the benefits associated with surviving all or part of a grid outage could change the optimal design of a backup power system. In particular, for scenarios that incorporate a “value of resilience,” the cost-optimal backup power system has increased PV capacity, energy storage duration, and net present value.
National Energy Technology Laboratory	
PLEXOS market simulation software	PLEXOS is a commercial electricity production simulation and capacity expansion model used by NETL researchers to test various power market conditions in terms of generation deployment and operation as well as revenue sufficiency.
PROMOD market simulation software	PROMOD is a commercial security constrained unit commitment and dispatch production simulation model of the electricity system used by NETL researchers to test various power market scenarios for operational impacts on generators, electricity costs, revenue sufficiency, probabilistic reliability, and emissions. PROMOD is used by multiple utilities and system operators to support their day-to-day dispatch operations.
PSS/E commercial power system simulator	The Power System Simulator for Engineering (PSS/E) is a commercial electricity system operational model used by NETL researchers to test the physical feasibility of dispatch solutions to ensure that production simulation models provide a reasonable result.
MARKet Allocation (MarkAL)	MARKAL is a commercial integrated energy systems modeling platform and it is a set of software tools that may be used to analyze energy, economic, and environmental issues. The MARKAL database used by NETL researchers to quantify the impacts of policy options on technology development and resource depletion at the North American, the U.S., and Census region levels over a time frame of up to several decades.
ECIO	The ECIO (econometric input-output) model is an economic impacts forecasting model that functions as an extension of the National Energy Modeling System (NEMS) and the U.S. MarkAL model. The ECIO model integrates a macroeconomic econometric forecasting model and an input-output accounting framework to generate estimates of the impacts to gross domestic product, employment, and labor income along derived forecast scenarios detailing a baseline of the U.S. energy-economy and an alternative forecast on how power generation resources can meet future levels of energy demand.
IMPLAN	IMPLAN is commercial economic input-output modeling software that is used to estimate economic impacts down to a county level of resolution depending on the purchased license.
Power Systems Financial Model Version for Grid Technologies (PSFM-GT)	PSFM-GT is an open-source, Python-based software for financial modeling of grid technologies. It is designed to be transparent and easy to use so that users can quickly understand and assess the impact that operational and financial parametric changes would have on the commercial viability of a technology.
Deloitte North American gas model	This model is a commercial simulation model used by NETL researchers to test the potential impacts on natural gas pricing, production, demand sector deliverability, infrastructure, and storage. It is designed to represent the full market structure of the supply, demand, transportation, conversion chains, and the operation characteristics of commodities. It can be applied across a range of energy commodities from oil and refined products to natural gas, liquified natural gas, and natural gas liquids to electricity and fuels including renewable credits and emissions allowances.

Capability	Description
LOAD	LOAD is a NETL-developed, open-source, Python-based simplified economic unit commitment model. It is used for rapid unconstrained system analysis. It can be used as a precursor to the more complex commercial security constrained unit commitment and dispatch simulation tools.
ASPEN+	ASPEN+ is a steady-state general chemical process simulator that is licensed by Aspen Technology. It was designed to solve the steady-state mass and energy balances for a wide variety of processes encountered in the chemical, petroleum, and pharmaceutical industries. Flowsheets are constructed using an intuitive graphical user interface (GUI) and drag-and-drop operations from pallets of fundamental unit operations models that perform heat transfer, chemical reaction, and pressure change operations, among many others. The simulation engine is backed up with a very large set of predefined chemical components and a comprehensive set of physical property models that can efficiently and accurately model a near-limitless variety of chemical processes.
Pacific Northwest National Laboratory	
Energy storage valuation	Through the OE Energy Storage Program, PNNL has developed techno-economic valuation approaches for energy storage systems that have been applied in more than 20 individual projects.
Energy storage policy and regulation	Through the OE Energy Storage Program, PNNL conducts technical assistance on energy storage topics for state utility regulators and policymakers. PNNL also maintains the Energy Storage Policy Database.
Grid interconnection	Through funding by OE and EERE, PNNL has provided technical assistance on grid interconnection standards and policy related to renewables and energy storage. Staff have also actively participated in the development of IEEE 1547 standards.
Energy storage system safety	Through the OE Energy Storage Program, PNNL has provided training and technical assistance on energy storage safety standards to stakeholders around the country. Also, staff actively participate in the development of fire and electrical safety code standards for energy storage.
Water power systems	Through the DOE Water Power Technologies Office, PNNL leads or participates in projects designed to improve the valuation, operation, and regulatory landscape for hydropower projects and marine energy assets.
Grid Storage Launchpad Facility	The Grid Storage Launchpad (GSL) facility at PNNL will support DOE's ESGC, the vision of which is to create and sustain global leadership in energy storage utilization and exports, with a secure domestic manufacturing supply chain that does not depend on foreign sources of critical materials. Through independent testing and validation of grid energy storage technologies, the GSL facility will develop and promulgate rigorous grid performance standards and requirements that span the entire energy storage R&D development cycle—from basic materials synthesis to advanced prototyping. This mission focuses on three outcomes that address critical challenges in grid energy storage development: **Collaborate:** Bringing together DOE, multidisciplinary researchers, and industry will lower the barriers to innovation and deployment of grid-scale energy storage technologies. **Validate:** The facility will enable independent testing of next-generation grid energy storage materials and systems under realistic grid operating conditions. **Accelerate:** From benchtop to systems for deployment, the facility will reduce risk and speed the development of new technologies by propagating rigorous performance requirements to all stages of grid storage development

Capability	Description
Sandia National Laboratories	
PRESCIENT	SNL has developed a software toolkit that uses stochastic programming to perform power system production cost model simulations. Named PRESCIENT, the software produces probabilistic forecasts automatically from deterministic historical forecasts for load, solar, and wind power production and their respective actuals, using a technology known as epi-splines.
Electrical Grid Research and Engineering Tools (EGRET)	EGRET is a package that provides tools for building electric grid optimization models. This software includes objects and functions for parsing, storing, and managing electric grid data. EGRET includes the following electric grid models: ACOPF (alternating current optimal power flow), DCOPF (direct current optimal power flow), a linearized transmission model, ACOPF relaxations, unit commitment, and economic dispatch.
Microgrid Design Toolkit (MDT)	The MDT is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user-defined objectives. Common examples of such objectives are cost, performance, and reliability.

A.2 Valuation Research and Support Capabilities at DOE National Laboratories

The DOE National Laboratories have developed a wide array of modeling tools and capabilities that are designed to perform valuation analysis for the assets that make up the power system. These tools can be qualitatively divided into what we refer to here as plant-level and grid-level optimization and simulation tools, which have been developed for both transmission- and distribution-connected assets.

Plant-level optimization tools typically do not consider energy prices as a design variable (e.g., resource adequacy models such as the Probabilistic Resource Adequacy Suite [PRAS] at NREL); or they use fixed energy price assumptions (e.g., price-taker models such as Revenue, Operation, and Device Optimization [RODeO] and System Advisor Model at NREL, Energy Storage Evaluation Tool [ESET] at PNNL). Computational frameworks that enable plant-level HES optimization exist at both INL (FORCE, encompassing RAVEN/HERON/TEAL) and NETL (IDAES), and each framework performs TEA of integrated energy systems comprising thermal generators. In addition, plant-level optimization tools have been developed for characterizing the capabilities of DERs using the concept of battery-equivalent modeling—which enables a technology agnostic assessment and aggregation of various DERs—to perform valuation from the perspective of the DER owner (Virtual Battery Assessment Tool [VBAT] at PNNL).

Plant-level optimization is also informed by cost modeling, which evaluates the capital, BOS, and operational costs for various system designs (e.g., IDAES at NETL, HybridBOSSE at NREL, and P2G and PSH thermal energy storage [TES] at PNNL). For this set of capabilities, simulations or optimization are often performed to maximize benefits for the hybrid system owner, typically through scenario analysis that compares economic metrics for candidate HES to those for alternative investment options (e.g., independent systems or other HES).

Grid-level optimization tools simulate the operations of the grid, typically to minimize power system costs while achieving the desired level of performance (e.g., adequacy or reliability). This class of models includes dynamic interactions of electricity prices and decisions related to asset investments (e.g., capacity expansion models such as ReEDS or REopt at NREL, and PLEXOS at NETL) or dispatch (e.g., production cost models such as

Prescient at SNL[76]; PLEXOS and SIIP::Power at NREL; PROMOD and PLEXOS at NETL; and GridView at PNNL); the goal of these models is to minimize bulk power system costs. Some models are beginning to link customizable market mechanisms, which can include products for both short-term grid services and forward markets for capacity-related attributes, to multiagent investment decisions made with imperfect information and heterogenous financing and risk parameters (e.g., EMIS at NREL). Unlike traditional CEMs that inherently guarantee cost recovery, this approach can identify potential resource adequacy and operational reliability shortfalls from market rule changes.

Despite the advanced state of these plant-level and grid-level optimization tools, the representation of transmission-connected hybrid systems within them is in the early stages, if present. NREL is working to represent HES in their capacity expansion and production cost models. These capabilities primarily represent solar+storage hybrids, but work is also underway to develop representations of other renewable energy-based HES.

By contrast, a variety of tools are designed to develop optimization-based designs for distribution-connected hybrid systems—including but not limited to microgrid systems that comprise a broad set of technologies—accounting for investment and operational decisions for subcomponents to maximize monetizable (e.g., IDAES at NETL; REopt and Hybrid Optimization and Performance Platform [HOPP] at NREL) or nonmonetizable benefits (e.g., MDT at SNL). Other tools simultaneously consider monetizable and nonmonetizable benefits for sizing and evaluation of DERs through stochastic optimization techniques (e.g., MASCORE at PNNL). Finally, work is underway to quantify nonmonetizable benefits, such as the value of resilience (e.g., through the resilience ICE calculator at LBNL).

Valuation research activities and capabilities at EPRI largely echo and complement those established at the DOE National Laboratories. For example, EPRI is beginning to explore HES costs, and it is similarly targeting an improved representation of HES in several of their plant-level and grid-level models, with the goal of informing many questions facing state regulators and utility or ISOs. In particular, EPRI is working to (a) enhance its production cost modeling tool, Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV), to incorporate numerous participation and modeling options for HES, and (b) consecutively analyze the impact on grid operating costs and steady-state reliability. Moreover, EPRI's US-REGEN (US Regional Economy, Greenhouse Gas, and Energy Model) model combines a detailed dispatch and capacity expansion model of the U.S. electric sector with a high-level dynamic model of the U.S. economy. Finally, EPRI's StorageVET and DER-VET software are open-source, optimization-based valuation and planning tools for both DERs and larger, centralized energy resources.

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[76] The PRESCIENT model includes contributions from LLNL and NREL, and it is being utilized by NETL.

Table 12. Valuation Research Capabilities Submitted by DOE National Laboratories

Capability	Description
Argonne National Laboratory	
Modeling and analysis	ANL has extensive technology modeling and simulation capabilities that can be applied for HES. ANL has also developed several computer models that can be applied for the modeling of HES in power systems and electricity markets. In addition to optimizing the operation of HES for power system needs, ANL can perform market analyses and optimize HES operation in electricity markets to maximize their contributions of energy and ancillary services. ANL has experience in techno-economic studies and valuation of various technologies in both traditionally regulated and restructured market environments. ANL also has experience in lifecycle analysis of many energy technologies. It uses novel techniques and methodological approaches (e.g., agent-based modeling and AI/ML) for the modeling of various HES technologies and their operations.
Joint Center for Energy Storage Research (JCESR)	JCESR has shifted its emphasis from specific battery systems to transformational materials that can be mixed and matched to build a diversity of next-generation batteries purpose-designed to specific applications. It has identified three fundamental challenges that underpin battery science and broadly impact the field of electrochemistry. JCESR is also introducing a new bottom-up constructionist approach for designing materials at the atomic and molecular levels that will provide the foundation for transforming the battery landscape by (a) enabling fast, high-power charging and discharging by understanding the motion of ions in battery materials, (b) introducing resilient behavior to active battery materials to enable for example, self-healing, through an exhaustive knowledge of materials synthesis and operational dynamics), and (c) introducing deliberate defects and imperfections in battery materials to significantly improve their performance.
Argonne Collaborative Center for Energy Storage Science (ACCESS)	The Argonne Collaborative Center for Energy Storage Science (ACCESS) is a powerful collective of scientists and engineers from across ANL who solve energy storage problems through multidisciplinary research.
Idaho National Laboratory	
FORCE	The FORCE computational framework is a flexible modeling ecosystem consisting of a suite of software tools for TEA of integrated energy systems that include opensource components. Capabilities include dynamic modeling of plants (HYBRID), Tool for Economic AnaLysis (TEAL) for assessment of complex cash flows, and Holistic Energy Resource Optimization Network (HERON) for modeling of the energy market. This suite of tools uses the INL-developed Risk Analysis Virtual Environment (RAVEN) software for optimization.
Risk Analysis Virtual Environment (RAVEN)	RAVEN is a flexible and multi-purpose uncertainty quantification, regression analysis, probabilistic risk assessment, data analysis and model optimization framework. Depending on the tasks to be accomplished and on the probabilistic characterization of the problem, RAVEN perturbs (e.g., Monte-Carlo, latin hypercube, reliability surface search) the response of the system under consideration by altering its own parameters. The system is modeled by third party software (e.g., RELAP5-3D, MAAP5, BISON, etc.) and accessible to RAVEN either directly (software coupling) or indirectly (via input/output files). The data generated by the sampling process is analyzed using classical statistical and more advanced data mining approaches. RAVEN also manages the parallel dispatching (i.e. both on desktop/workstation and large High Performance Computing machines) of the software representing the physical model. RAVEN heavily relies on artificial intelligence algorithms to construct surrogate models of complex physical systems in order to perform uncertainty quantification, reliability analysis (limit state surface) and parametric studies.
Tool for Economic AnaLysis (TEAL)	TEAL is a financial performance calculator plugin for the RAVEN code, framework, resolving around the computation of Net Present Value and associated financial metrics. TEAL enables

Capability	Description
	the capability to compute the NPV (Net Present Value), IRR (Internal Rate of Return) and the PI (Profitability Index) with RAVEN. Furthermore, it allows NPV, IRR, or PI search, i.e. TEAL will compute a multiplicative value (for example the production cost) so that the NPV, IRR or PI has a desired value. The plugin allows for a generic definition of cash flows, which drivers are provided by RAVEN. Furthermore, TEAL includes flexible options to deal with taxes, inflation, discounting and offers capabilities to compute a combined cash flow for components with different component lives.
Holistic Energy Resource Optimization Network (HERON)	HERON is a generic software plugin of RAVEN to perform stochastic technoeconomic analysis of grid energy-resource systems with economic drivers. The development targets analysis of electricity and secondary product generation and consumption in regional balancing areas, including flexibility to include arbitrary resources as well as arbitrary resource consumers and producers. HERON is developed to drive optimization via economic drivers such as system cost minimization, profitability, and net present value (NPV) maximization. As a plugin of RAVEN, HERON provides two primary functions: the automatic generation of RAVEN workflows, and models for optimizing high-resolution dispatch of arbitrary systems including resources, resource consumers, and resource producers. HERON leverages the synthetic history training and generation tools, sampling workflows, code Application Programming Interfaces (API), and optimization schemes.
HYBRID	The HYBRID repository is a collection of dynamic models and workflows used to assess the technical and economic feasibility of different HES. The repository provides a library of high fidelity Modelica models developed using the Dymola compiler that includes models of nuclear reactors, gas turbines, hydrogen production facilities, energy storage technology, and other integrated energy system technologies.
Lawrence Berkeley National Laboratory	
Networked electricity	LBNL capabilities include control architectures that enable a “network model of power,” leveraging architectural insights from Internet technology
National Energy Technology Laboratory	
Analysis capabilities	NETL’s broad analysis capabilities include TEA, life cycle analysis (LCA), and markets in its Systems Engineering and Analysis Directorate. See Table 11 for details.
Institute for the Design of Advanced Energy Systems (IDAES)	IDAES provides a dynamic modeling and optimization computational framework. It is also the foundation for the GMLC Hybrids project (with NREL, INL, SNL, and LBNL). Specifically, IDAES provides an approach for optimization-based design of hybrid systems that take advantage of electricity markets.
National Renewable Energy Laboratory	
Energy Markets and Investment Suite (EMIS)	EMIS is a capacity expansion model for evaluating the impact of market design and investor heterogeneity on investment decisions and reliability that can be used to (a) represent individual investor firms with heterogenous beliefs about the future and risk representations, (b) explore how different market designs perform under uncertainty and imperfect information, (c) allow nonoptimal investment (i.e., overinvestment or underinvestment) by firms with imperfect information, and (d) leverage and integrate with the SIIP modeling framework that includes NREL’s next generation of integrated modeling tools.
Regional Energy Deployment System (ReEDS)	ReEDS is a bottom-up electric sector capacity expansion model for the contiguous United States that finds the least cost construction and operation of generation, storage, and transmission assets through 2050.
Renewable Energy Potential (reV) Model	The Renewable Energy Potential (reV) model is a platform for the detailed assessment of renewable energy resources and their geospatial intersection with grid infrastructure and land use characteristics. The reV model currently supports PV, CSP, and land-based wind turbine technologies. Modules in the reV framework function at different spatial and temporal

Capability	Description
	resolutions, allowing for the assessment of resource potential, technical potential, and supply curves at varying levels of detail. The platform runs on NREL's high-performance computing system, providing scalable and efficient performance from a single location up to a continent, for a single year or decades of time-series resource data. Coupled with NREL's System Advisor Model (SAM), reV supports resource assessments from 5-minute to hourly temporal resolutions and supports the analysis of long-term (i.e., year-on-year) variability of renewable generation (e.g., interannual variability and exceedance probabilities).
System Advisor Model (SAM)	SAM is a free techno-economic software model that facilitates decision-making for people in the renewable energy industry.
PLEXOS market simulation software	PLEXOS is a commercial electricity production simulation model used by NREL researchers to test various power market designs in terms of flexibility incentives for generation and demand response resources as well as revenue sufficiency.
Hybrid Optimization and Performance Platform (HOPP)	NREL is developing robust open-source modeling tools capable of simulating and optimizing a range of hybrid energy systems. HOPP is a software tool in NREL's suite of systems engineering tools that enables detailed analysis and optimization of hybrid power plants down to the component level. It has the capability to assess and optimize projects that contain combinations of wind (onshore and offshore), solar, storage, geothermal, and hydro. HOPP aims to answer the crucial question: when and where do hybrid plants make sense, and how can we design them optimally? HOPP leverages other NREL-developed tools—REopt, SAM, the Wind Plant Integrated Systems Design and Engineering Mode [WISDEM]—to size, analyze, and design the hybrid power plants of the future, allowing for detailed output on myriad design conditions, from number and type of turbine to the overall layout and topology of assets within the system.
Scalable Integrated Infrastructure Planning Power Systems (SIIP::Power)	SIIP::Power provides a flexible framework for defining and solving power systems analysis problems, including a variety standard unit commitment and economic dispatch formulations. As a result of research completed under this study, SIIP::Power can now model a value of lost load that varies over the duration of a power interruption and by node. SIIP::Power uses this information to select which buses to serve at each time-step when there is insufficient energy to serve all loads in order to minimize total system cost (including both outage and generation costs). Exercising the production cost modeling framework in SIIP::Power with this duration-dependent value of lost load results in operational differences, such that the total level of lost load (in megawatt-hours) is similar, but the overall system costs and the maximum hours of outage experienced by any bus on the network are reduced.
Renewable Energy Optimization (REopt)	REopt is a techno-economic decision support model used to optimize energy systems for buildings, campuses, communities, and microgrids. Based on research completed under this study, the tool can now incorporate the avoided cost of a power interruption into the lifecycle cost calculation for backup power systems. Initial results indicate that accounting for the benefits associated with surviving all or part of a grid outage could change the optimal design of a backup power system. In particular, for scenarios that incorporate a "value of resilience," the cost-optimal backup power system has increased PV capacity, energy storage duration, and net present value.
Pacific Northwest National Laboratory	
Energy storage valuation	Through the OE Energy Storage Program, PNNL has developed techno-economic valuation approaches for energy storage systems that have been applied in more than 20 individual projects.
Water power systems	Through the DOE Water Power Technologies Office, PNNL leads or participates in projects designed to improve the valuation, operation, and regulatory landscape for hydropower projects and marine energy assets.

Capability	Description
Grid architecture	PNNL has been OE's lead DOE National Laboratory on the Grid Architecture project, which seeks to define the relationships between the various components of the grid and its interconnected resources.
Grid analytics	Through several projects, PNNL has developed robust grid modeling and monitoring capabilities, including the EIOC. Other projects include OE's Advanced Modeling Grid Research Program, ASC's Power Grid Math Program, ARPA-E's Grid Optimization Competition, and the North American SynchroPhasor Initiative.
Sandia National Laboratories	
PRESCIENT	SNL has developed a software toolkit that uses stochastic programming to perform power system production cost model simulations. Named PRESCIENT, the software produces probabilistic forecasts automatically from deterministic historical forecasts for load, solar, and wind power production and their respective actuals, using a technology known as epi-splines.
EGRET	EGRET is a package that provides tools for building electric grid optimization models. This software includes objects and functions for parsing, storing, and managing electric grid data. EGRET includes the following electric grid models: ACOPF (alternating current optimal power flow), DCOPF, a linearized transmission model, ACOPF relaxations, unit commitment, and economic dispatch.
Microgrid Design Toolkit (MDT)	The MDT is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user-defined objectives. Common examples of such objectives are cost, performance, and reliability.
QuESt	QuESt is an open-source, Python-based software application suite for energy storage simulation and analysis. It is designed to give users access to models and analysis for energy storage used and developed by SNL. It is also designed to be transparent and easy to use without requiring knowledge of the mathematics behind the models or how to develop code in Python. At the same time, because it is open-source, users may modify it to suit their needs.

A.3 Technology Development Research and Support Capabilities at the DOE National Laboratories

The primary technology development topics to which the existing DOE National Laboratory capabilities can be applied are hardware-in-the-loop (HIL) and materials research. HIL testing facilities currently focus on the optimized coupling of specific subcomponents, and most are not designed to consider an inclusive list of hybrid technologies. Most of these capabilities support solar+storage systems research (e.g., a variety of CSP testing facilities at SNL), with a few integration facilities having microgrids with grid emulators and the capability to incorporate other technologies such as wind, electrolyzers, and electric vehicles (e.g., ARIES and the Flatiron Campus at NREL and the Systems Integration Laboratory and Microgrid Test Bed at INL).

Capabilities that are commonly included within HIL facilities include power electronics, controls, and sensors and telemetry, which can be studied with reported capabilities such as:

- DETAIL, the Power and Energy Real-Time Laboratory (PERL), high-temperature steam electrolysis (HTSE), high-temperature electrolyzer (HTE), TEDS, Electric Vehicle Infrastructure Laboratory (EVIL), Battery Test Center, and other capabilities at INL
- HyPer at NETL
- The EIOC, PowerNET, Building Operations Control Center, and LabHomes at PNNL
- Unnamed capabilities at LBNL
- ARIES at NREL.

In particular, ARIES provides a reconfigurable platform for at-scale emulation of power and energy systems at multiple scales, ranging from microgrids to multimegawatt hybrid systems using 20-MW hardware controllable grid interface. ARIES, through HERTH, also includes real-time emulation of communication and control for high-fidelity real-world evaluation of hybrid technologies. Reported capabilities for cybersecurity and manufacturing and supply chain research were limited to just one capability each (the Cybercore Integration Center at INL and the Grid Storage Launchpad Facility at PNNL).

Capabilities supporting the materials subcategory are focused on the characterization of materials and components, including a comprehensive suite of materials characterization instruments, performance measurement instruments and tools, fabrication of small-scale materials or components, accelerated aging chambers or platforms, and field-aging of components. None of these capabilities was designed specifically for hybrid systems, but they might be valuable in the future for evaluating new hybrid system designs and utilization profiles.

Finally, DOE National Laboratories are active in technology standards development through a variety of Standards Development Organizations, the most prominent of which for HES is IEEE. Such activities are especially relevant for technology development purposes, but they are also important for regulatory considerations (see Appendix A.2).

Table 13. Technology Development Research Capabilities Submitted by DOE National Laboratories

Capability	Description
	Argonne National Laboratory
Joint Center for Energy Storage Research (JCESR)	JCESR has shifted its emphasis from specific battery systems to transformational materials that can be mixed and matched to build a diversity of next-generation batteries purpose-designed to specific applications. It has identified three fundamental challenges that underpin battery science and broadly impact the field of electrochemistry. JCESR is also introducing a new bottom-up constructionist approach for designing materials at the atomic and molecular levels that will provide the foundation for transforming the battery landscape by (a) enabling fast, high-power charging and discharging by understanding the motion of ions in battery materials, (b) introducing resilient behavior to active battery materials to enable, for example, self-healing, through an exhaustive knowledge of materials synthesis and operational dynamics, and (c) introducing deliberate defects and imperfections in battery materials to significantly improve their performance.
Argonne Collaborative Center for Energy Storage Science (ACCESS)	The Argonne Collaborative Center for Energy Storage Science (ACCESS) is a powerful collective of scientists and engineers from across Argonne who solve energy storage problems through multidisciplinary research.
General research capabilities	ANL is home to multiple battery research and testing facilities. As a multidisciplinary lab, ANL also conducts extensive research on other generation technologies, including hydropower, solar, wind, geothermal, biomass, hydrogen fuel cells, nuclear, fossil, DERs, and other technologies that are often combined into hybrid energy systems.
	Idaho National Laboratory
Systems Integration Laboratory (SIL)	SIL comprises a combination of connected assets that can be reconfigured to research specific topics related to technology grid-integration and hybridization. The constituents of SIL include several lab environments operated to assess several technology-specific questions. A few of the assets include low- and high-power (350-kW) electric vehicle service equipment, a microgrid with multiple generation and electrical storage assets, high temperature electrolyzers, and thermal loops capable of emulating the heat profiles from thermal power plants. These technologies are integrated through digital real time simulators and grid emulators to enable hardware testing during emulated normal and off-normal grid conditions. The interconnected facility test beds are referred to as the Dynamic Energy Transport and Integration Laboratory (DETAIL).
Power and Energy Real-Time Laboratory (PERL)	PERL provides a suite of digital real-time simulation platforms, grid emulators, power system hardware (e.g., relays, micro-PMUs, communications systems, and energy storage). Supports rapid prototyping and validation of controls, communications, and hardware.
Microgrid Test Bed	The Microgrid Test Bed is a megawatt-scale laboratory platform with microgrids incorporating wind, solar, and energy storage, and with the ability to emulate additional DERs. The platform includes load control capabilities and grid interaction algorithms that (a) allow researchers to study demand response, peak shaving, microgrid control interactions and ancillary services, and (b) enable testing of grid-connected and islanded operations.
High Temperature Electrolyzer (HTE)	The HTE test unit includes an 800 °C steam generator, 900 °C furnace, power inverter, and hydrogen conditioning system to support testing a wide variety of solid oxide electrolysis cell (SOEC) stacks to provide up to 25 kW of input power for both dynamic ramping capability and long-term durability performance. The facility is currently being expanded to allow testing of multiple SOEC stacks at up to 250 kW of input power in FY2021.

Capability	Description
Thermal Energy Distribution System (TEDS)	TEDS includes a 200-kW heat source and thermal energy storage system. It is designed to test heat transfer components, distribution systems, instruments, and controls for hybrid generation of electrical power and nonelectrical products.
Microreactor AGile Non-nuclear Experimental Testbed (MAGNET)	MAGNET is a non-nuclear testing and demonstration facility that will be interconnected with TEDS to comprise DETAIL. MAGNET is a 250 kW, electrically-heated test bed for performance evaluation of microreactor design concepts (e.g., heat pipe, gas-cooled) that includes a detailed reactor core and heat removal section and will provide thermal hydraulic performance data for prototypical geometries and operating conditions. MAGNET will support demonstrating integration with relevant power conversion units, allow assessment of advanced heat exchangers, and provided validation data for various modeling and simulation efforts (heat pipes, advanced energy systems).
Electric Vehicle Infrastructure Laboratory (EVIL)	EVIL is designed to provide information on the performance and grid interaction of existing and next-generation electric vehicle service equipment including low power (AC Level I and II, DC fast chargers) and high power (up to 350 kW). EVIL includes wireless chargers and the ability to monitor the efficiency and safety margins of both conductive and wireless systems, including impacts associated with cybersecurity.
Power systems simulation	INL uses a full range of power system dynamics and transient analysis tools, from Power System Simulator for Engineering (PSS/E) and DigSilent to the Real-Time Simulation Software Package (RSCAD) and Opal-RT to model grid scales that are relevant to each phenomenon and device connectivity. Models such as PSS/E and DigSilent enable T&D modeling up to the interconnection scale. This is useful to answering questions about how new bulk power system assets will integrate. RSCAD and Open-RT are digital real time simulation (DRTS) software that enable testing of how real hardware and controls assets will integrate at local points of interconnection and interface with the grid. DRTS can be used in conjunction with PERL and the Microgrid Test Bed to enable prototyping and validation or can be deployed in the field as part of field demonstration.
Battery Test Center Lab	This facility can be used to evaluate the performance of electrochemical devices from lab-scale to full systems with charge and discharge capability to 440 kW and 1,000 V. The lab consists of more than 900 test channels and environmental chambers and is structured to evaluate both devices as well as controls and management systems. The Battery Test Center is used to assess the factors affecting cycle and lifetime performance and how specific uses affect these.
Cybercore Integration Center	Cybercore brings together experts in critical infrastructure security assessments, cyberforensic analysis, threat detection, and consequence-based targeting to provide real-world technical solutions and innovations that protect operational environments from an ever-evolving threat landscape. Cybercore aligns national science and engineering resources, technical expertise, and collaborative partnerships to focus on scalable and sustainable control system cybersecurity solutions that protect the U.S. grid, other critical infrastructure and military systems.
Lawrence Berkeley National Laboratory	
Networked electricity	LBNL capabilities include control architectures that enable a “network model of power,” leveraging architectural insights from Internet technology
DC power distribution	LBNL capabilities enable evaluation of the impacts of DC coupling generation, storage, and loads for increased efficiency, reduced costs, and greater reliability.
Research	LBNL research capabilities include metal-supported SOFC and electrolysis cells.
General research capabilities	LBNL’s metal-supported solid oxide fuel cells (MS-SOFC) design uses thin ceramic active materials on robust porous metal supports. These cells withstand rapid thermal excursions,

Capability	Description
	which allows them to operate intermittently or follow load requirements in real time. They can convert fuel to electricity, or steam/CO_2 to hydrogen and syngas by using electricity.
National Energy Technology Laboratory	
Power systems and markets simulation	NETL uses a range of power systems and markets simulation tools to evaluate technologies at operational and macroeconomic levels.
General research capabilities	NETL's general research capabilities include (a) fabrication, characterization, and testing of sensors for gas, temperature, pressure, and strain monitoring across a range of conditions and applications, (b) controls development (both theoretical and experimental testing/validation), and (c) cybersecurity testing of connected plant components such as sensors and actuators.
Institute for the Design of Advanced Energy Systems (IDAES)	IDAES provides a dynamic modeling and optimization computational framework. It is the foundation for the GMLC Hybrids project (with NREL, INL, SNL, and LBNL). Specifically, it provides an approach for optimization-based design of hybrid systems that take advantage of electricity markets.
Hybrid Performance (HyPer)	HyPer is a cyberphysical test facility that was recently connected with the NREL-INL real time microgrid virtual test platform.
National Renewable Energy Laboratory	
Advanced Research on Integrated Energy Systems (ARIES)	ARIES is a research platform designed to de-risk, optimize, and secure current energy systems and to provide insight into the design and operation of future energy systems. It will address the fundamental challenges of variability in the physical size of new energy technologies being added to energy system, controlling large numbers (millions to tens of millions) of interconnected devices, and integrating multiple diverse technologies that have not previously worked together.
Hybrid Optimization and Performance Platform (HOPP)	NREL is developing robust open-source modeling tools capable of simulating and optimizing a range of hybrid energy systems. HOPP is a software tool in NREL's suite of systems engineering tools that enables detailed analysis and optimization of hybrid power plants down to the component level. It has the capability to assess and optimize projects that contain combinations of wind (onshore and offshore), solar, storage, geothermal, and hydro. HOPP aims to answer the crucial question: when and where do hybrid plants make sense, and how can we design them optimally? HOPP leverages other NREL-developed tools—REopt, SAM, WISDEM—to size, analyze, and design the hybrid power plants of the future, allowing for detailed output on myriad design conditions, from number and type of turbine to the overall layout and topology of assets within the system.
Renewable Energy Optimization (REopt)	REopt is a techno-economic decision support model used to optimize energy systems for buildings, campuses, communities, and microgrids. Based on research completed under this study, the tool can now incorporate the avoided cost of a power interruption into the lifecycle cost calculation for backup power systems. Initial results indicate that accounting for the benefits associated with surviving all or part of a grid outage could change the optimal design of a backup power system. In particular, for scenarios that incorporate a "value of resilience," the cost-optimal backup power system has increased PV capacity, energy storage duration, and net present value.
Energy Systems Integration Facility (ESIF)	This 182,500-ft^2 research facility provides state-of-the-art laboratory and support infrastructure to optimize the design and performance of electrical, thermal, fuel, and information technologies and systems at scale.
Flatirons Campus	NREL's wind energy research at the National Wind Technology Center (NWTC), located on the Flatirons Campus, has pioneered wind turbine components, systems, and modeling methods that have driven the industry's acceleration over the past 40 years. Research into land-based, offshore, and distributed wind includes (a) analyzing offshore wind energy needs in the United

Capability	Description
	States, (b) designing, researching, and validating advanced wind power plant control systems, and (c) developing computer-aided engineering tools to support distributed and small wind development.
Oak Ridge National Laboratory	
Commander	ORNL's COordinated Management of Microgrids and Networked Distributed Energy Resources (COMMANDER) test bed incorporates multiple microgrids for testing technical performance in networked microgrid interactions, controller/device/SCADA (supervisory control and data acquisition) interactions, scalable control architectures, secure and flexible communications, islanded protection schemes, and large data set management. The goal of COMMANDER is to demonstrate reliability, flexibility, affordability, security, resilience, and sustainability of networked microgrids while addressing challenges of large-scale demonstrations and cautious regulatory cost recovery approvals that hinder utility innovation. COMMANDER incorporates multiple microgrids that each can include DERs, a controllable load bank, protection elements, and a microgrid controller. Power electronic sources are driven from programmable, bidirectional DC supplies and can be made to represent different fuels associated with solar power, battery energy storage, and other power electronic-based DERs. Rotating generation will also be incorporated to represent traditional diesel, natural gas, and hydro generators. The load bank is power-electronic based, regenerative, and programmable to represent different load types, patterns, and industries. The main grid connection occurs through a grid simulator, allowing researchers to see how microgrids behave in "stressed grid" scenarios. The test bed supports up to 300 kW of configurable generation and load.
Pacific Northwest National Laboratory	
Power electronics	PNNL's energy storage technology development team includes significant technical expertise on the power electronics of energy storage system design.
Sandia National Laboratories	
National Solar Thermal Test Facility (NSTTF)	SNL operates the NSTTF, the only facility of its kind in the United States with research and test capabilities for CSP technologies. It includes a 6-MWth central receiver test facility with 200+ heliostats, a 1-MWth falling particle receiver system, an engine test facility, solar furnace, high-flux solar simulator, rotating platform, and other facilities and equipment for testing CSP components and systems. For over 30 years, SNL has been leading R&D in solar thermal energy technologies, including research in power production, thermal energy storage, process heat, thermochemistry, and solar fuels. High-performance computing resources are also available for detailed computational fluid dynamics modeling of complex, coupled processes associated with solar thermal processes.
Solar tower and heliostat field	The tower is a 61-m (200-ft) concrete structure with three test locations on the north side and the top of the tower. The tower can support testing for CSP experiments and large-scale, high-flux materials samples. Equipment in the tower includes a 100-ton capacity elevating module for lifting experiments to the top of the tower, internal cranes for receiver fabrication, water glycol cooling systems and air coolers to provide heat removal from experiments, air compressors, control valves, generators, uninterruptible power supplies, piping systems, and pressure relief valves. The heliostat field has 218 individual heliostats. This capability can support SunShot projects with prototype scale testing by providing flux levels of greater than 250 W/cm^2 and total power in excess of 6 MWth. The capabilities of the heliostat field include a thermal capability of 6.0 MWth. The solar tower has a target located at the 29-m height, and test bays at 37.5 m, 42.7 m, and 48.8 m, and on the tower top at the 61 m. The tower has an integrated cooling water/glycol system for the cooling of targets under test. The top tower-top flux gage system permits flux measurement for the full power of the field.
Solar furnace	The 16-kW solar furnace has a primary heliostat, a secondary concentrator, and a test table where experiments or calibrations are performed. The peak flux provided is greater than 600

Capability	Description
	W/cm^2. The furnace is used for selective absorber testing, small-scale receiver testing, and material screening. Recently, the furnace has been used to demonstrate the feasibility of the SNL Sunshine-to-Petrol initiative.
Optics lab	Optical equipment located in this lab space and tools developed using DOE funds allow for detailed optical characterization of heliostat, trough, and dish facets. These flexible analytical tools, along with the on-site expertise support the evaluation and development of low-cost, high-performance heliostat facets. In addition, field support for characterization and alignment of CSP systems is provided. The SNL Optical Fringe Analysis Slope Technique (SOFAST) is a highly accurate fringe-reflection based measurement tool that is used to characterize and set the focus heliostat facets in the laboratory at sizes to 6x12 feet. The Heliostat Focusing and Canting Enhancement Technique (H-FACET) is an optical-based alignment tool that is used to efficiently realign the facets after reattaching them to the heliostat. Alignment Implementation for Manufacturing using Fringe Analysis Slope Technique (AIMFAST) is used to characterize dish facets and align dish systems.
High Flux Solar Simulator with Automated Sample Handling and Exposure System (ASHES)	ASHES was developed to rapidly expose multiple samples to simulated concentrated sunlight and high temperatures. It provides accelerated lifetime-aging tests of materials under high-temperature/high-flux conditions. A robotic sample handling system automatically moves coupons into and out of the concentrated flux sequentially to expose multiple samples to predetermined temperatures, fluxes, and durations. The high flux simulator consists of four 1,800-Watt (W) metal-halide lamps. The total emitted radiative power is 1,500 W per lamp (6,000 W total) with a peak irradiance of ~1.1 MW/m^2 and an average irradiance of ~0.9 MW/m^2 over a spot size of ~1 inch (2.5 cm). The lamps and elliptical reflectors are arranged in a beam-down configuration to provide ease of sample handling and exposure on a horizontal surface beneath the lamps
Molten Salt Test Loop (MSTL)	The MSTL system is a unique facility for the testing of solar components and on-sun collectors in molten flowing nitrate salt in realistic plant-like conditions. It provides three parallel test loops for customers to evaluate components in salt service. The system can provide flowing salt at 400–600 gallons per minute (gpm) (depending on temperature), 300–580°C, and pressure to 600 psi. The system has a 1.4-MWth air cooler to remove heat from on-sun testing of CSP collector systems. This system is the largest flowing salt system available for customer testing of components and on-sun collectors in the world.
Molten salt compatibility test vessels	These vessels are used by SNL for long-term evaluation of salt corrosion mechanisms, materials compatibility, and electrochemical work. The items, contained in two facilities, include 700°C salt vessels for 3,000-hr tests of 32 coupons per vessel. The second design is of smaller capacity (~0.5 kg salt), but it can achieve nearly 800°C, with a gas overpressure and it has an interchangeable liner. This vessel is also instrumented with mass spectroscopic capabilities to allow analysis of the ullage space over time, which would allow determination of possible off gas products. In addition, this vessel will be used for the electrochemical work including corrosion testing at high temperature.
Rotating platform	This outdoor 10'x 20' platform, which rotates 360 degrees under computer control, can be used to test components under specific solar angles of incidence.
Dish Test Facility	At this facility, dish systems of 41 m^2 and 80 m^2 are available for on-sun testing. Each is capable of peak concentration over 10,000 suns and delivers highly characterized beam profiles to customer packages. Supportive optical modeling is available to predict flux profiles on shaped packages.
Component Test Facility	This facility features an assembly bay, two test cells, control room, and bench test capabilities. Each bay has a variety of energy supply options. An eddy current dynamometer is available for engine testing, and an external cooling system is available. The facility can be used for testing components under high temperature conditions, with analog and digital data collecting systems and protected viewing from the control room.

Capability	Description
Super Critical CO_2 (sCO2) Brayton Test Loops	The Nuclear Test User Facility (NTUF) at SNL is dedicated to closed-loop Brayton cycle testing with three unique test loops: a 30-kWe closed-loop air turbine, a 50-kWth sCO_2 research loop, and a 1-MWth sCO_2 recompression Brayton cycle capable of producing 250 kWe. These loops have served as a test bed for closed Brayton cycle research for 10 years, and they represent the world's most advanced technology in this field. This facility may be used for power cycle testing using the MSTL.
Mechanics of Materials Laboratory	This facility has capabilities for conducting solid mechanics-related research on a wide range of materials (metals, composites, organics, ceramics), components and structures. It focuses on enabling constitutive model development by developing physically based understanding of complex processes that occur in materials during loading or use. Experimental equipment and capabilities are available for mechanics of materials study of strain rate (creep, quasi-static through 104 s^{-1}), combined loading and loading history, temperature (cryogenic through melt), and environmental effects. An extensive array of measurement and diagnostic equipment are routinely used for detailed understanding of material behavior during deformation and failure. The laboratory is staffed by four research staff members whose experience in experimental mechanics ranges from 10 to 30 years, and three technologists. Staff have extensive experience in custom design of unique, complex experimental capabilities including fully coupled thermomechanical test setups, such as the fatigue setup currently in use for study of strain, stress ratio, temperature, hold times, and coupled parameters on the in-service performance of solar receiver alloys (e.g., Haynes 230).
Thermal Spray Research Laboratory (TSRL)	TSRL is a recognized leader in the development of spray technology and ranks among the best-equipped thermal spray labs in the world. Customers of the TSRL leverage SNL's three-decade investment of more than $50 million in thermal spray equipment and expertise. The ~2,500 ft^2 facility has four spray stations. Three are traditional thermal spray booths equipped with six-axis robots and more than a dozen thermal spray torches. The fourth spray station is a 1,000 L3 vacuum plasma spray chamber equipped with enough pumping capacity to maintain 1 torr while operating a Metco 03C plasma torch. Processes available at the TSRL include air plasma spray, vacuum plasma spray, very low pressure (thin film) plasma spray, twin wire arc spray, high velocity oxy-fuel spray, wire flame spray, powder flame spray, and cold spray. In addition, the TSRL maintains a suite of diagnostics equipment on-site for characterizing thermal spray feedstocks and coating properties.
Beam Characterization System (BCS)	The BCS provides a real-time means for capturing and characterizing the concentrated beam from one or more heliostats onto a flat target area. The resulting data are useful for characterizing heliostat performance, calibrating heliostat tracking, and correlating data with models.
Thermomechanical cycling experimental setup	This experimental setup offers coupled thermomechanical cycling for evaluation of alloy performance under fatigue loadings, with options to use the Materials Test Systems (MTS) test frame, induction heating with custom coil design, and coupling between strain and temperature cycling
Microgrid Design Toolkit (MDT)	The MDT is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user-defined objectives. Common examples of such objectives are cost, performance, and reliability.

Appendix B. Summary of Current HES Research at EPRI: Technical Memo to Support DOE Hybrid Systems Research Opportunity Analysis

Research related to hybrid energy systems (HES) at the Electric Power Research Institute (EPRI) spans several research programs and multiple research focus areas. Using the definition that hybrid energy systems combine "*multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives*" EPRI reviewed the range of past, ongoing, and planned research activities related to HES. Though EPRI's full portfolio of research includes both behind-the-meter and front-of-the-meter hybrid projects, as well as electricity-only and polygeneration hybrid plants, the scope of this summary is limited to research about HES that produce electricity as their only output and excludes behind-the-meter HES.

Variable Renewables + Batteries

EPRI studies about hybrid plants consisting of VRE technologies (solar PV or wind) combined with battery storage systems have explored some of the cost and performance trade-offs associated with different hybrid configurations, both generically and in a specific case study, and test protocols for building these plants. In addition, studies are underway to try to understand the value of these hybrid plants, from both the perspective of capacity contributions to an existing power system and how a hybrid system's cost and performance might compare to more traditional fossil-based peaking and baseload resources. These analyses are supported by several EPRI research programs, including the Renewable Generation (P193), Energy Storage (P94), Bulk System Renewables and Distributed Energy Resources Integration (P173), Energy Systems and Climate Analysis (P201), and Resource Planning for Electric Power Systems (P178) programs.

- **Integration Costs and Value of Solar and Storage Coupled Systems**: evaluated the various ways that PV and battery storage systems can be coupled together (independent, AC-coupled, and DC-coupled) and examined some of the cost and value trade-offs of these different coupling configuration strategies (*valuation*)
- **Solar-Plus-Storage Cost Assessment and Design Considerations**: evaluated the market applications and costs for paired solar PV+battery systems, comparing the costs and operating characteristics of AC-coupled systems versus DC-coupled systems (*valuation*)
- **Integrating Energy Storage System with Photovoltaic Generation:** analysis within Los Angeles Department of Water and Power (LADWP) service territory to meet California SB801 requirements; ran parallel analysis to evaluate the cost-benefit and grid service feasibility of a 100-MW, 4-hour battery energy storage system paired with a 200-MW solar generating facility interconnected with high-voltage transmission, assuming procurement constructed as a PPA with a third-party developer, who would be able to claim the 30% federal investment tax credit (ITC) incentive (*valuation*; *markets, policy, and regulation*)

- **Solar-Plus-Storage Test Protocols**: will develop site acceptance test protocols for DC-coupled solar-plus-storage systems (*technology development*)
- **Assessing the Capacity Contribution of Renewables + Storage Resources**: evaluated the capacity contribution of combined renewable-plus-storage resources, exploring how parameters such as operational mode, existing renewable penetration, and battery design impact a renewable-plus-storage plant's ability to support a system in meeting capacity adequacy goals (*valuation*)
- **Understanding the Value and Costs of Renewable + Battery Virtual Generation for Peaking and Baseload Applications**: will examine the value and costs of virtual power plants, such as PV or wind + storage, the cost-minimizing mixes of wind, solar, and storage required to meet capacity, load-following, and baseload needs under different market conditions, and will compare these hybrid systems with peaking/baseload resources (*valuation*)

Concentrating Solar Power (CSP) + Thermal Energy Storage (TES)

EPRI's current research on CSP + TES plants is in support of the DOE Solar Energy Technology Office (SETO) Generation 3 Concentrating Solar Power Systems (Gen3 CSP) program. EPRI is supporting three projects, working with SNL, NREL, and Brayton Energy by providing technical analysis and coordinate technical advisory committees for each project. While the EPRI effort is led by its Renewable Generation (P193) program, support comes from experts throughout EPRI, including its Bulk System Renewables and Distributed Energy Resources Integration (P173), Advanced Nuclear Technology (P41), Advanced Generation and Bulk Energy Storage (P66), and Resource Planning for Electric Power Systems (P178) programs.

- **Gen 3 Particle Pilot Plant (G3P3): Integrated High-Temperature Particle System for CSP**: development of particle-based Gen 3 CSP technology with integrated TES for use with supercritical CO_2 Brayton power cycle (*technology development*; *valuation*)
- **Liquid-Phase Pathway to SunShot**: development of liquid-based Gen 3 CSP technology--liquid sodium receiver and integrated molten salt TES--for use with supercritical CO_2 Brayton power cycle (*technology development*)
- **Gen3 Gas Phase System Development and Demonstration**: development of gas-phase Gen 3 CSP technology--pressurized CO_2 receiver and integrated particle-based TES--for use with supercritical CO_2 Brayton power cycle (*technology development*; *valuation*)

Solar Augmented Steam Cycles

Between 2008 and 2011, EPRI conducted several studies examining the use of steam generated in a concentrating solar field, either parabolic trough or power tower, to augment the power cycle of a thermal plant, including pulverized coal (PC), natural gas combined-cycle (NGCC), and biomass plants. Four cases studies, two for existing PC plants and two for existing NGCC plants, were conducted, as well as were generic conceptual design studies for PC, NGCC, and biomass plants. An additional study examined design considerations for a new build NGCC augmented with solar steam. Based on tools developed as part of the initial analyses, EPRI supported NREL with a project to assess the suitability of the existing fleet of PC and NGCC plants to incorporate solar thermal energy with results incorporated into NREL's Solar Power Prospector and an NREL-published report. Though EPRI research into solar-augmented steam cycles has waned in recent years, the Renewable Energy (P193) program continues to monitor global activity in this space (*technology development*; *valuation*).

Fossil Generation + Storage

As the generation mix changes and the role of fossil generation evolves from baseload units to more flexible operations, EPRI is evaluating opportunities to combine fossil power plants with storage technologies to understand plant and system benefits and technological barriers. The work is led by EPRI's research programs that are more focused on fossil assets, including the Advanced Generation and Bulk Energy Storage (P66) and Combined Cycle Turbomachinery (P79) programs with support from and collaboration with the Energy Storage (P94) and Operations Management and Technology (P108) programs.

- **Molten Salt Thermal Energy Storage Retrofit to Fossil Units—Design and TEA of the Integrated System**: will include a detailed feasibility study on integrating molten salt TES to an existing fossil power plant, first to store heat from the plant and eventually to convert the system to generate heat from excess grid electricity and use the existing steam power island to generate power when needed (*valuation*)
- **Reciprocating Internal Combustion Engines (RICE) + Batteries Review**: reviewed cost, performance, and gaps associated with integrating a lithium-ion battery with a large-scale, medium-speed RICE; included several technical presentations by engine original equipment manufacturers that offer integrated solutions for engines + batteries, along with a battery vendor, who discussed the viability and costs associated with battery integration and safety issues (*valuation*)
- **Hybrid Gas Turbine (GT) Working Group**: will develop a paper assessing potential value streams of GT + batteries and identifying barriers to quantifying and monetizing value (*valuation*; *markets, policy, and regulation*)

Incorporating Hybrid Resources into Planning and Markets

In addition to the technology-specific evaluations of HES, EPRI also conducts research focused on the broader picture of how hybrid resources are being represented and incorporated into utility resource plans, how hybrid systems are valued, and the market participation models for these hybrid systems. These efforts combine the expertise of EPRI programs such as the Energy Storage (P94), Bulk System Renewables and Distributed Energy Resources Integration (P173), Grid Operations (P39), Energy Systems and Climate Analysis Group (P201), and Resource Planning for Electric Power Systems (P178) programs, as well as external experts from the ESIG Operations and Market Design Working Group and LBNL.

- **Survey of Energy Storage in Resource Planning**: will conduct a survey of how storage, including hybrid energy systems, is being addressed in utilities' existing resource plans (*markets, policy, and regulation*)
- **Long-Term Planning Considerations for Hybrid Resources**: will evaluate longer-term resource planning considerations that are unique to hybrid systems, such as how different configurations (e.g., storage capacity and storage duration) map to cost and value, how key policy provisions shape the value proposition of HES specifically, and the eligibility of hybrid resources for benefits of such policies (*markets, policy, and regulation*)
- **Hybrid Resource Modeling for Transmission Planning Studies**: will develop and validate generic models for representing hybrid plants in positive sequence transmission planning tools (*valuation*)
- **StorageVET and DER-VET**: development and support of EPRI's open-source, optimization-based valuation and planning tool for DERs and larger, centralized energy resources (*valuation*)
- **Electricity Market Participation Models for Hybrid Storage Resources**: focuses on the possible participation models from a market design and market clearing software perspective for hybrid storage

resources; efforts are underway in which the team evaluates the ways in which hybrid resources can participate in electricity markets, as well as more broadly in steady-state operations (i.e., scheduling), and assess the different implications of these different participation models (*valuation*; *markets, policy, and regulation*)

- **Hybrid and Flexible Resources Task Force**: ESIG "HyFlex" Task Force participation to develop and synthesize information about hybrid and flexible resources and integration into system and market operations (*technology development*; *valuation*; *markets, policy, and regulation*)

Technology Demonstration Pilot Projects

In 2015, EPRI launched a series of demonstration projects called the Integrated Grid Pilot Projects. These projects were done in collaboration with EPRI utility members to explore utility-scale solar PV, energy storage, electric vehicle charging infrastructure, smart inverters, advanced controls, and microgrids to understand the impact, benefits, and costs of these advanced technologies on the grid. Though not all these projects involved hybrid-related technologies, several examined PV + storage, microgrids, and general integration considerations (*technology development*; *valuation*; *markets, policy, and regulation*)

Storage Research Applicable to Hybrids

Finally, several projects conducted under EPRI's Energy Storage (P94), Advanced Generation and Bulk Energy Storage (P66), and Energy Systems and Climate Analysis Group (P201) programs are focused primarily on energy storage are applicable to a broader understanding of hybrid technologies. A few are highlighted here:

- **Energy Storage in Long-Term System Models: A Review of Considerations, Best Practices, and Research Needs:** provides recommendations to analysts on approaches for representing energy storage in long-term electric sector models given energy storage technologies' complex and diverse cost, value, and performance attributes relative to other generation technologies, navigating trade-offs in model development, and identifying research gaps for existing tools and data; also provides guidance to consumers of model outputs on proper use and interpretation based on model strengths and limitations
- **Emerging Energy Storage Technology Testing and Demonstration:** characterization of new alternatives to the current energy storage incumbent (lithium-ion) to identify potential value, performance advantages, and challenges of specific technologies in lab and field environments, including investigations of safety, cost, and commercialization pathways of emerging technologies and in-depth engagement with technology suppliers and demonstration host sites to assess technology readiness
- **Energy Storage Controls for Optimized Performance:** benchmarking of storage economic benefits by capturing key performance metrics in a variety of operating scenarios, verifying product functional specifications against actual plant performance, and maximizing energy storage utilization by assessing opportunities to "stack" grid services.
- **Battery Energy Storage Fire Prevention and Mitigation:** characterization of site-specific battery storage fire hazard potential, including threats, consequences, and potential mitigations; investigation of scientific studies, leading practices, interim guidance and lessons learned from battery storage system design and operations in lab and field environments; collaboration with industry stakeholders to prioritize future testing and research activities; and follow-on work to collect data, address modeling needs, and validate models with test data to better quantify safety hazards and efficacy of solutions.

Appendix C. Challenges of Different Hybrid Types

Table 14. Challenges Created by Different Hybrid Types for the Design, Operation, and Regulation of ISO/RTO Markets

Market trends and drivers	- Understanding market trends and drivers for HES	Colocated resources, virtual power plants, full hybrids
Transmission planning and interconnection	- Modeling HES in transmission planning and interconnection studies - Rules and requirements for interconnection of hybrid resources	Colocated resources, virtual power plants,[a] full hybrids
Resource adequacy planning and markets	- Capacity accreditation for HES - Capacity market performance obligations and must-offer rules for HES - Calculation and allocation of capacity interconnection rights for HES	Virtual power plants, full hybrids
Markets and operations	- Forecasting requirements and metering and telemetering requirements for HES - Ancillary services participation by HES and methods for determining ancillary services capabilities - Participation models for HES (forecast/bid parameters, corresponding ISO/RTO processes) - Impact of HES on market price formation and uplift charges - Market monitoring and market mitigation rules for HES - Policy compliance tracking and reporting for HES	Virtual power plants, full hybrids

[a] Virtual power plants could, in principle, apply for interconnection as a single resource, leading to many of the same interconnection and transmission planning challenges posed by colocated resources and full hybrids.

Table 15. Challenges Posed by HES for Resource Permitting, Utilities, and State Policies

Distribution planning	- Evaluation of distribution-level hybrid resources in utility non-wires alternatives procurement	Virtual power plants, full hybrids
Resource planning and acquisition	- Evaluation of HES in utility resource planning and acquisition - Developing avoided costs and rules for hybrid PURPA projects - Contract forms and terms and conditions for HES	Colocated resources, virtual power plants, full hybrids
Permitting and interconnection	- Siting, permitting, and licensing rules for HES - Utility interconnection requirements and costs for HES	Colocated resources, virtual power plants, full hybrids
Utility dispatch	- Forecasting, metering, and telemetering requirements for HES - Methods for determining hybrid AS capabilities and integration charges - Storage dispatch for storage-paired HES	Virtual power plants, full hybrids
Utility business models	- Understanding potential opportunities and regulatory challenges of utility business models for HES	
Policy and regulatory design	- Regulation of HES in state policy mandates (policy eligibility, accounting, and tracking) - Understanding the role of HES in meeting state policy goals	Colocated resources, virtual power plants, full hybrids

Appendix D. Use Cases and Services

The preliminary, nonexhaustive list of use cases and services by HES include:

- Dispatchable energy services and flexibility services with resource forecast
    - Reduced curtailment, increased energy production, higher capacity factors, and reduced emissions from the same plant footprints
    - Fully dispatchable, load-following operation using long-term (hours and days) and short-term (5-minute) production forecasts, and capability to bid into day-ahead and real-time energy markets (like conventional generation), forecast error mitigation
    - Capacity and flexibility services
    - Aggregate plant level ramp limiting, variability smoothing, and cloud and wake impacts mitigations
    - Various strategies to provide different types of reserve and flexibility products
- Essential and advanced reliability services
    - Automatic generation control (AGC) and primary frequency response
    - Fast frequency response (FFR) and synthetic inertia
    - Superior plant-level four-quadrant dynamic reactive power/voltage control
    - Stable operation with weaker grids
    - Enhanced fault ride-through performance/recovery profiles, programmable reactive current injection
    - Advanced controls for damping all types of power system oscillations, control interactions, and resonances
- Transient performance
- Resiliency services
    - Grid-forming, black start, participation in grid restoration
    - Islanded operation.

Appendix E. List of Acronyms and Abbreviations

AC	alternating current
ACCESS	Argonne Collaborative Center for Energy Storage Science
ACOPF	alternating current optimal power flow
AGC	automatic generation control
AI	artificial intelligence
AIMFAST	Alignment Implementation for Manufacturing using Fringe Analysis Slope Technique
AMES	Agent-Based Modeling of Electricity Systems
ANL	Argonne National Laboratory
ARIES	Advanced Research on Integrated Energy Systems
ARPA	Advanced Research Projects Agency–Energy
ASHES	Automated Sample Handling and Exposure System
ATB	Annual Technology Baseline
BCR	benefit-cost ratio
BCS	Beam Characterization System
BOS	balance of system
CAES	compressed air energy storage
CAISO	California Independent System Operator
CCUS	carbon capture, utilization, and storage
CESER	Cybersecurity, Energy Security, and Emergency Response
CHP	combined heat and power
CO_2	carbon dioxide
COMMANDER	COordinated Management of Microgrids and Networked Distributed Energy Resources
CSP	concentrating solar power
DC	direct current
DCOPF	direct current optimal power flow
DER	distributed energy resource
DER-VET	Distributed Energy Resource Value Estimation Tool
DETAIL	Dynamic Energy Transport and Integration Laboratory
DETL	Distributed Energy Technologies Laboratory
DISPATCHES	Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems
DOE	U.S. Department of Energy
DRTS	digital real time simulation
ECIO	econometric input-output
EERE	DOE Office of Energy Efficiency and Renewable Energy
EGRET	Electrical Grid Research and Engineering Tools
EIA	U.S. Energy Information Administration
EIOC	Electricity Infrastructure Operations Center
EIR	eligible intermittent resource
EMIS	Electricity Markets and Investment Suite
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESA	Energy Storage Association

ESET	Energy Storage Evaluation Tool
ESGC	Energy Storage Grand Challenge
ESIF	Energy Systems Integration Facility
ESIG	Energy Systems Integration Group
EVIL	Electric Vehicle Infrastructure Laboratory
FACTS	flexible AC transmission systems
FE	Fossil Energy, DOE Office of
FERC	Federal Energy Regulatory Commission
FESTIV	Flexible Energy Scheduling Tool for Integrating Variable Generation
FFR	fast frequency response
FIRST	flexible, innovative, resilient, small, transformative
GMI	Grid Modernization Initiative
GMLC	Grid Modernization Laboratory Consortium
gpm	gallons per minute
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
GSL	Grid Storage Launchpad
GT	Gas Turbine
GUI	graphical user interface
GW	gigawatts
H_2	hydrogen
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HERON	Heuristic Energy Resource Optimization Network
HERTH	hybrid energy real-time time hub
HES	hybrid energy systems
H-FACET	Heliostat Focusing and Canting Enhancement Technique
HFTO	Hydrogen and Fuel Cell Technologies Office
HIL	hardware-in-the-loop
HOPP	Hybrid Optimization and Performance Platform
HTE	high-temperature electrolyzer
HTSE	high temperature steam electrolysis
ICE	internal combustion engine
IDEAS	Institute for the Design of Advanced Energy Systems
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
IRENA	International Renewable Energy Agency
IRP	integrated resource plan
IRPTF	Inverter-Based Resource Performance Task Force
ISO	independent system operator
ITC	investment tax credit
JCESR	Joint Center for Energy Storage Research
kg	kilograms
kW	kilowatt
kWe	kilowatt-equivalent
LADWP	Los Angeles Department of Water and Power
LBNL	Lawrence Berkeley National Laboratory
LCA	life cycle analysis
m^2	square meters
MAGNET	Microreactor Agile Nonnuclear Experiment Testbed
MARKAL	MARKet ALlocation
MASCORE	Microgrid Asset Sizing Considering Cost and Resilience
MDT	Microgrid Design Toolkit

MS-SOC	metal-supported solid oxide fuel cells
MSTL	Molten Salt Test Loop
MTS	Materials Test Systems
MW	megawatts
MWth	megawatts-thermal
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NGCC	natural gas combined cycle
NGR	nongenerator resource
NE	Nuclear Energy, DOE Office of
NREL	National Renewable Energy Laboratory
NSTTF	National Solar Thermal Test Facility
NTUA	Navajo Tribal Utility Authority
NTUF	Nuclear Test User Facility
NWTC	National Wind Technology Center
OE	Office of Electricity, DOE
ORNL	Oak Ridge National Laboratory
PC	pulverized coal
PERL	Power and Energy Real-Time Laboratory
PNNL	Pacific Northwest National Laboratory
PPA	power purchase agreement
PRAS	Probabilistic Resource Adequacy Suite
PSFM	Power Systems Financial Model for Grid Technologies
PSH	pumped-storage hydropower
psi	pounds per square inch
PSS/E	Power System Simulator for Engineering (PSS/E)
PUC	public utility commission
PURPA	Public Utility Regulatory Policy Act of 1978
PV	photovoltaics
R&D	research and development
RAVEN	Risk Analysis Virtual Environment
RICE	Reciprocating Internal Combustion Engines
RODeO	Revenue, Operation, and Device Optimization
RPS	renewable portfolio standard
RSCAD	Real-Time Simulation Software Package
RTO	regional transmission operator
SAM	System Advisor Model
SCADA	supervisory control and data acquisition
sCO_2	supercritical CO_2
SEL-RTAC	Schweitzer Engineering Laboratories—Real-Time Automation Controller
SETO	Solar Energy Technology Office
SIIP	Scalable Integrated Infrastructure Planning
SIL	Systems Integration Laboratory
SNL	Sandia National Laboratories
SOEC	solid oxide electrolyzer cell
SOFAST	Sandia Optical Fringe Analysis Slope Technique
SOFC	solid oxide fuel cell
T&D	transmission and distribution
TEA	techno-economic analysis
TEAL	Tool for Economic AnaLysis

TEDS	Thermal Energy Distribution System
TES	thermal energy storage
TSRL	Thermal Spray Research Laboratory
US-REGEN	US Regional Economy, Greenhouse Gas, and Energy Model
USC	ultra-supercritical
UQ	uncertainty quantification
V	volts
VBAT	Virtual Battery Assessment Tool
StorageVET	Storage Value Estimation Tool
VRE	variable renewable energy
W	watts
WISDEM	Wind Plant Integrated Systems Design and Engineering Mode