# Hybrid Distributed Wind and Battery Energy Storage Systems

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## NOTICE

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*Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.*

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# List of Acronyms

| | |
|---|---|
| AC | alternating current |
| BESS | battery energy storage system |
| DC | direct current |
| DER | distributed energy resource |
| DFIG | doubly-fed induction generator |
| HVS | high voltage side |
| Li-ion | lithium-ion |
| LVS | low voltage side |
| MIRACL | Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad |
| MW | megawatt |
| NREL | National Renewable Energy Laboratory |
| PV | photovoltaic(s) |
| SM | synchronous motor |
| SOC | state of charge |
| WTG | wind turbine generator |

# Executive Summary

For individuals, businesses, and communities seeking to improve system resilience, power quality, reliability, and flexibility, distributed wind can provide an affordable, accessible, and compatible renewable energy resource. Distributed wind assets are often installed to offset retail power costs or secure long term power cost certainty, support grid operations and local loads, and electrify remote locations not connected to a centralized grid. However, there are technical barriers to fully realizing these benefits with wind alone. Many of these technical barriers can be overcome by the hybridization of distributed wind assets, particularly with storage technologies. Electricity storage can shift wind energy from periods of low demand to peak times, to smooth fluctuations in output, and to provide resilience services during periods of low resource adequacy.

Although interconnecting and coordinating wind energy and energy storage is not a new concept, the strategy has many benefits and integration considerations that have not been well-documented in distribution applications. Thus, the goal of this report is to promote understanding of the technologies involved in wind-storage hybrid systems and to determine the optimal strategies for integrating these technologies into a distributed system that provides primary energy as well as grid support services. This document achieves this goal by providing a comprehensive overview of the state-of-the-art for wind-storage hybrid systems, particularly in distributed wind applications, to enable distributed wind system stakeholders to realize the maximum benefits of their system. As battery costs continue to decrease and efficiency continues to increase, an enhanced understanding of distributed-wind-storage hybrid systems in the context of evolving technology, regulations, and market structure can help accelerate these trends.

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# 1 Introduction

A distributed hybrid energy system comprises energy generation sources and energy storage devices co-located at a point of interconnection to support local loads. Such a hybrid energy system can have economic and operational advantages that exceed the sum of the services provided by its individual components because of synergies that can exist between the subsystems. The coordination between its subsystems at the component level is a defining feature of a hybrid energy system. Recently, wind-storage hybrid energy systems have been attracting commercial interest because of their ability to provide dispatchable energy and grid services, even though the wind resource is variable. Building on the past report "Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) Controls Research Road Map," which highlights the challenges and opportunities for distributed wind grid integration and control mechanisms, this report initiates and establishes a baseline for future research on wind-storage hybrids in distribution applications (Reilly et al. 2020).

The objective of this report is to identify research opportunities to address some of the challenges of wind-storage hybrid systems. We achieve this aim by:

- Identifying technical benefits, considerations, and challenges for wind-storage hybrid systems
- Proposing common configurations and definitions for distributed-wind-storage hybrids
- Summarizing hybrid energy research relevant to distributed wind systems, particularly their control, operation, and dispatch
- Suggesting strategies for sizing wind-storage hybrids
- Identifying opportunities for future research on distributed-wind-hybrid systems.

A wide range of energy storage technologies are available, but we will focus on lithium-ion (Li-ion)-based battery energy storage systems (BESS), although other storage mechanisms follow many of the same principles. The Li-ion technology has been at the forefront of commercial-scale storage because of its high energy density, good round-trip efficiency, fast response time, and downward cost trends.

## 1.1 Advantages of Hybrid Wind Systems

Co-locating energy storage with a wind power plant allows the uncertain, time-varying electric power output from wind turbines to be smoothed out, enabling reliable, dispatchable energy for local loads to the local microgrid or the larger grid. In addition, adding storage to a wind plant can enable grid-forming or related ancillary grid services such as inertial support and frequency responses during transitions between grid-connected and islanded modes. A hybrid system can also increase revenue by storing rather than wasting energy that cannot be used because of system rating limits or the absence of loads.

Additional benefits of hybrid energy systems can come from sharing components between other generation sources such as inverters and optimizing electrical system ratings and interconnection transformers. It is worth noting, however, that limiting the full system rating can result in a decrease in revenue. For example, the use of storage during periods of high wind energy output might be limited restricted because of a limit on the total power output of the combined system. For this reason, rigorous assessments—including hybrid system modeling, planning, and sizing of the components—are critical to maximize system benefits based on the application, expected load, and desired grid services. An assessment should also consider the specific grid and local weather conditions.

The following are some high-level benefits of wind-storage hybrid systems:

- **Dispatchability of variable renewable resources**. A storage system, such as a Li-ion battery, can help maintain balance of variable wind power output within system constraints, delivering firm power that is easy to integrate with other generators or the grid. The size and use of storage depend on the intended application and the configuration of the wind devices. Storage can be used to provide ramping services, as has been done with wind installations in Kodiak and along the Alaskan Railbelt with wind facilities in Anchorage or Fairbanks; for time-of-day shifting, as was deployed in Kotzebue, Alaska; or to allow for transitions between sources, as has been deployed in Tuntutuliak and other remote Alaskan communities. In larger grid-connected systems, photovoltaics (PV) has a diurnal cycle that fits well with a 4-hour storage cycle, charging the storage device during the day to expand energy supply to, typically, evening peak load hours. Depending on a site's wind profile and the driver for energy services, a wind-storage hybrid system will require different considerations for storage size. These requirements have prompted storage asset developers and owners to look to new battery technologies beyond the short-duration Li-ion systems deployed so far (Energy Storage Systems, Inc. 2016). Various technologies are evolving to provide long-duration storage.

- **Economic impact**. The demand for electricity varies with time, changing with time of day, weather, and various socioeconomic factors. Similarly, the price of electricity also varies with system conditions, congestion, and time of day. A storage system can leverage this varying pricing to schedule its charging and discharging to increase the effectiveness of energy arbitrage. Research has also shown that arbitrage can be achieved across energy and ancillary markets to improve the economics of wind-storage hybrids (Das, Krishnan, and McCalley 2015). This economic value proposition further improves for a hybrid resource, which can rely on low-cost renewable energy (or no-cost renewable energy at times when curtailment requires shutting down wind turbines) to charge and sell in the larger grid's energy and ancillary markets. The benefits of a hybrid system depend on the resource configuration and specific context of the project, and research is needed to tailor hybrid solutions to specific locations and grid scenarios.

- **System flexibility**. Modern energy systems require electricity to maintain constant frequency and voltage. However, wind energy is a variable resource that, when combined with a variable load, increases the overall power variability of the energy system. Hence, maintaining a balance of supply and demand requires balancing engineering and economics. To achieve this balance, balancing authorities have look-ahead generation scheduling and operational planning, starting from day-ahead unit commitment and dispatch and continuing to real-time dispatch at 5 minutes. This scheduling ensures that generation resources have sufficient flexibility (e.g., headroom capacity and ramping capabilities) to meet the energy, load following, ramping, and ancillary service (regulation and spinning reserves) requirements for reliability. As system size decreases, there are fewer devices on the grid and less need to stabilize frequency and voltage, requiring faster system response even below 1 hertz (Hz). Regarding flexibility, hybrid wind systems can provide:

  - Load leveling or energy shifting to avoid steep ramps and negative prices caused by excess renewable generation
  - Complementarity with solar, thereby mitigating issues such as the duck curve (California ISO 2016), with its mismatch between generation and load, leading to severe morning and evening net-load ramps
  - Ramping up or down to support the increase in the frequency and severity of ramping events in the grid related to increasing variable renewable contributions. With improved wind forecasting and adequate energy storage, hybrid systems can provide ramping capability, thereby avoiding generation scarcity events and real-time price spikes that would otherwise necessitate expensive gas generation starts.

- **Enhanced grid stability**. In a power system, especially localized grids, generation and demand must remain balanced to maintain stability. This balance ensures that voltage, frequency, and small-signal oscillations remain within acceptable North American Electric Reliability Corporation and American National Standards Institute levels. A storage system can function as a source as well as a consumer of electrical power. This dual nature of storage combined with variable renewable wind power can result in a hybrid system that improves grid stability by injecting or absorbing real and reactive power to support frequency and voltage stability.

- **Grid reliability and resilience**. A distribution hybrid system with local loads can also function as a microgrid, and the microgrid, with appropriate controls, can operate in both grid-tied and islanded modes. A microgrid with on-site renewable generation and storage can enhance grid resilience and ensure power supply to critical loads during major physical or cyber disruptions. Additionally, a distributed wind system can support a stable and reliable grid when hybridized with storage as well as dispatchable generation as appropriate. Further reliability improvements can be made by adding redundancy to the system (by physically distributing assets with parallel capabilities) or using advanced controls to provide services (such as black start capabilities).

- **Economics with common and standardized components**. Most modern utility-scale wind turbines have power converters to allow for variable-speed operation of the wind generator for maximum efficiency and to convert the power to grid-standard voltage and frequency. The power converter may include AC/DC and DC/AC conversion. A battery storage system also requires such power converters to regulate charging/discharging. Other relevant services that these power converters can provide include ramp rate, decoupled control of real and reactive power for frequency and voltage support, and DC-to-AC power conversion in an AC grid-tied scenario. These services are also relevant to many other distributed energy resources (DERs). Battery systems can utilize the existing power converter and inverter hardware infrastructure in a wind turbine, and the components can be optimally sized for their intended uses. The incremental cost of the hardware, even when the component size is increased, can be an economic option for some deployments, especially in an isolated environment or use case.

- **Other benefits from the circular economy and recycling**. Small-scale wind energy developers are looking at the economics of employing used batteries from the transportation industry. Bergey Windpower Co. is planning to use secondhand battery systems from a nearby Nissan electric car factory to create a home microgrid system. The Bergey Excel 15 Home Microgrid System uses 18-kilowatt-hour (kWh) recycled electric vehicle battery packs (Bergey 2020). The batteries used in electric vehicles can be evaluated for a range of options for reuse and recycling. The research at National Renewable Energy Laboratory has revealed that the second use of electric vehicle batteries is both viable and valuable (NREL 2020). NREL's battery second-use calculator can be used to explore the effects of different repurposing strategies and assumptions on economics. Before batteries are recycled to recover critical energy materials, reusing batteries in secondary applications, like the Excel 15 Home Microgrid System, is a promising strategy (Ambrose 2020). The value propositions from the circular economy can make wind-hybrid systems a cost-effective as well as an environmentally friendly option for a reliable and resilient energy system.

## 1.2 Considerations and Challenges of Hybrid Wind Systems

Although a hybrid wind system has many benefits, it can pose operational challenges as well. The following are some high-level considerations and challenges when considering the deployment of a wind-storage hybrid system or upgrade of a standalone wind power plant to include storage:

- **Complicated dispatch and valuation of combined resources**. A variable wind resource can cause cycling of the battery, which can affect its life cycle (Wenzl et al. 2005; Corbus et al. 2002). How daily cycling compares with random charge/discharge is an economic question that may be specific to the context. The hybrid system may have challenges associated with co-location, such as transmission constraints and inverter capacity limits. Some of these challenges can be managed with a better forecast and control/dispatch logic. However, a detailed assessment for specific grid scenarios and weather situations is needed to size the hybrid systems appropriately and optimize resource utilization. Further, the economic assessment must maximize storage utilization while reducing curtailments and battery cycling, especially for isolated power systems (Baring-Gould et al. 2001).

- **Feasibility studies are not as defined and generic as they are for conventional generators**. For systems on a central grid, governing market rules and policy incentives can make or break the finances of a wind-hybrid project. A co-located wind-storage system can share infrastructure to provide reliable power at a low cost. Such a system may also qualify for incentives such as the investment tax credit, provided it complies with terms and conditions specific to the state, region, or country. In some states, a battery system must get 75% of its energy from renewable energy sources such as solar and wind to qualify for the investment tax credit. Depending on policy, the hybrid system may or may not make sense technically and/or financially.

- **The current production tax credit for wind does not consider the addition of energy storage**. There are also operational limits to hybridization. These will depend on the available resource in a region and the ability to forecast and develop appropriate resource bids or self-schedules (if participating in markets or central dispatch and compensation mechanisms) to enhance the value of a hybrid system. The investment tax credit for PV was expanded to include investments in battery storage (NREL 2018b), but the production tax credit for wind does not include such considerations.

- **Integrating multiple technologies is complex, and plug-and-play solutions are needed to simplify design**. The literature review conducted as part of this report is intended to inform the development of control solutions to maximize the benefits of wind-hybrid system configuration and sizing. A "plug-and-play" distributed wind turbine system is needed to enhance the market share and realize the full potential of wind to serve the global demand for clean energy. A defining aspect of "plug and play" is continued innovation on par with evolving grid codes and other technology solutions.

Considering the possible range of benefits, challenges, and opportunities, this paper will explore how wind-hybrid systems, with a current focus on wind-storage hybrid systems, can be efficiently configured to operate within different environments. A detailed quantitative study will be undertaken later, and results will be reported. Taking lessons learned from other hybrid technologies (e.g., hybrid-solar or hybrid-hydro [Poudel, Manwell, and McGowan 2020]) in the energy industry, this literature review aims to identify the opportunities and challenges of wind-hybrid systems in various operational use cases. These use cases include isolated grids or microgrids in island mode, grid-connected resources providing energy and ancillary services to the grid, and the ability to transition from grid-connected to island mode.

# 2 Wind-Storage Hybrids: Possible Configurations

Increasingly, wind turbines are being coupled with batteries to mitigate variability and uncertainty in wind energy generation at a second-by-second resolution. Storage may be integrated with wind turbines in three ways:

1. Virtually, if the hardware is not co-located but is controlled as a single source
2. Physically co-located yet separately metered and dispatched as a separate source
3. Co-located behind the same meter, in which case the two components act as a singular source with respect to the grid.

Within this context, wind-storage hybrids can also be coupled in two ways:

1. AC-coupled, in which wind and storage share a point of common coupling on an AC-bus
2. DC-coupled, in which wind and storage share a point of common coupling on a DC-bus.

As we discuss in Section 2.3, AC coupling can be done in all three storage integration cases, but to date DC-coupled systems are exclusively behind-the-same-meter systems.

In a wind power plant, which may contain two or more wind turbines, the storage can be sited either at the power plant level (i.e., central storage, as shown in Figure 1a) or at the individual wind turbine level (i.e., integrated storage, as shown in Figure 1b). Individual turbine-level storage can either be deployed as a unit behind the dedicated turbine interconnect, typically with a lower-voltage AC connection, or integrated behind the turbine power converter, which will take place at a DC voltage. For example, each of the 100 GE 1.6-megawatt (MW) wind turbines at Tehachapi has 200 kWh of integrated storage (Miller 2014) in the DC link. Unlike turbines with integrated storage that use the turbines' existing power conversion equipment, a wind power plant with AC-connected individual or central storage requires additional equipment such as a dedicated power converter, switchgear, and transformer. This is one of the trade-offs that need to be considered when choosing a storage topology and location. A study of the GE turbines at Tehachapi builds on a precursor study (Fingersh 2003) that explored using the turbine's controller and power electronics system to operate an electrolyzer to generate hydrogen from water, thereby using a component-level strategy for a hybrid system. The GE study (Miller 2014) does not provide many details about the sizing of integrated storage and the associated power electronics architecture; we believe this is an opportunity for future research.

a) Central storage at the plant level  b) Integrated storage at each turbine

**Figure 1. Possible wind-storage hybrid configurations**

A hybrid system can be coupled on a common DC bus, AC bus, or both, depending on the type of wind turbine. The four main types of wind turbines are summarized in Figure 2 (Singh and Santoso 2011). Some of these configurations are more amenable to sharing DC-to-AC-conversion equipment. A review paper (Badwawi, Abusara, and Mallick 2015) presents power electronics topologies and control for hybrid systems. A good description of AC versus DC solar coupling, including their pros and cons with reference to the solar energy industry, is documented in (Marsh 2019).

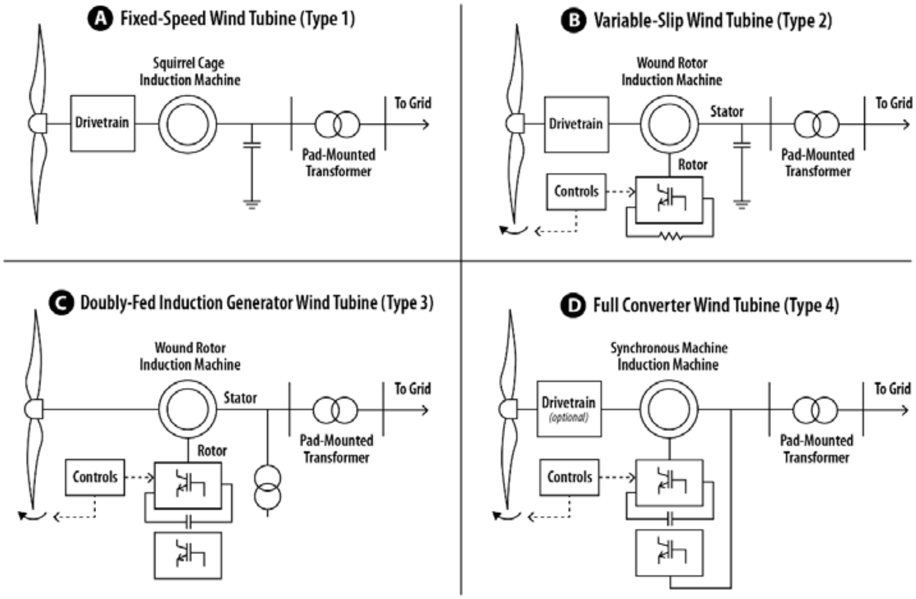


**Figure** 2**. Dominant wind turbine technologies.**

Source: Singh and Santoso (2011)
Key: DFIG – doubly-fed induction generator; IM – induction motor; SM – synchronous motor.

## 2.1 AC-Coupled Wind-Storage Hybrid Systems

In an AC-coupled wind-storage system, the distributed wind and battery connect on an AC bus (shown in Figure 3). Such a system normally uses an industry-standard, phase-locked loop feedback control system to adjust the phase of generated power to match the phase of the grid (i.e., synchronization and control). To integrate electrical power generated by DERs efficiently and safely into the grid, grid-side inverters accurately match the voltage and phase of the sinusoidal AC waveform of the grid (Denholm, Eichman, and Margolis 2017).

An AC-coupled wind-storage system has some advantages over DC-coupled systems. AC-coupled systems use legacy hardware and standardized equipment commonly available in the market, making them relatively easy to install. In an AC-coupled system, energy stored by the battery can be independent of the output of the wind turbine, allowing the combined system to be sized and operated based on the energy and grid services that the project will provide. Two independent units will also have a high total capacity because both units can provide full output simultaneously. In this scenario, the battery storage can have fewer charging/discharging cycles than it would in the DC-coupled system. However, this may not always be the case if the hybrid system is in an isolated mode of operation.

For Type 3 and Type 4 wind turbines (see Figure 2), an AC-coupled wind-storage system would require two inverters: one DC/AC one-way inverter for the wind (after the DC/AC converter) and a bidirectional DC/AC inverter for the battery system for charging/discharging, as depicted in an example system shown in Figure 3. The power conversion equipment is costly but allows the full capacity of both generation sources to be used.

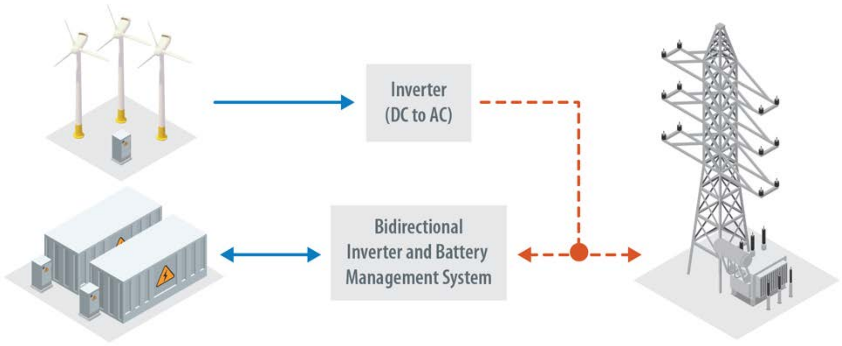


**Figure 3. Common topology of an AC-coupled wind-storage hybrid system.**

Source: Adapted from Denholm, Eichman, and Margolis (2017)

## 2.2 DC-Coupled Wind-Storage Hybrid System

In a DC-coupled wind-storage system, the wind turbine and BESS are integrated at the DC link behind a common inverter, as detailed for PV by Denholm, Eichman, and Margolis (2017) and adapted for wind-plus-storage systems in Figure 4. The electricity generated by the wind turbine is rectified and coupled with the BESS, and the battery is maintained through the DC-DC converter. The grid-side inverter can be one-directional (i.e., DC/AC) or bidirectional, and the battery can store energy from just the turbine or from both the turbine and the grid. This is shown in Figure 4 and discussed in further detail for PV by Denholm, Eichman, and Margolis (2017).

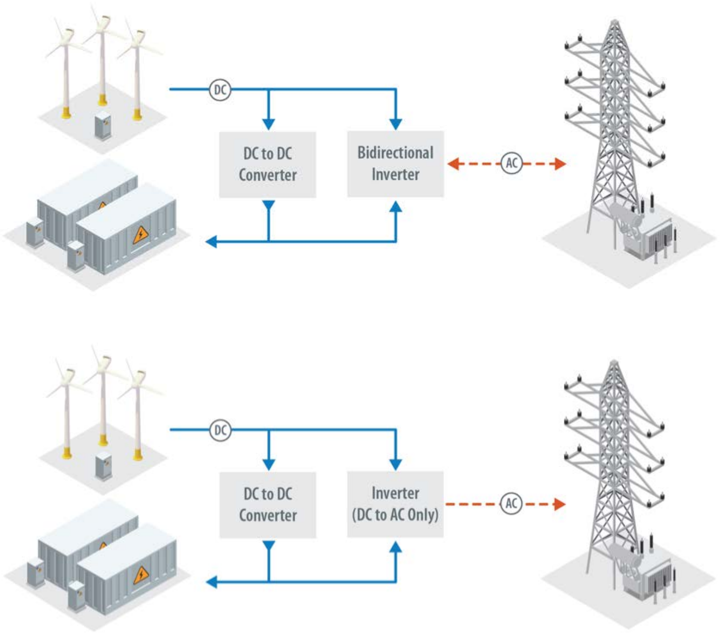


**Figure** 4**. Schematics of DC-coupled wind-storage systems.**

Source: Adapted from Denholm, Eichman, and Margolis (2017)

In a DC-coupled system using a one-directional DC/AC inverter, the battery can only be charged using the wind turbine. Some states and federal programs offer tax credits for such systems (NREL 2018b). With a bidirectional inverter, the stacked value streams for the BESS may increase because it can serve energy-shifting functions and participate in energy arbitrage. In addition, such a system may qualify for tax credits and other incentives available to one-directional inverters.

Type 3 and Type 4 wind turbines share many of the same components as energy storage systems and can often share a significant portion of AC/DC and DC/AC infrastructure, with a DC link capacitor in between (Miller 2013, 2014). In this case, a battery with a DC output can be connected directly or via its own bidirectional DC-DC converter for power regulation. This type of storage is known as an integrated storage in the DC link of the wind turbine. A recent master's degree thesis at the Norwegian University of Science and Technology evaluated he modular multilevel converter for medium-voltage integration of a battery in the DC link (Rekdal 2018). A multilevel converter is a method of generating high-voltage waveforms from lower-voltage components. Modular multilevel converters are considered a promising battery interface as they have very high efficiency; excellent AC waveforms; and a scalable, modular structure, while also allowing for the use of semiconductors with low ratings. However, there is not much research available in the public domain about how to optimize the size of integrated storage for given wind power plant sizes and energy resources.

For hybrid systems, there has been recent interest in revisiting multiport DC/DC converters to share power electronics components, simplify operational logics, and develop compact/efficient architectures. For an isolated application, Zeng et al. (2019) present a four-port DC/DC converter that can handle wind, PV, battery storage, and loads (see Figure 5). The authors claim that their multiport converter has the advantage of using a simple topology to interface with sources of different voltage/current characteristics.

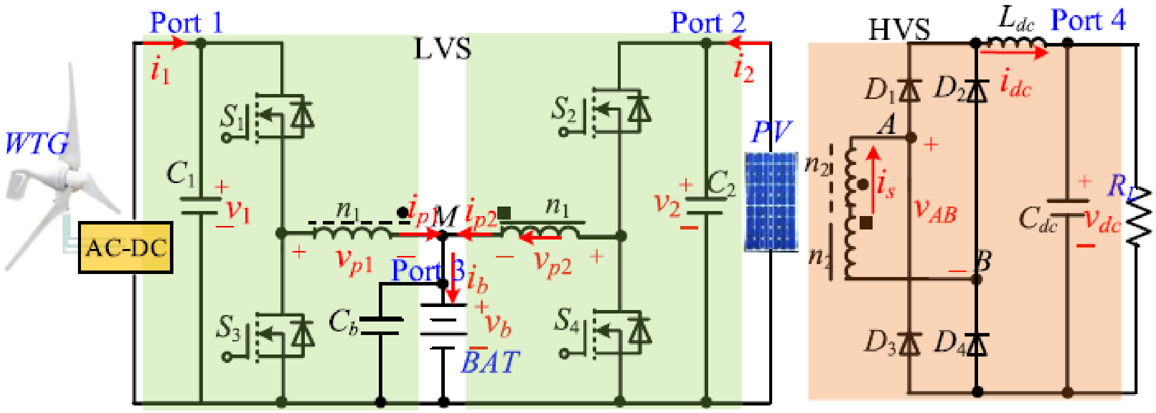


**Figure 5. Four-port DC/DC converter for an isolated system.**

Source: Zeng et al. (2019)
Key: WTG = wind turbine generators; LVS = low voltage side; HVS = high voltage side; BAT = battery storage; PV = solar photovoltaic.

## 2.3 Comparison of AC and DC Configurations

Both AC and DC wind-storage hybrids have advantages and disadvantages that depend on the details of the specific installation. For example, direct-drive, Type 4, full-conversion wind turbines (e.g., EWT, Enercon) are suitable for integrated AC and DC coupling, as both an AC and DC bus exist in their typical configuration. However, conventional Type 1 turbines are more suited for AC coupling because of the lack of a DC bus in their typical configuration. The configuration also depends on the specifics of the project and economic factors such as market price for energy and grid services, and tax credit policies for hybrid plants. The following is a high-level comparison of characteristics of AC and DC hybrid configurations:

- **AC system maturity and battery independence**. AC-coupled systems use standard AC interconnection equipment available in the market that is easy to install. This allows more flexibility in the sizing of the wind turbine and battery, both in terms of power and capacity. In an AC-coupled system, energy stored by the BESS can be independent of the output of the individual wind turbines.

- **DC systems for smaller and distributed hybrids**. As the size of the DER project increases, a clear demarcation begins to emerge between the AC and DC coupling based on the economics of the project and other nontechnical constraints. A DC-based system is known to interface better with other DC-based distributed generation on the system, but currently is limited to rather small sizes. Such a system can communicate and supply power over a single distribution line, and interconnection with other on-site DC generation sources such as PV is simplified. Experts on the future of direct current in buildings (Glasgo, Azevedo, and Hendrickson 2018) suggest that the two biggest barriers for DC coupling are industry professionals unfamiliar with DC and comparatively small markets for DC devices and components.

- **Trends in power-electronic-interfaced sources and loads favoring DC coupling**. Recent advances achieved in power electronics—which made DC voltage regulation a simple task—have increased the penetration of DC loads and sources and encouraged researchers to reconsider DC distribution for portions of today's power system to increase overall efficiency (Elsayed, Mohamed, and Mohammed 2015). Although the conventional rotating-electric machine-based power system predominantly operates via AC transmission, microgrids intrinsically support DC power. Many distributed energy systems are driven by static electronic converters (Gu, Li, and He 2014). Compared to its AC counterpart, a DC microgrid has the potential to achieve higher efficiency, power capacity, and controllability. Because of these advantages, a DC-based power system with DC-coupled wind and storage is an enabling technology for microgrids, especially in small-scale residential applications such as green buildings, sustainable homes, and energy access applications in areas inaccessible by the national grid.

- **System efficiency and cost**. An AC-coupled system will have lower roundtrip efficiency for battery charging than a DC-coupled system, which charges the battery directly and does not have power flow through two inverters (one wind turbine inverter and one BESS inverter). However, only a portion of the wind turbine power produced goes into the storage and is thus subject to the losses. An NREL study based on a utility-scale PV project suggests that using DC coupling rather than AC coupling results in a 1% lower total cost (Fu, Remo, and Margolis 2018), which is the net result of cost differences between solar inverters, the structural and electrical balance of system, labor, developer overhead, sales tax, contingency, and profit. For an actual project, however, cost savings may also need to account for additional factors such as retrofit considerations, system performance, design flexibility, and operations and maintenance.

Further design considerations for different hybrid configurations to promote reliability and flexibility include:

- **DC systems**. A DC-coupled wind-storage system requires one less inverter than an AC-coupled system (see Figure 3), which reduces wiring and housing costs as well as conversion losses. Type 3 and Type 4 wind turbines also have hardware components that can be used for DC coupling at the DC link. Because the BESS is connected directly to the distributed wind turbine system, excess generation that might otherwise be clipped by an AC-coupled system at the inverter level can be sent directly to the BESS, which could improve system economics (DiOrio and Hobbs 2018).

- **AC systems**. AC systems use off-the-shelf components, and they do not require technology-specific modification or engineering. In addition, AC system components are modular, which reduces retrofit costs, and they stack well with each other compared to a DC-coupled system. They require less maintenance time because, unlike a DC-coupled system, batteries do not need to be installed next to the bidirectional inverter. AC-coupled systems can also use larger battery racks per megawatt-hour of battery capacity and thus reduce the number of heating, ventilating, and air-conditioning and fire-suppression systems in the battery containers (Fu, Remo, and Margolis 2018). These systems allow manageable battery health monitoring and state-of-charge (SOC) planning with an independent battery management system that has its own bidirectional DC-AC inverter and can use redundant inverters that provide increased reliability and available capacity.

- **Retrofit to add storage to existing generation**. For a retrofit scenario with individual wind turbines (i.e., adding battery storage to existing wind turbine generators), an AC-coupled BESS may be the only practical option because of the extensive turbine-specific modifications that would need to be implemented for a DC-coupled system.

- **Synchronization**. A hybrid system coupling in a DC common bus does not require the synchronism an AC bus configuration requires. The voltage is fixed for all subsystems in the hybrid system, and the current from each subsystem is controlled independently. A battery bank connected directly or through a DC/DC link can regulate the DC bus voltage. The subsystem can independently perform maximum power point tracking by using an AC/DC converter for the wind turbine and DC/DC converter for the PV case. A common DC/AC inverter maintains the voltage across the load.

The wind and solar industries have many similarities for AC- and DC-coupled systems. Badwawi, Abusara, and Mallick (2015) present a summary of research regarding power electronic topologies and control. Marsh (2019) also provides a good description of AC versus DC solar coupling, including pros and cons related to the solar energy industry. A co-located wind-storage system can share some components and leverage some transmission-level constraints.

To expand on the grid support capabilities of wind-storage hybrids, GE conducted a study on wind power plants with integrated storage on each turbine rather than central storage, along with an extra inverter and transformer for redundancy (Miller 2014). There are always some trade-offs involved in choosing a storage topology. The GE study does not present details about sizing integrated storage but rather demonstrates the benefits of the technology. As part of the MIRACL project, NREL plans to explore integrated storage sizing and configurations using theoretical and computational approaches through desktop simulations and power-hardware-in-the-loop validation.

# 3 Hybrid System Controls: Stable Integration and Maximum Utilization

A defining feature of hybridization is the ability to coordinate generation to effectively balance varying load or net load (load minus variable renewables), resulting in an economic dispatch of the generation and storage assets. This is possible by controlling individual devices (e.g., generators, storage, load) within the hybrid system, or by controlling the hybrid system as a single unit, providing a precise power output to benefit the overall power system. A system-level controller utilizes algorithms to issue commands to each device within the hybrid system based on load and variable renewable forecasts.

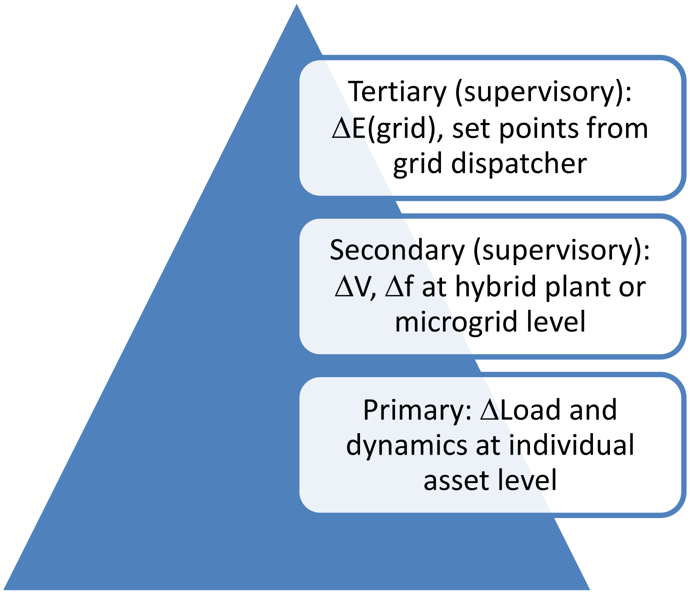


**Figure 6. Hierarchy of hybrid system control**

Typically, controls use a hierarchical architecture as well as two-way communication from individual subsystems or devices in a hybrid system to achieve the best hybridization outcomes. A typical hierarchical control can be classified into three levels, as shown in Figure 6. The primary control manages the load/current sharing through droop control. The secondary control responds to the steady-state error on the voltage and frequency, and the tertiary control maintains coordination based on the status at the point of common coupling.

The objective of control is to maintain the electrical system parameters within acceptable limits by balancing generation with demand at the hybrid system level, taking system constraints and the health trajectory of subsystems and individual components into account. It should also be recognized that these control functions are made at different time steps, with electrical system parameter adjustments needing to happen very quickly whereas others, such as decisions based on balancing load or varying renewable energy production, can typically be made over minutes or hours.

## 3.1 Distributed Hybrid System Controls

Well-designed controls can enable several capabilities that improve hybrid system economics.

### *3.1.1 Essential Reliability Services and Stability*

Hybrid controls should be flexible (or customizable) to accommodate various essential reliability services that the hybrid system may provide. Control and coordination between the hybrid technologies becomes more challenging as the contribution of variable renewables increases on the grid and more is expected of hybrid systems to support grid stability. For example, toward the end of rural extension lines or long transmission lines where voltage and frequency are more sensitive to the dynamic load/generation (i.e., weakly interconnected systems), the phase-locked loop measurement system, on which frequency and phase estimation and subsequent controls rely, is known to have issues with frequency and phasor measurement, adversely affecting stability. Therefore, the controls in a hybrid system should be able to ease and enhance the stability of the services provided. The use of a battery to provide services such as inertial response will also decrease mechanical load in the wind turbine (extending its life). Similarly, wind turbines can provide damping control to offset oscillations (e.g., local, forced, or interarea), which will be further enhanced with interconnected battery storage.

### *3.1.2 Frequency Response*

In addition to the (natural or synthetic) inertial response to any generator outages causing frequency drop, the grid typically uses three additional levels of frequency response: 1) primary or governor response subject to frequency deviation beyond a “dead band”; 2) secondary response that uses 4- to 6-second-level automatic generation control signals coming from a central dispatcher (taking into account both frequency deviation as well as tie-line transactions) into a variable called an area control error; and 3) tertiary response, typically coming from additional reserves through market dispatch. For each of these services, there must be headroom reserved from the maximum available power for both a wind turbine and PV plant. In a hybrid plant, a battery can complement the variable renewable power and provide these frequency response services, removing the need to curtail and reserve headroom in the wind turbine, unless it becomes necessary for reliability reasons.

Droop control is a common way to control and coordinate multiple distributed resources in a hybrid plant, allowing them to share power and support multiple grid services. A droop for a resource with a rated power P(rated) in a power system with frequency f = 60 Hz is defined as:

$$\frac{1}{droop} = \frac{\Delta P/P(rated)}{\Delta f/60(Hz)} \tag{1}$$

For example, Xcel Energy has used wind turbine droop control for years (Porter, Starr, and Mills 2015). The most common droop setting used in many power systems is 5%, but in some cases more aggressive 3% droop is used as well (NREL 2018b). A 5% droop means that a 5% change in frequency would result in a 100% change in power. For a BESS system operating at 5% droop control at a nominal frequency of 60 Hz, a decrease or increase in frequency of 3 Hz (i.e., 5/100 × 60 Hz) should deliver/absorb the rated power of the battery. However, the deliverability of the power for a BESS and any source of generators will depend on the available headroom or the current state of the resource (i.e., maximum generation, current generation set point, or battery SOC).

As the contribution level of variable renewable energy grows in a microgrid, additional design challenges emerge for the integration of BESS and appropriate levels of droop settings. A 2015 study (Weaver et al. 2015) looked at the energy storage requirements of DC microgrids with high-penetration renewables under droop control. This study suggested that decentralized control architecture is possible with a distributed or adaptive droop control that is subject to evolving net-load disturbance or area control error fluctuations, and, consequently, the energy storage requirements in a microgrid may be minimized with the optimal choice of droop settings. Another study related to DC microgrids (Zhao and Dörfler 2015) demonstrated that the droop control strategy can achieve fair and stable load sharing (even in the presence of actuation constraints) or follow set points provided by the economic dispatch.

### 3.1.3 Voltage and Reactive Power Support

In addition to frequency support, voltage and reactive power control are another criterion for hybrid plants. The control may be to maintain a specific voltage set point or power factor at the point of interconnection or to maintain the voltage within American National Standards Institute limits of 0.95 to 1.05 per unit (or 0.90 to 1.1 per unit) for certain locations or contingency situations. Type 1 and Type 2 wind turbines will typically need external reactive power resources, such as capacitor banks and static synchronous compensators (STATCOMS) to provide reactive support and voltage control. Type 3 wind turbines come with a limited range (+/- 30%) of reactive power control, given the size of the rotor-side converter. Type 4 turbines come with a full range of reactive power capabilities, just like a PV inverter, and could be operated like a STATCOM even when the turbine is not producing real power. However, given the need to curtail real power to produce reactive power, the storage in the hybrid plant can alleviate the issue by providing reactive power support. With the help of energy storage, the hybrid plant's range of reactive power control can be increased and maximized to support the required power factor or voltage performance.

### 3.1.4 Flexibility and Economic Grid Services

Although all the services mentioned are needed to ensure that the hybrid power plant can be integrated into the grid and support grid reliability and stability, the most important factors from a project developer's perspective are the nest utilization of all assets and maximizing profit. To do that, the modelers will have to understand every possible combination of individual devices suited for a particular location and develop optimization and management algorithms that can harness the synergies among various components. For example, among various objective functions of the hybrid resource optimization and control, reducing energy from a diesel genset is a desirable outcome, especially in a remote, isolated grid scenario. Efficient use of fuel, or hedges against winter fuel shortages, should also be accounted for when designing and operating hybrid plants. For example, this is the case in Alaskan microgrid designs.

In a grid-tied scenario, maximizing the revenue from energy and ancillary markets will be key. The increased use of variable renewable energy resources has also increased the necessary reserve, regulation, and ramping capability needed in the grid. A wind-storage hybrid plant is well-suited to provide these flexibility and ancillary services in addition to firm dispatchable energy.

### 3.1.5 Enabling Fast and Accurate Response

Although energy storage can make wind turbines more versatile when hybridized, appropriate controls and tests must be done to ensure that coordination and response times are good enough to provide the necessary services. For example, fault ride-through and black-start capability will need prompt response and even near-instantaneous synchronization with the grid. NREL researchers have achieved Li-ion battery response times of less than 30–40 milliseconds (ms) (NREL 2018a). The response time also depends on which mode the Li-ion battery is operating in. In a grid-following mode, the response time is about 25 ms, whereas it is about 50 ms in a grid-forming mode.

In grid-forming mode, a hybrid resource is the primary source of the voltage and frequency regulation. The underlying inverter of the hybrid resource consists of voltage and current regulators working together to maintain the nominal state of the grid. The grid-forming inverter may work as the master or work in parallel with other inverters in the microgrid. The main challenges during grid-forming mode are to maintain the stability of operation during changing set points and ensure black start of the microgrid (Fusero et al. 2019). During transitions, such as connecting and disconnecting from the utility grid or energizing and de-energizing other DERs in islanded mode, the grid-forming inverter should be able to resynchronize the system with minimum transients. The mode requires correcting active and reactive power sharing in tandem with other DERs. To summarize, the inverter in grid-forming mode should be able to mimic the dynamic behavior of synchronous generators. A precise control of the virtual inertia of the inverter is important for system stability in both grid-following and grid-forming modes.

## 3.2 Modeling Controls and Time Scales

The wind-hybrid models used for a simulation could be discrete or continuous. Depending on the time scales of a discrete simulation, we can capture various dynamics of the hybrid system using simulation models ranging from electromagnetic transient to the phasor solution at a given frequency (e.g., 60 Hz). Different resolutions and fidelities of model physics are essential to capture events ranging from dynamics to minute and hourly deviations. The ability to visualize and generate data demonstrating the interactions of inverters and batteries at various scales will aid in an expanded understanding of stability. In general, the power system simulation models for wind-hybrid systems may be classified as:

- Detail electromagnetic transient simulation (about 1 nanosecond-microsecond, including modeling power electronics switching).
- Average simulation (about 100 microseconds-milliseconds; good enough to capture the electrical transients, phase imbalances, faults, and dynamics).
- Phasor solution (at 60 Hz, typically balanced modeling). Sometimes, we may be interested in a solution at a frequency, such as 60 Hz. A phasor solution solves a much simpler set of algebraic equations relating to the voltage and current phasors. This method computes voltages and currents as phasors. Phasors are complex numbers representing sinusoidal voltages and currents at a particular frequency (Mathworks 2020). They can be expressed either in Cartesian coordinates (real and imaginary) or in polar coordinates (amplitude and phase). As the electrical states are ignored in the phasor solution, the simulation is therefore much faster to execute.

- Hybrid simulation and co-simulation (in which certain spatiotemporal characteristics could be modeled with higher fidelity whereas others could use simpler models for faster computation). Such modeling can also be done using co-simulation of several existing tools of varying modeling fidelity to ensure scalability to larger systems and faster computation. Hybrid simulations may combine simulations at various time scales and model topologies. One example is combining the electromagnetic transient and transient stability simulations (Athaide 2018). Another example is the co-simulation of bulk transmission systems, along with market dispatch, and the individual distribution system feeders that may connect to a hybrid distributed wind system. The bulk system and market representation may have to be modeled at 5-minute time scales, whereas the distribution network may have to be simulated at a higher temporal resolution to respect voltage bounds (quasi-static steady state).

# 4 Operation and Dispatch of Wind-Storage Hybrids

Operation and dispatch of wind-storage hybrids depend on the intended function as well as the configuration of the hybrid in relation to the external power grid. For example, a hybrid system operating in an isolated grid may differ significantly than the same hybrid system in grid-connected mode. In an isolated grid, the wind-storage hybrid system may need to operate as a grid-forming asset, whereas in the grid-connected mode it could normally operate in a grid-following mode. This is a common challenge for generation employed in microgrids, and the complexity increases slightly for a hybrid system in a microgrid.

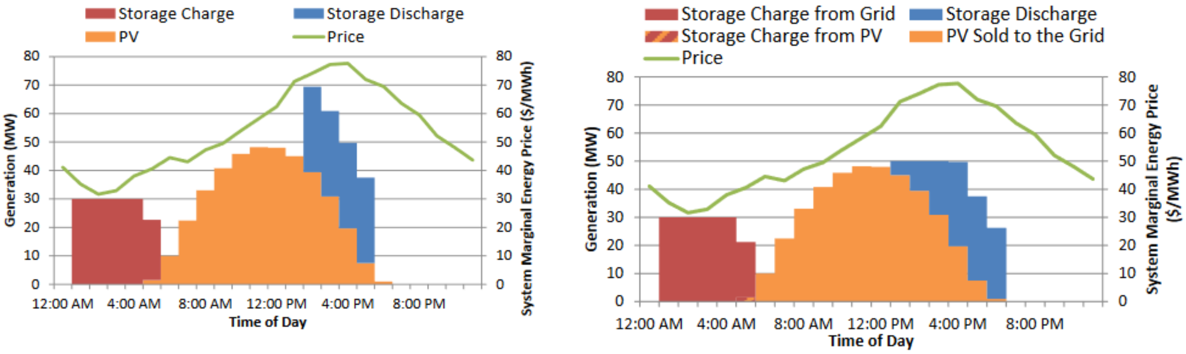
## 4.1 Wind-Storage Hybrids Optimal Dispatch

Operating a wind-storage hybrid system involves uncertain intrinsic and extrinsic factors. One of the major flaws of energy storage dispatch algorithms is that they are often based on forecasts relying on perfect foresight and/or historical trends. These forecasts are used to optimize net benefits of the operation and dispatch for a set of geospatial and temporal constraints. Optimizing operation is governed by technical and economic requirements and can include multiple time scales or multiperiod formulation of the operation and dispatch of a wind-storage hybrid system. A margin for error must be included for a real-world system to ensure that its technical and economic goals are met.

A hybrid system model can have different objectives than the individual subsystem models. The model may include objective functions, such as optimizing revenue from co-optimized markets, not just from energy, which is a departure from how energy storage and distributed wind turbines have been traditionally modeled and dispatched. A wind-storage hybrid system mitigates variability by injecting more firm generation into the grid. This is particularly helpful in high-contribution systems, weak grids, and behind-the-meter systems that have different market drivers. A battery combined with a wind generator can provide a wider range of services than either the battery or the wind generator alone.

A study conducted for an isolated system (Barley and Winn 1996) examined three dispatch strategies. The results illustrate the nature of the optimal strategy for two simple dispatch strategies load following and cycle charging (HOMER Energy 2020) for a minimum run time. The study found that the combination of a simple diesel dispatch strategy with the frugal use of stored energy is virtually as cost-effective as the ideal predictive strategy.

An NREL study compared an independently coupled and uncoupled dispatch of PV and storage for a day with a DC-coupled dispatch. As shown in Figure 7, in this case, the DC-coupled system seems to lose revenue because the shared 50-MW inverter cannot fully utilize the storage system (the total solar and storage power output is limited to a 50-MW inverter limit) (Denholm, Eichman, and Margolis 2017). However, such a system (with inverter and load ratio > 1) at times can avoid clipped energy by forcing the storage to charge with the excess power from PV.



(a) Independent

(b) DC-coupled

**Figure 7. Dispatch of photovoltaics-plus-storage system on a typical day**

Several considerations remain regarding operating and dispatching hybrid plants in grid-tied mode, including:

- If the hybrid plant is self-scheduled, it needs an algorithm to use forecasts of distributed wind and prices to dispatch the hybrid wind and storage, considering the maximal utilization of the storage SOC for multiple look-ahead periods.
- If the hybrid plant will be dispatched by a centralized scheduler and dispatcher, then new challenges and opportunities arise for the construction of bids and offers that will be sent from the hybrid plants. If the plant is wind only, then forecasts with their bounds are typically sent, and in some rare utility-scale applications, the ability of the wind plant to provide down-regulation (by curtailment) is communicated. If the plant has energy storage, then communication of SOC and charging and discharging schedules will be key. For a hybrid plant, the central dispatcher may only want to know 1) the maximum and minimum generation capability (considering forecasts, available SOC, and price forecasts for maximizing storage arbitrage); 2) up and down ramp rates for 5- and 10-minute intervals relevant for regulation and spinning reserve services (from storage rates and forecasted wind ramps); and 3) operational cost, which may be a function of nominal wind turbine and storage operational costs, including the impact of cycling on battery life.

## 4.2 Wind-Storage Hybrids Supporting Black Start

Black start is the procedure used to restore power when it is lost. It requires a gradual ramping up of wind turbine power in coordination with other subsystems, including controllable loads. Wind-storage hybrids of the correct capacity can support black starts of microgrids in island mode and in permanently isolated grids. In grid-connected mode, the grid normally provides the required reference voltage to start a wind turbine. Black start is an advanced operation that requires collaboration and coordination among many subsystems, including storage, using an advanced control algorithm.

Wind turbines can provide black start in conjunction with an inverter (grid forming) and external auxiliary power supplies such as battery storage to maintain a minimum DC voltage to initiate the power ramp-up operation. In the case of the SMA Solar Technology inverter at NREL's

Flatirons Campus microgrid (SMA 2016), the black-start operation starts when, after closing the DC load-break switch, the inverter checks for voltage at the AC terminals. If no AC voltage is applied, the AC disconnection unit is closed, and the configured AC voltage set point is ramped up. The AC voltage set point is usually specified via an external plant control using a Modbus protocol. If an AC voltage already exists to the inverter terminal, the inverter can synchronize with the external auxiliary power supply, close the AC disconnection, and support the power grid. The start voltage must be at least 20% of the nominal AC voltage.

Wind turbines have demonstrated the ability to provide a black start in some special circumstances. Figure 8 demonstrates a black-start operation utilizing three distributed wind turbines in an isolated grid. This illustration (Majumder 2020) demonstrates how control systems gradually adjust the DC voltage, AC voltage, and load to build up the voltage reference for the second wind turbine to come online and aid the black-start process.

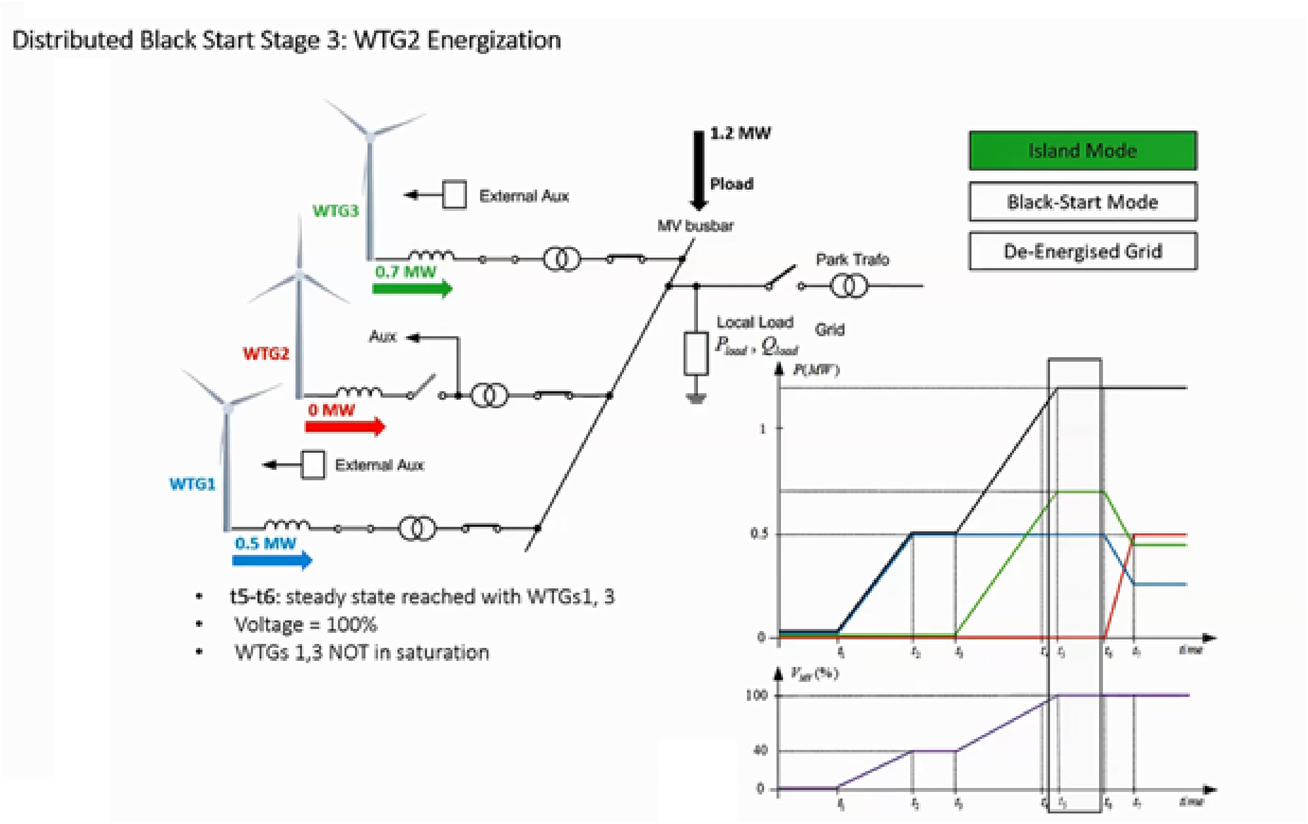


**Figure 8. Distributed black start of wind turbines in an island mode.**

Source: Majumder (2020)

In Figure 8, the black-start operation starts at time, t1, with wind turbine generator 1 (WTG1) energized using an external auxiliary supply to bring the bus voltage up to 40% of the reference voltage at t2. From t2 to t3, the wind turbine attains a steady operation at 0.5 MW. At t3, WTG3 is brought into the process and the load in the bus is increased accordingly to 1.2 MW to match the generation. The voltage ramps up linearly following an external AC reference and reaches the reference voltage at t5. The system remains at steady state until t6, at which point WTG2 is energized fully to deliver the rated 0.5 MW of power.

Obviously, the black-start operation of the wind turbine is contingent upon the wind resource. An integrated storage in the DC link of the wind turbine may function as an external auxiliary source during the operation. For a microgrid with more than one inverter, a superordinate plant control is required to coordinate various stages of the black start among the inverters.

In the United Kingdom, National Grid ESO has started an ambitious project called Distributed ReStart (National Grid ESO 2020), which plans to demonstrate the black-start service through the coordinated operation of DERs.

# 5 Techno-Economic Sizing of Wind-Storage Hybrids

Techno-economic evaluation of hybrid plants depends on both the benefits and costs (e.g., investment, installation, balance of system, soft, life cycle, and operational costs). Benefits could include increased revenue by utilizing otherwise trimmed variable renewable energy. Some components could also be shared for effective cost reduction. With the added flexibility of energy storage, a hybrid wind power plant may be able to provide—in addition to firm energy—flexibility and ancillary services with very high dependability. However, because of the shared inverter, the system may generate less revenue under configurations of hybrid coupling that limit storage operation during periods of high wind output. We will review some of these trade-offs in this section, based on the state-of-the-art sizing methods proposed for wind-storage hybrids in the open-source literature.

The sizing of storage in a wind-storage hybrid depends on various factors, such as resource profile, load profile, desired storage functions, energy, and other essential reliability services pricing signals, and the time scale of the analysis. Here, our focus will be on batteries that can capture and store excess wind turbine energy and send it to the utility grid or a local microgrid as necessary. The batteries can be integrated with each wind turbine or installed at the wind farm level, as shown in Figure 1.

The techno-economic sizing of wind-storage systems depends largely on cost models of storage and wind-hybrid systems. Such sizing tools go beyond conventional decision -making based on levelized cost of energy-based decision-making. These computer-aided-engineering tools aim to capture market structure more accurately, along with synergies and value streams from grid services that may exist at different levels of the co-located subsystems. The market price signal can make or break the viability of storage for an integrated wind hybrid project. Hence, it is very important that the different value streams of a hybrid system be evaluated fairly. Some of the value streams of a wind-hybrid system are not recognized (or are taken for granted) in the legacy energy market structure that is dominant today.

## 5.1 Storage Cost Models

In this section, we summarize storage cost models of Li-ion batteries, using data from both the energy and vehicle industries. We anticipate that the cost models will not deviate significantly for a hybrid wind power plant compared to a hybrid PV plant, even if a typical wind turbine is AC, whereas PV is DC. The analyses we include here are taken mainly from Denholm, Eichman, and Margolis (2017); Fu, Remo, and Margolis (2018); and Cole and Frazier (2019).

An NREL study (Cole and Frazier 2019) looked at the cost projection for 4-hour Li-ion systems in 2018 dollars. Figure 9 shows the overall capital cost for a 4-hour battery system. Regional capital cost multipliers for battery systems range from 0.948 to 1.11, with Long Island having the highest multiplier. This study uses a separate cost projection for the power and energy components of Li-ion systems. Although the range is considerable, all projections show a decline in capital costs, with cost reductions of 10%–52% by 2025.

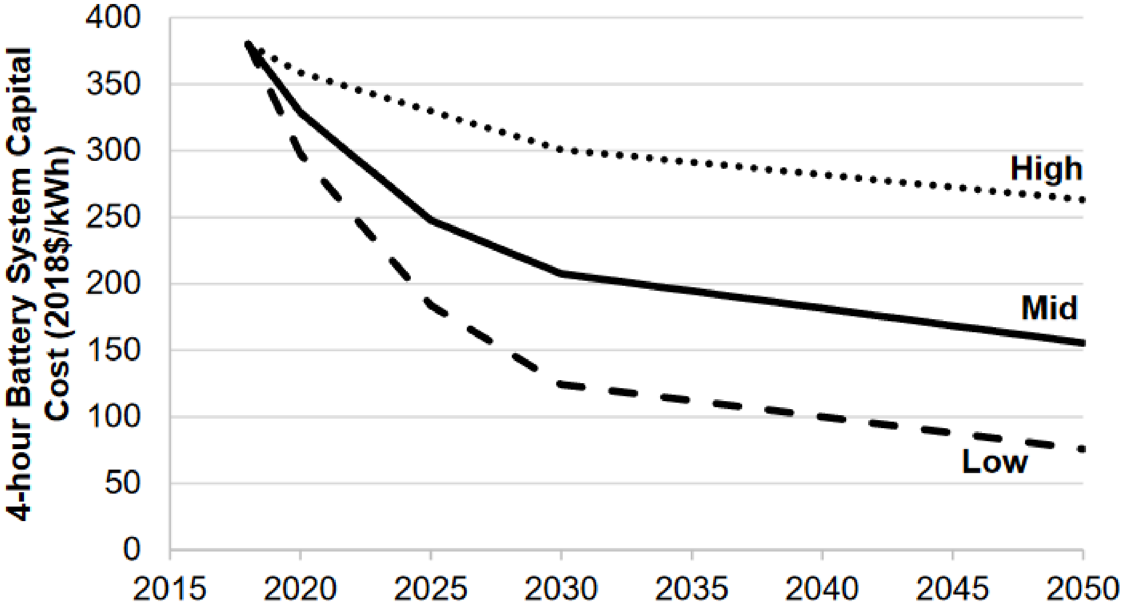


**Figure 9. Battery cost projections for 4-hour Li-ion systems**

Another study analyzed the total net present cost of the hybrid system and compared it with a system without storage (Dufo-López and Bernal-Agustín 2015) to determine cost per kilowatt-hour (cycled) of the Li-ion batteries for an economically feasible project. The techno-economic evaluation of grid-connected storage under a time-of-day electricity tariff suggests that the Li-ion battery cost would need to be reduced to about 0.085 $/kWhcycled.

## 5.2 Wind-Hybrid Models

There are a handful of first-generation tools to support techno-economic sizing of storage in relation to wind-hybrid systems. The popular wind-hybrid models in the industry use performance analysis at hourly or subhourly time scales. The performance-analysis-based tools focus on energy balance at each time step of simulation for a typical year. The default time step of many such models is an hour; hence, there will be 8,760 time steps in a typical year. The most popular models are Hybrid Optimization of Multiple Energy Resources (Lilienthal 2005); the Distributed Energy Resources Customer Adoption Model (Stadler et al. 2014, Stadler et al. 2016); and Hybrid2 (Manwell et al. 2006, Baring-Gould 1996), among others. There are in-house NREL models such as Renewable Energy Integration and Optimization (Cutler et al. 2017) and the System Advisor Model (Blair et al. 2018) for sizing and analyzing hybrid systems, all of which include the value of resilience (i.e., hours of support during complete grid outage). These tools use exhaustive performance analysis and/or some optimization techniques like mixed-integer linear programming to determine the optimal storage size. These models help design and optimize hybrid systems generally based on the levelized cost of energy or other relevant objective functions under a set of constraints. They also use market price signals on a limited basis ($/kWh) but at times miss the value streams associated with hybridization, such as enhanced essential reliability services; spatiotemporal values of energy and ancillary services resulting from changing conditions and transmission congestions; associated value streams; and sharing of infrastructure at component levels. The metrics based on levelized cost of energy-based metrics do not consider the difference in value between various distributed-wind-plus-storage configurations. There are not many studies that compare the cost of AC-coupled distributed wind with DC-coupled distributed-wind-hybrid systems. However, there are some solar studies that can be used to make an educated guess. Some extra components are needed for AC-coupled systems, and corresponding labor and balance-of-system costs may range from 1% to 5% depending on the size and geospatial coordinates of the hybrid project.

There are other tools, such as NREL's Hybrid Optimization Performance Platform software (National Renewable Energy Laboratory. Version 1.0. (2021). ), that further consider the synergy of wind turbine and hybrid systems at the component level and optimize their use. In addition to quantifying value streams associated with energy and capacity services, they also provide a value methodology to evaluate the essential reliability services that a wind-hybrid system may provide.

A Joint Institute for Strategic Energy Analysis white paper (Ericson et al., "Hybrid Storage Market Assessment," 2017) gives an optimistic evaluation of hybrid storage markets. The paper evaluates which markets are best suited for battery storage and storage hybrid systems and reviews regulations and incentives that support or impede the implementation of stand-alone storage and battery hybrids. California is found to be the most attractive geographic market for U.S. battery storage because of its storage mandates, high renewables penetration, and regulatory framework conducive to battery storage projects.

Recently, the scope for adding batteries to grid-connected wind projects is expanding around the world (Parnel and Stromsta 2020), building on the considerable momentum that already exists for hybrid solar-plus-storage plants. An earlier study (Ericson et al., "U.S. Energy Storage Monitor," 2017) forecasts a twenty-two-fold increase in battery storage and hybrid system capacity in the United States by 2023 compared to the 2017 baseline.

# 6 Conclusion

In this report, we provide a comprehensive overview of the state-of-the-art for wind-storage hybrid systems, particularly in distributed applications, to enable distributed wind system stakeholders to realize the maximum benefits from their system. The goal of this report is to promote understanding of the technologies involved in wind-storage hybrid systems and to determine the optimal strategies for integrating these technologies into a distributed system that provides primary energy as well as grid support services.

In our summary of technical benefits and modeling considerations, we identify the main benefit from storage integration with wind to smooth power output and match energy production with demand. In addition to smoothing output from the variable wind resource and supporting grid stability, coupling wind energy generation with a storage system can provide quick-response frequency and voltage support as well as active power control. Wind-storage hybrid systems can also support black start of a power system, which can be very beneficial in bringing a power system back online following a major grid disruption.

Our comparison of distributed-wind-storage hybrid system configurations highlights that turbine technology, the size of the distributed system, as well as non-technical factors such as market price for energy and grid services as well as tax credit policies determine which configuration is best suited to meet generation and load demands while keeping the grid stable. Control strategies to enable these configurations to meet energy and service demands include baseline reliability and grid stability control, but also frequency response, as well as voltage and reactive power support. Additional considerations for controls include enabling flexibility for optimal and resilient control and achieving time scales for measurement and response that enable these assets to provide advanced services and operation.

In our assessment of optimal operation and dispatch for distributed-wind-storage hybrid systems, we highlight the dependence of this optimal operation on the distributed system configuration. Namely, whether the distributed system is behind or in front of the meter, and whether it is grid connected or not dictates the optimal operation to achieve both market and grid resilience benefits.

Similarly, our review of techno-economic feasibility models for hybrid power plant design indicates that the techno-economic sizing of wind-storage systems depends largely on the system configuration (whether it is grid connected or not, behind the meter or not) as well as storage system costs. The hybrid plant design models considered in this report aim to capture market structure accurately, along with synergies and value streams from grid services. The market price signal determines the viability of storage in hybrid project design. Hence, it is critical to comprehensively evaluate hybrid plant value streams, some of which are not recognized by our current energy market participation and compensation structures.

Based on our assessment of the state-of-the-art of wind-storage hybrid energy systems, particularly for distributed system applications, opportunities for future work include:

- Developing well-documented, publicly available models for both AC and DC systems

- Expanding on the opportunities that complementary wind and solar resources might provide to a power system
- Evaluating systems in a simulated and power-hardware-in-the-loop environment to aid in the development of useful case studies to support industry acceptance of distributed-wind-storage hybrid systems
- Using wind-storage hybrid simulations to assess various configurations to support the development of advanced sizing methods for AC- and DC-coupled wind-storage hybrid systems
- Including other distributed energy resources (such as solar) into distributed hybrid systems research.

The opportunities for future work outlined here have directly impacted the research to be addressed through the remainder of the MIRACL project, under which this report was written. With the remaining life of the project, we plan to conduct research and develop further publicly available reports that address each of these opportunities.

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