The Roles and Impacts of PV-Battery Hybrids in a Decarbonized U.S. Electricity Supply

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National Renewable Energy Laboratory

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List of Acronyms and Abbreviations

AC	alternating current
BIL	Bipartisan Infrastructure Law
BIR	battery-to-inverter ratio
DC	direct current
DOE	U.S. Department of Energy
GW	gigawatts
GW_{DC}	gigawatts-direct current
GWh	gigawatt-hours
ILR	inverter loading ratio
IRA	Inflation Reduction Act
PV	photovoltaic
PVB	photovoltaic and battery
ReEDS	Regional Energy Deployment System
TW	terawatts
W_{AC}	watts-alternating current

This Report and the Inflation Reduction Act and the Bipartisan Infrastructure Law

The analysis presented in this report was conducted prior to the passage of the Bipartisan Infrastructure Law (BIL) of 2021 and the Inflation Reduction Act (IRA) of 2022, which include incentives for and investments in clean energy technologies along with other energy system modernization provisions. Initial analyses estimate that the energy provisions of these new laws could lower U.S. economy-wide greenhouse gas emissions to approximately 40% below 2005 levels by 2030. The impacts of these provisions are expected to be most pronounced for the power sector, with grid emissions initially estimated to decline to 68%–78% below 2005 levels by 2030 and the share of generation from clean electricity sources estimated to rise to 60%–81%. Investments in end-use sector decarbonization measures, including efficiency and electrification, are also supported by the IRA provisions.

Existing state and federal policies relevant to the power sector as of June 2021 are represented in the modeled scenarios; none of the scenarios presented in this report include the energy provisions from the IRA or BIL, or other, newer enacted federal or state policies or actions. The study's qualitative findings are expected to still apply, but given the potentially significant impact of the IRA and BIL, the incremental differences between the Reference and carbon constrained scenarios are expected to be lower than estimated here. Including IRA and BIL provisions would likely lower emissions in the Reference scenarios, and it would further increase the relative competitiveness of standalone storage projects. In turn, including IRA and BIL would likely result in smaller differences between the Reference and carbon constrained scenarios, both in terms of capacity expansion and incremental electricity system costs. These changes have not been quantified, and the analysis in this report does not provide any estimates of the impacts of these new laws.

Executive Summary

In September 2021, the U.S. Department of Energy (DOE) published the *Solar Futures Study* (DOE 2021), which explored the role of solar in decarbonizing the U.S. electricity supply. The *Solar Futures Study* implemented an emissions reduction requirement for the U.S. bulk power system that assumed policies will drive a 95% reduction (from 2005 levels) in the grid's carbon dioxide emissions by 2035 and a 100% reduction by 2050. The combination of this emissions reduction requirement with aggressive cost-reduction trajectories for all renewable energy and energy storage technologies defines the "Decarb" scenario from the *Solar Futures Study*.

The Decarb scenario was evaluated using the Regional Energy Deployment System (ReEDS) model (Ho et al. 2021), which is a power sector capacity expansion model that identifies the least-cost mix and operation of electricity generation, transmission, and storage assets that simultaneously meet load, all other electricity service requirements, and physical and environmental constraints. ReEDS results for the Decarb scenario indicated that combining aggressive cost reductions and supportive policies could allow solar to account for 44% of the nation's electricity supply by 2050; this represents a 20 percentage point increase compared to a business-as-usual ("Reference") scenario (DOE 2021).[1] The study further identified that achieving such an outcome would require a dramatic acceleration in the deployment of solar technologies—especially solar photovoltaic (PV) technologies—along with significant expansion of energy storage, transmission, and flexible loads.

This report builds off the *Solar Futures Study* by exploring how its results and findings could be impacted by the growing industry trend of hybrid systems comprising PV-and-battery (PVB) technologies. At the end of 2020, there were 73 PVB projects in operation on the U.S. bulk power system, comprising more than 1 gigawatt (GW) of PV capacity. An additional 830 PVB projects—comprising 150 GW of PV generation capacity—have been proposed in U.S. interconnection queues to come online by the end of 2026 (Bolinger et al. 2021). The details of these existing and proposed PVB projects remain sparse, but some projects likely take the form of PVB hybrids, which we define as involving increased efficiency and synergies through the colocation, physical coupling, and coordinated operation of multiple component technologies (Schleifer et al. 2022; Murphy, Schleifer, and Eurek 2021).

To evaluate the impacts of PVB hybrids on the outcomes and findings of the *Solar Futures Study,* we employ the same ReEDS model and Reference and Decarb scenario definitions,[2] but we perform two versions of each scenario: one in which PV and battery technologies must be deployed separately ("No Hybrids"), and one in which the model has the option of deploying them together as PVB hybrids ("With Hybrids"). The With Hybrids versions of each scenario

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[1] A third core scenario in the *Solar Futures Study* was the "Decarbonization with Electrification" ("Decarb+E") scenario, which allowed for exploring the potential for solar to contribute to a future with more complete decarbonization of the U.S. energy system by 2050. We do not explore the Decarb+E scenario in this study because of challenges associated with disentangling the effects of increasing demand-side and supply-side flexibility.

[2] Despite the similar scenario definitions and settings, quantitative results in our No Hybrids scenarios differ from those in the *Solar Futures Study* due to slight differences in model versions and inputs. For example, we apply aggressive cost reduction trajectories to PV and battery technologies (only) to reveal more targeted insights around impacts associated with the availability of PVB hybrids.

include two exogenously defined PVB hybrid configurations, which involve a shared bidirectional inverter[3] and PV and battery sizing that correspond to the greatest PVB hybrid deployment under the *Solar Futures Study* scenarios explored. The first exogenously defined PVB hybrid configuration involves sizing that is comparable to standalone PV systems, and the second involves a more forward-looking configuration with a significantly oversized PV array and a larger coupled battery.

Through comparison of the No Hybrids and With Hybrids versions of each scenario, we isolate the potential impacts of hybridization on total PV deployment, PV's share of total generation, the role of battery storage, transmission expansion, and bulk power system costs. In addition, we separately explore the impacts of the emissions reduction requirement ("Decarb-ModCost") and aggressive cost-reduction trajectories ("LowCost") to understand potential interactions between the evaluated policy and cost drivers. Note that this scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022, which introduced an investment tax credit for standalone storage technologies, among other provisions. For the model formulation presented in this report, representing the *Inflation Reduction Act* provisions could reduce the competitiveness of PVB hybrid technologies, since standalone storage systems would receive similar federal tax credit incentives.

Based on results from the full suite of scenarios explored, we identify the following key findings.

1. PVB Hybrids Displace a Share of Standalone PV Capacity

PVB hybrids capture a sizable share of PV deployment by 2050, but their availability has only modest impacts on cumulative PV deployment (Figure ES-1). Deployment of the candidate PVB hybrid configurations begins in the late 2020s and continues throughout the simulation period. The dominant effect of introducing candidate PVB hybrid configurations is direct competition between standalone and hybrid PV capacity, such that growing PVB hybrid deployment displaces standalone PV capacity.

Looking across scenarios, both standalone and hybrid deployments of PV increase under low-cost and/or decarbonization policy assumptions. Therefore, the share of PV capacity that is captured by hybrid configurations—13% to 16% based on alternating current (AC) rated capacity and 16% to 19% based on direct current (DC) rated capacity in 2050—is relatively similar across all scenarios explored (Figure ES-1).

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[3] Throughout this report, the term "PVB hybrid" refers to our exogenously defined configurations that involve a shared bidirectional inverter for the PV and battery components. Industry interest in PVB hybrids also includes so-called "AC coupled" systems, in which the coupled PV and battery components are designed and operated to achieve increased efficiencies and synergies but through separate PV and battery inverters.

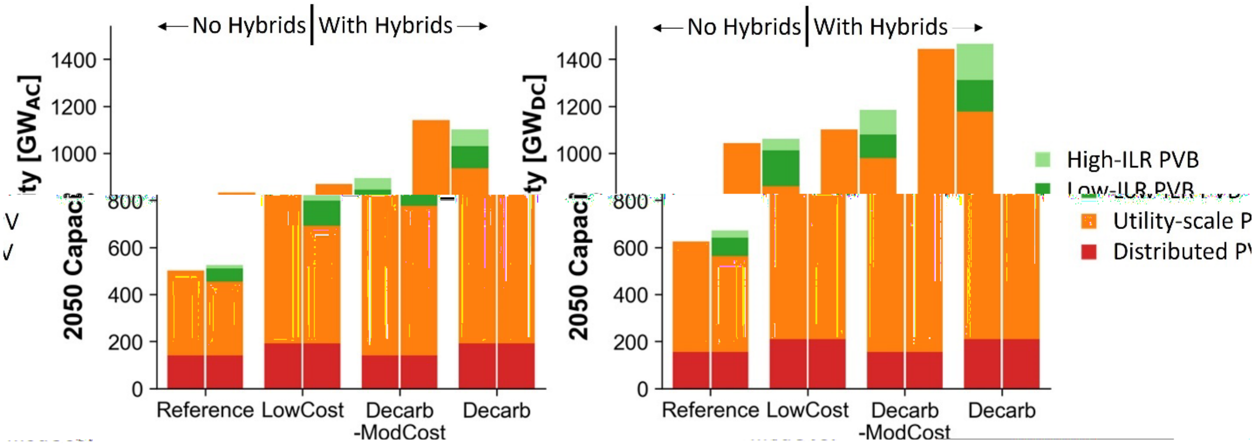

Figure ES-1. PVB hybrids capture a sizable share of PV deployment under the explored *Solar Futures Study* scenarios, but their availability has a modest impact on cumulative AC-rated (left) and DC-rated (right) PV capacities in 2050.

2. The Highest-Net-Value PVB Hybrid Configuration Depends on Carbon Policy

In the absence of a power sector decarbonization policy (Reference and LowCost scenarios), the highest-net-value PVB hybrid configuration involves PV sizing that is comparable to standalone systems (dark green bars in Figure ES-1). Deployment of this configuration reflects the fact that standalone PV and battery technologies are already part of the least-cost solution in many regions, and deploying them together has the system cost benefits of lower capital costs (because of shared equipment and balance-of-system costs) and the battery component's eligibility for the federal investment tax credit.[4]

By contrast, the emissions reduction requirement from the *Solar Futures Study* increases the value proposition of a hybrid configuration that involves significantly oversized PV arrays (i.e., a larger inverter loading ratio) and larger batteries (light green bars in Figure ES-1). This more forward-looking hybrid configuration has a higher capacity factor (~40%) due to its ability to efficiently recover and shift excess generation from the oversized PV arrays, and it is found to be economic even in low-solar-resource regions.

3. PVB Hybrid Configurations Expand PV's Share of U.S. Electricity Supply in 2050

The widespread deployment of PVB hybrids leads to an increase in the capacity factor of the overall PV fleet in 2050. In turn, PVB hybrid availability drives a 1–2 percentage point increase in PV's share of electricity generation in 2050 due to the oversized PV arrays in the hybrid configurations. As a result, the availability of PVB hybrids allows PV to provide 48% of U.S. electricity generation in 2050 under the Decarb scenario, which exceeds any of the estimates produced in the original *Solar Futures Study* (DOE 2021). This outsized role for PV in the 2050 U.S. electricity mix primarily reflects the fact that PVB hybrid deployment under the Decarb scenario is dominated by the more forward-looking configuration, which has a higher capacity

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[4] This analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in 2022, which expanded eligibility for the federal ITC to standalone storage projects. However, the Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

factor (38%–42%) than standalone PV (24%–29%) and the comparable hybrid configuration (29%–33%).

4. PVB Hybrids Influence the Future Mix of Battery Technologies

The availability of PVB hybrids influences the future role of utility-scale battery technologies, the details of which depend on technology cost assumptions (Figure ES-2). Beyond the direct competition between hybrid and standalone deployments of PV (described above), the introduction of candidate PVB hybrid configurations leads to a substantial increase in 4-hour (4-hr) duration batteries (i.e., the sum of the light green, dark green, and light blue bars in Figure ES-2). Under low-cost assumptions for PV and battery technologies, the availability of PVB hybrid configurations drives a 10%–29% increase in 4-hr battery capacity (compared to the corresponding No Hybrids scenarios), but this hybrid-induced expansion of 4-hr battery capacity is partially or fully offset by the reduced deployment of longer-duration batteries. Under default cost assumptions, the availability of PVB hybrid configurations increases deployment of all battery durations, which reflects the system cost benefits associated with hybridization (i.e., shared costs and the battery component's ability to qualify for the federal investment tax credit).

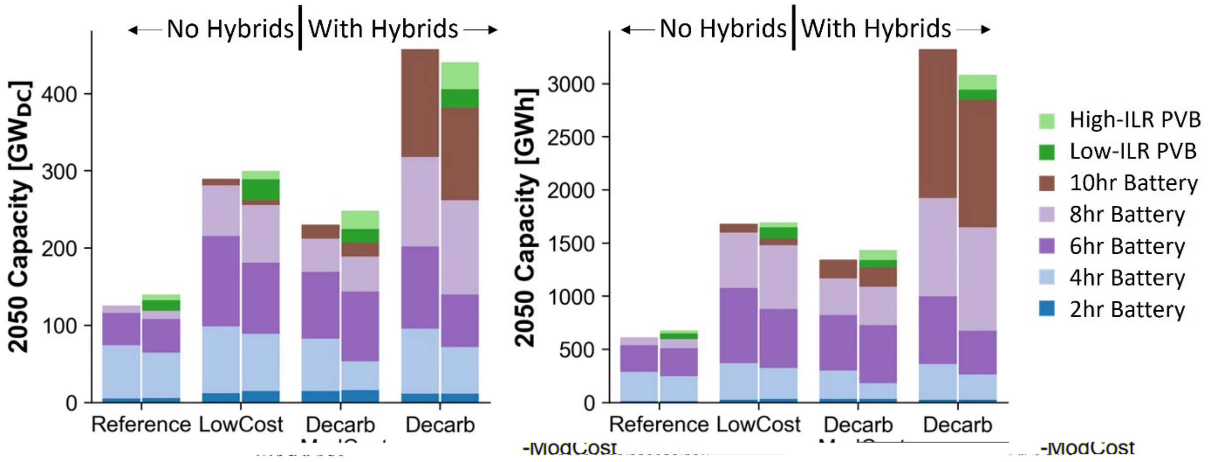

Figure ES-2. Total installed battery capacity for all scenarios (top) and the difference between With Hybrids and No Hybrids versions of each scenario (bottom) in 2050

5. PVB Hybrids Reduce Transmission Buildout

The availability of PVB hybrids reduces transmission expansion across all scenarios explored (Figure ES-3). The impacts of PVB hybrid configurations on new transmission capacity are relatively modest under the Reference and LowCost scenarios; however, introducing the PVB hybrid configurations in scenarios that involve a power sector decarbonization policy reduces transmission expansion by 8%–15% (or 8–20 terawatt- [TW-] miles; Figure ES-3), which primarily reflects avoided long-distance transmission expansion.

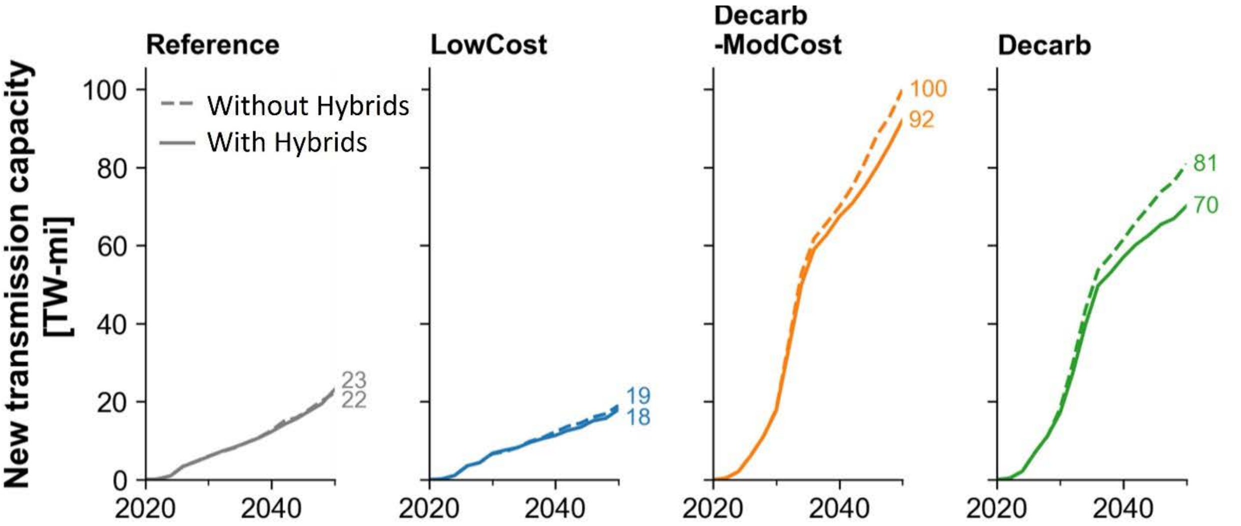

Figure ES-3. New transmission capacity over time across the No Hybrids (dashed lines) and With Hybrids (solid lines) versions of all scenarios explored.

This pronounced reduction in transmission capacity reflects multiple impacts associated with the availability of PVB hybrids, but it is primarily rooted in their higher capacity factors—and, therefore, higher transmission utilization rates—compared to standalone PV. In turn, the avoided transmission expansion contributes to a consistently observed reduction in bulk power system costs under scenarios that include PVB hybrids as a candidate investment option. Across most scenarios, the bulk power system cost impacts associated with the availability of PVB hybrid configurations are modest (0.1%–0.2%) because standalone PV and battery technologies were already part of the least-cost solution. The largest-magnitude system cost impact is observed under the Decarb scenario, in which the availability of PVB hybrids drives a 0.7% ($21 billion) reduction in bulk power system costs, primarily because of avoided transmission expansion.

In summary, the hybridization of utility-scale PV and battery technologies generates synergies that include greater PV efficiency and inverter utilization. As a result, introducing PVB hybrid configurations into the *Solar Futures Study* scenario definitions has a modest impact on the total number of PV panels installed (DC-rated PV capacity), but it leads to a 1–2 percentage point increase in solar’s share of total generation in 2050. Under the Decarb scenario definitions, PVB hybrids provide 9% (and all solar PV technologies provide nearly one-half) of total generation in 2050; this represents an expanded role for solar PV compared to the original *Solar Futures Study* results, along with reduced levels of transmission expansion and bulk power system investment. Future analysis is needed to understand how the provisions of the *Inflation Reduction Act* (U.S. Congress 2022) would influence the relatively competitiveness of standalone and coupled PV and battery systems.

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1 Introduction

The deployment of solar photovoltaic (PV) and energy storage technologies on the U.S. bulk power system continues to grow in response to rapid cost and performance improvements (Ramasamy et al. 2021) and policy drivers. Interconnection queues across the contiguous United States contain large volumes of proposed PV and battery storage projects, which take various forms. At the end of 2020, U.S. interconnection queues contained requests for 830 projects—comprising more than 150 gigawatts (GW) of PV generation capacity—that combine PV and battery technologies as a coupled PV-and-battery (PVB) system (Figure 1). Almost all of this proposed PVB capacity had requested to come online by the end of 2026, and 20 GW already had an executed interconnection agreement (Bolinger et al. 2021). More recent estimates indicate that industry interest continues to expand, with more than 280 GW (40%) of PV generation capacity in U.S. interconnection queues being proposed in a coupled configuration as of the end of 2021 (Rand et al. 2022).

Industry interest in PVB systems has grown for many reasons. A coupled PVB project could benefit from reduced costs (relative to separate PV and battery projects) due to the potential for shared component and balance-of-system costs (Ramasamy et al. 2021) and a faster interconnection process (Ericson et al. 2022).[5] Historically, hybrid systems have also been motivated by a battery's unique ability to qualify for the federal investment tax credit (ITC) (Elgqvist, Anderson, and Settle 2018); however, the *Inflation Reduction Act* (U.S. Congress 2022) introduced an ITC for standalone storage as well, which will likely influence the relative competitiveness of standalone and coupled battery projects.[6] Finally, in market regions where PV systems already provide a significant share of total generation (e.g., the California Independent System Operator region), battery storage is also seen as a prominent strategy for combatting the declining marginal value of standalone PV (Sivaram and Kann 2016).

The characteristics of proposed PVB projects are not well known from interconnection queue data (Bolinger et al. 2021). A PVB project can be classified as a "colocated resource," in which the technologies share a point of interconnection, but each resource operates (and bids into markets) in a largely independent fashion. Alternatively, in a fully integrated PVB hybrid, the technologies share a point of interconnection, are physically coupled, and share a control system, such that the asset operates (and bids into markets) as a single resource (Murphy, Schleifer, and Eurek 2021; Ahlstrom et al. 2021). PVB hybrid projects can further be characterized based on (a) the relative sizing of the PV, battery, and inverter components, and (b) the nature of coupling, including whether they use a shared inverter ("DC coupled") or separate PV and battery inverters ("AC coupled").

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[5] In CAISO, developers can add batteries to existing (proposed or operating) PV projects without having to initiate a new interconnection request, as long as doing so does not require additional interconnection service capacity. This allows developers to add battery storage "more quickly and at a lower cost than establishing new and separate interconnections for the storage units" (CAISO 2021).

[6] The Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

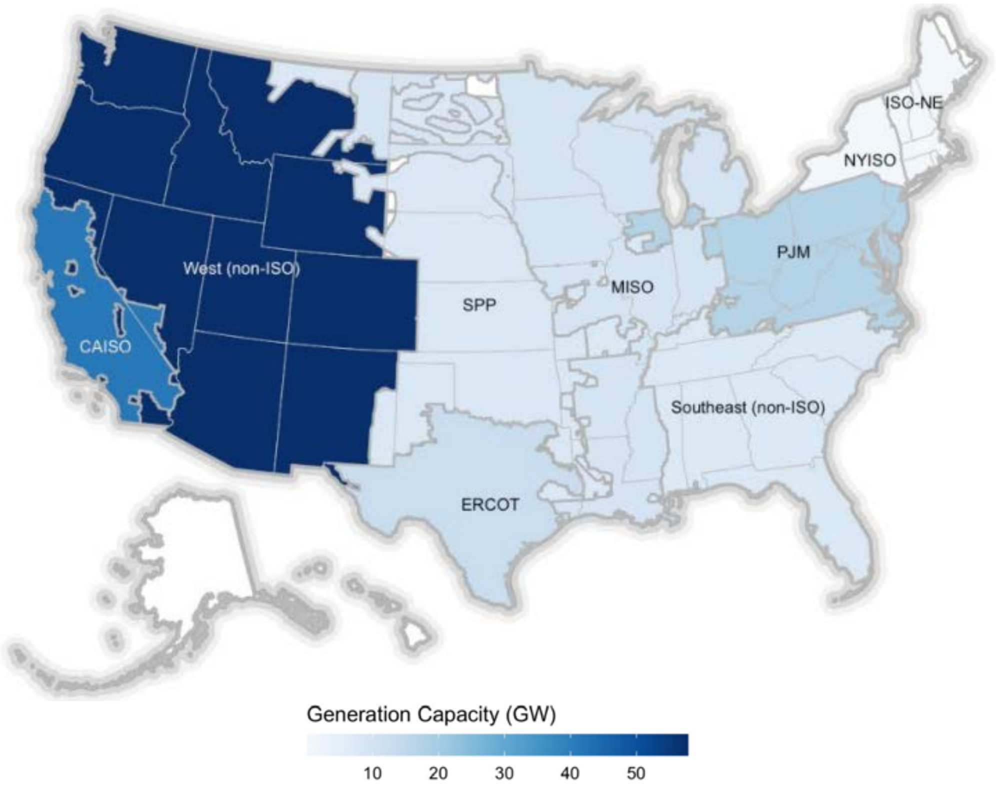

Figure 1. A regional breakdown of solar-plus-storage capacity in U.S. interconnection queues as of the end of 2020

Figure source: Bolinger et al. (2021)

Despite the apparent industry interest in coupled PVB projects on the U.S. bulk power system, studies of their deployment potential using capacity expansion models remain limited. The U.S. Energy Information Administration's National Energy Modeling System includes a PVB representation. In addition, Eurek et al. (2021) recently documented a methodology for representing PVB hybrids in the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) model, which involves exogenously defined PVB hybrid configurations with a shared bidirectional inverter. However, we are aware of only limited analysis of national-scale deployment potential for utility-scale PVB hybrids. Eurek et al. (2021) presented a simple analysis of the ReEDS input assumptions that have the greatest impact on PVB hybrid deployment. Analysis results that included PVB hybrid deployment in the same model have been presented for wide-ranging policy and technology scenarios (Cole et al. 2021), but that study did not include detailed discussion of the role of PVB hybrids on the future U.S. bulk power system.

This report investigates the role of PVB hybrids on the U.S. bulk power system under previously established scenarios that were designed to explore the role of solar in decarbonizing U.S. electricity supply. In particular, we explore two of the core scenarios from the U.S. Department of Energy's (DOE) 2021 *Solar Futures Study* (DOE 2021)*:*

- The Reference scenario outlines a business-as-usual future, which includes existing state and federal clean energy policies (as of 2021) but lacks a comprehensive effort to decarbonize the grid.

- The Decarbonization (Decarb) scenario assumes that policies drive a 95% reduction (from 2005 levels) in the grid's carbon dioxide emissions by 2035 and a 100% reduction by 2050. This scenario assumes more aggressive cost-reduction projections, but it uses standard future projections for electricity demand.

This report recreates these two core scenarios from the *Solar Futures Study*[7] and explores whether the availability of PVB hybrids could materially alter the key outcomes and findings of that study. Moreover, it makes several original contributions to the PVB hybrid literature. First, we present the results of a parameter sweep that was designed to identify the PVB hybrid configurations that offer the greatest net value to the U.S. bulk power system across a range of technology advancement and policy assumptions. Second, we present the first analysis in which multiple PVB hybrid configurations are allowed to compete against one another in ReEDS for market share; this allows us to evaluate whether the highest-net-value configuration evolves over time and across a range of policy and technology assumptions. Finally, we quantify the extent to which PVB hybridization influences total PV deployment, PV's share of total generation, the role of battery technologies, transmission expansion, and bulk power system costs under the explored *Solar Futures Study* scenarios.

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[7] The third core scenario from the *Solar Futures Study* was the "Decarbonization with Electrification (Decarb+E)" scenario, which included large-scale electrification of end uses and allowed for exploring the potential for solar to contribute to a future with more complete decarbonization of the U.S. energy system. We do not explore this third core scenario in the present report.

2 Methods

2.1 Overview of the ReEDS Capacity Expansion Model

ReEDS is a national-scale capacity expansion model that optimizes the deployment and operation of bulk power system assets through 2050 (Ho et al. 2021). ReEDS takes a central decision-making approach that minimizes total bulk power system costs, subject to meeting physical and policy constraints. It simultaneously considers generation, storage, and transmission when making system buildout and operational decisions.

The ReEDS model includes high spatial resolution, which is defined by 134 modeled balancing areas and 356 renewable energy resource regions. The trading of energy and capacity services between modeled balancing areas is facilitated by inter-regional transmission lines. The 356 renewable energy resource regions include resource supply curves, which limit the amount of capacity that can be built in each region and capture the cost of connecting remote resources to existing transmission capacity. ReEDS further represents the impacts of growing deployment of variable renewable energy resources, including (1) their curtailment, (2) their contributions to planning reserve margin requirements, and (3) the need to hold additional operating reserves.

Finally, ReEDS is temporally resolved into 17 time-slices that are blocks of non-chronological aggregate hours for an average day within each of the four seasons.[8] For each solution interval from 2010 to 2050, ReEDS dispatches all generation and storage in each of these 17 time-slices to capture seasonal and diurnal electricity load and renewable generation profiles.

2.2 PVB Hybrid Representation in ReEDS

While the architecture of ReEDS inherently captures many of the interactions of PV and storage as independent systems (Cole et al. 2018; Frazier et al. 2020; Cole et al. 2020), modifications were needed to represent synergies that could be enabled through hybridization. Eurek et al. (2021) documented the ReEDS representation of a loosely DC-coupled PVB hybrid system; this system involves a single, bidirectional inverter that is shared by both the PV and battery components, thus allowing the battery component to be charged with energy from the coupled PV and the grid. This technology option in ReEDS should be thought of as a fully integrated hybrid system that, compared to separate PV and battery projects, involves:

- Lower capital costs, as described below and by Feldman et al. (2021);
- The ability to capture and use more generation from the PV component due to oversizing of the PV arrays and increased charging efficiency (Schleifer et al. 2022);
- A joint capacity credit and greater localized contribution to resource adequacy; and
- The battery component's ability to qualify for the federal ITC[9] (Elgqvist, Anderson, and Settle 2018).

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[8] Each day comprises four time-slices, including morning, afternoon, evening, and night. Additionally, one peak time-slice represents the highest 40 hours of load during the year.

[9] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, the battery in a PVB project could qualify for the federal

The ReEDS PVB hybrid technology may not represent the full set of value propositions (or cost savings) that underpin the recent explosion in industry interest in PVB hybrids (Ahlstrom et al. 2021). In addition, the temporal resolution of ReEDS does not allow for full consideration of price volatility, which varies significantly over the course of the year and across transmission nodes and influences a PVB hybrid's value proposition (Gorman et al. 2022).

The loosely DC-coupled PVB hybrid technology in ReEDS is defined by an inverter loading ratio (ILR) for the PV component (or its DC-to-AC ratio), a battery-to-inverter ratio (BIR, based on power rating), and a battery duration. The ILR defines the degree of oversizing of the PV arrays relative to the inverter, which further defines the time series of PV generation. For the time periods in which PV generation exceeds the inverter capacity, the generation that would otherwise be clipped can be used to charge the DC-coupled battery. This pathway for charging the coupled battery is assumed to be slightly more efficient (87% roundtrip efficiency) compared to charging from the grid (85% roundtrip efficiency) (Eurek et al. 2021).

While many of the details of the ReEDS PVB hybrid technology can be found in Eurek et al. (2021), the technology representation in the present study involves several updates (Table 1) that were implemented to facilitate exploration of our scenario matrix. For example, we define and compete multiple PVB hybrid configurations in the model's least-cost optimization, which requires four model updates to allow for configuration-dependent representations. First, we use explicit time series profiles for the ILR-dependent amount of clipped energy that can be recovered and used by the coupled battery.

Second, we represent the cost impacts associated with hybridization based on the shared inverter cost (taken as a fixed 5% fraction of the standalone PV $\$/W_{AC}$ cost) and a fixed balance of system cost (taken as a fixed $\$0.0623/W_{AC}$). In practice, this means that PVB hybrid configurations with larger degrees of oversizing (i.e., larger ILRs or BIRs) have a smaller percentage cost savings (applied to the sum of standalone PV and battery systems), since the shared AC costs make up a smaller share of total capital costs (compared to PVB hybrid configurations with smaller degrees of oversizing).

Third, we adopt a modified representation of the coupled battery component's ability to capture energy arbitrage value (Table 1). Previous versions of ReEDS assigned an energy-price arbitrage value to batteries based on an hourly price-taker simulation that was performed between ReEDS solve years. Analysis of scenarios with widespread deployment of PV and battery technologies suggested that this price-taker approximation did not adequately account for the declining marginal value of batteries in the context of rapid battery deployment, and thus over-incentivized investments in battery capacity. We therefore remove the arbitrage credit for both standalone and coupled batteries, but we maintain the curtailment-reduction benefit associated with charging batteries directly from renewable energy. This update was chosen to avoid overestimating the

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ITC if 75%–100% of its stored energy is derived from the coupled PV during the first 5 years of operation, where the rate of incentive scales based on this percentage. The *Inflation Reduction Act* (U.S. Congress 2022) expanded ITC eligibility to standalone storage projects which will likely influence the relative competitiveness of standalone and coupled battery projects. However, the Internal Revenue Service has not issued guidance clarifying how the tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

marginal value of batteries under the decarbonization trajectories defined in the emissions reduction requirement from the *Solar Futures Study*.

Table 1. Previously Published and Updated Representation of PVB Hybrids in the ReEDS Model

Model Feature	Representation in Eurek et al. (2021)	Updated Representation for the Present Study
PVB Component Sizing and Number of Available Configurations	A single configuration with an ILR of 1.3, a BIR of 0.65, and a battery duration of 4 hr	Two configurations that represent near-term and forward-looking use cases for PVB hybrids (Table 3)
PV Capacity Factor in the Hybrid Configuration	AC capacity factor adjustment of +0.2%	Explicit time series profiles for clipped energy that can be recovered and used for a given PVB hybrid configuration (ILR)
Cost Impacts Associated with Hybridization	PVB hybrid capital costs were reduced by 5% relative to the sum of capital costs for separate PV and battery systems	PVB hybrid capital costs are reduced based on the cost of a shared inverter and other balance-of-system components, such that the percentage savings varies by configuration
Battery Qualification for the ITC	75% of the ITC value (sensitivity)	100% of the ITC value[10]
Battery Hourly Arbitrage Value	The coupled battery received an hourly arbitrage value, consistent with an independent battery technology	Hourly arbitrage value disabled for both the independent and coupled (PVB) battery technologies for all years

Fourth, we adopt a modified representation of the coupled battery component's qualification for the federal ITC (Table 1). We now assume that the battery component in a PVB hybrid receives 100% of the ITC value, following the incentive schedule prior to the passing of the *Inflation Reduction Act* (U.S. Congress 2022) (i.e., the ITC value steps down to 10% for projects that commence construction after December 31, 2023, or are placed in service after December 31, 2025). Allowing the battery component in a PVB hybrid to receive 100% of the ITC value reflects input from industry partners but has a relatively modest impact on model solution.

2.3 Scenario Matrix

As previously described, the scenarios explored in this report are rooted in two of the core scenarios from the *Solar Futures Study* (DOE 2021). In particular, we replicate the Reference and Decarb scenario settings (Table 2) in a more recent version of the ReEDS model, with the following modifications:

- For the "Advanced cost reductions" setting, we modify cost and performance assumptions for only PV and battery technologies (as opposed to adopting advanced cost

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[10] Based on existing policy prior to the signing of the *Inflation Reduction Act* (U.S. Congress 2022), a coupled battery would qualify for 100% of the ITC value if all of its stored energy were derived from the coupled PV in its first 5 years of operations.

reductions for all renewable energy generation and storage technology options); this modification is designed to maximize insights related to PVB hybridization.

- We run and report additional scenarios considering aggressive cost-reduction trajectories (LowCost) and supportive policies (Decarb-ModCost) in isolation.
- We perform two versions of each core scenario, both without (No Hybrids) and with (With Hybrids) the PVB hybrid technology option enabled in ReEDS; the former version represents a simple update to the core scenarios from the *Solar Futures Study* (including recent model enhancements), and comparison between the No Hybrids and With Hybrids versions of a given scenario allows for isolating the impacts of hybridization.
- We do not explore the third core scenario from the *Solar Futures Study*—the Decarb+E scenario—which envisioned decarbonization of the broader U.S. energy system through large-scale electrification of buildings, transportation, and industry. We do not explore the Decarb+E scenario in this study because of challenges associated with disentangling the effects of increasing demand-side and supply-side flexibility.

Altogether, the bullets above lead to the scenario matrix presented in Table 2.

Table 2. Scenario Matrix and Definitions for the Present Study

Scenario Name	PV and Battery Costs[b]	Power Sector Decarbonization Policies	Electricity Demand[c]	PVB Hybrid[d]
Reference[a]	Moderate reductions	Existing policies as of June 2021	Default	Disabled in ReEDS (No Hybrids)
LowCost	Advanced reductions			
Decarb-ModCost	Moderate reductions	95% reduction by 2035, 100% by 2050		
Decarb[a]	Advanced reductions			
Reference With Hybrids	Moderate reductions	Existing policies as of June 2021		Enabled in ReEDS (With Hybrids)
LowCost With Hybrids	Advanced reductions			
Decarb-ModCost With Hybrids	Moderate reductions	95% reduction by 2035, 100% by 2050		
Decarb With Hybrids	Advanced reductions			

[a] These scenarios largely replicate settings from the core scenarios of the *Solar Futures Study* (DOE 2021).

[b] Moderate (Advanced) technology costs follow Mid Case (Advanced) assumptions from the 2021 Annual Technology Baseline (NREL 2021).

[c] Default electricity demand assumptions are based on the Mid Case from the 2021 Standard Scenarios (Cole et al. 2021).

[d] For scenarios in which the PVB hybrid technology is enabled, the parameterization follows that presented in Table 3.

The With Hybrids version of each scenario involves the inclusion of two candidate PVB hybrid configurations. Limited data exist for the PVB hybrid configurations that have been (or are likely to be) deployed on the U.S. bulk power system (Bolinger et al. 2021); moreover, the highest-net-value PVB hybrid configuration in the future is highly uncertain and likely depends on many factors (Crespo Montanes et al. 2022). To identify candidate PVB hybrid configurations, we performed a parameter sweep in which we systematically varied the parameters that define a single PVB hybrid configuration (ILR and BIR) for each of the scenario settings presented in Table 2, assuming a 4-hr duration battery. Based on the full suite of scenarios and ILR and BIR combinations explored, we identified two configurations that resulted in the greatest PVB hybrid deployment and the lowest bulk power system costs (based on the ReEDS objective function). Interestingly, these two configurations (far right column of Table 3) represent very different use cases for PVB hybrids.

Table 3. Explored and Selected PVB Hybrid Configurations for This Study

Parameter	Values Explored	Selected Configurations	
		Low-ILR PVB	High-ILR PVB
ILR	1.4, 1.6, 1.8, 2.0, 2.2	1.4	2.2
BIR	0.25, 0.5, 1.0	0.25	0.5

The Low-ILR PVB hybrid configuration (Table 3) represents one in which the PV component is similar to what would be deployed in a standalone PV project. Given the relatively small ILR in this configuration, a small battery size is sufficient for recovering otherwise clipped energy. The Low-ILR PVB hybrid configuration's competitiveness is primarily rooted in the potential for modest cost savings (due to shared inverter and balance of system costs) and the battery component's ability to qualify for the ITC, particularly in regions where standalone PV and storage projects are already part of the least-cost solution.[11]

The High-ILR PVB hybrid configuration (Table 3) represents a very different hybrid use case, in which significant amounts of otherwise-clipped energy can be funneled into the coupled battery and used during high-value (or just non-daylight) periods. For all scenario settings explored, the PVB hybrid deployment and system cost impacts were similar under configurations that involved an ILR of 2.2 and BIRs of both 0.25 and 0.5. We opted for the larger battery size to explore a greater diversity of configuration options. We cannot comment on the competitiveness of PVB hybrid configurations that fall outside of our defined parameter sweep (e.g., ILR < 1.4 and ILR > 2.2); it is possible that smaller or larger ILR values would further increase the competitiveness of loosely DC-coupled PVB hybrids in ReEDS.

In the With Hybrids versions of each scenario (Table 2), both PVB hybrid configurations are simultaneously enabled and allowed to compete with one another and with other generation and storage options in ReEDS. In the No Hybrids versions of each scenario, the PVB hybrid technology is disabled, and all PV and battery deployment takes the form of standalone systems.

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[11] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, only batteries in a PVB project could qualify for the federal ITC. The *Inflation Reduction Act* expanded ITC eligibility to standalone storage projects, which will likely influence the relative competitiveness of standalone and coupled battery projects. However, the Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

3 Results

The impacts of hybridization under the explored *Solar Futures Study* scenario definitions are detailed through the presentation of AC-rated and DC-rated capacities and gigawatt-hours (GWh) of generation for PVB hybrids. This combination of results provides insights regarding the total deployment and efficiencies associated with different PVB hybrid configurations, as well as interactions with other standalone generation and energy storage projects. In addition, we explore the impacts of PVB hybridization on other output results, including transmission expansion and bulk power system costs. Throughout this section, the presentation of results emphasizes comparison between the No Hybrids and With Hybrids versions of each scenario, which helps to isolate the impacts of hybridization.

3.1 Capacity Mix

Figure 2 presents the least-cost mix of generation and storage capacity in select years for the No Hybrids versions of each scenario. Comparing across scenario definitions (and consistent with previous analyses), we find that adopting advanced technology cost assumptions for PV and battery technologies (LowCost) drives an increase in their share of the capacity mix, typically at the expense of land-based wind capacity. A power sector decarbonization policy drives the replacement of fossil generation capacity with additional solar, wind, battery, and renewable-based combustion turbine capacity, the relative shares of which vary based on technology cost assumptions (Decarb-ModCost versus Decarb).

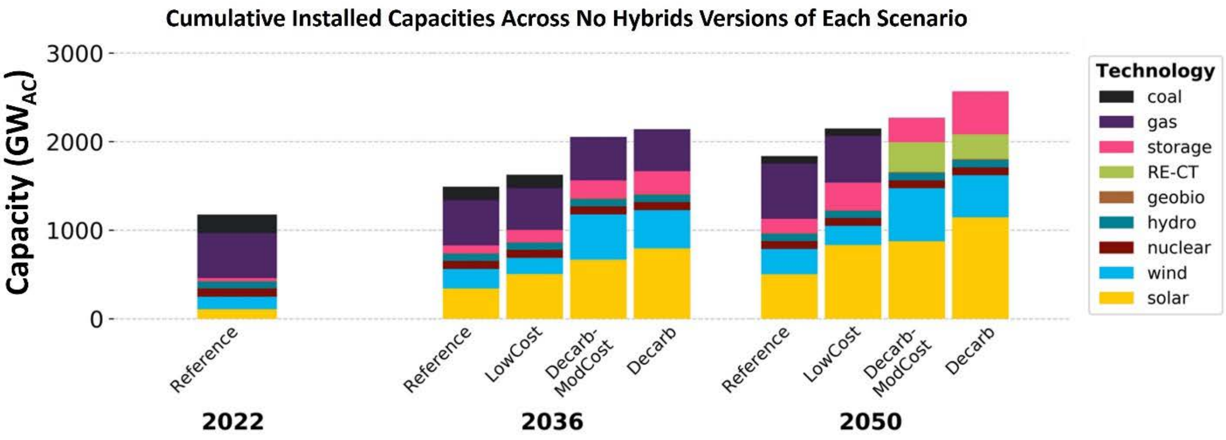

Figure 2. Capacity mix results from ReEDS for select years, based on the No Hybrids versions of all scenarios explored

To isolate the effects of enabling the PVB hybrid configurations in ReEDS, Figure 3 presents changes in the capacity mix between the No Hybrids (Figure 2) and With Hybrids versions of each scenario. Across all scenarios explored, the most visible tradeoff is between the PVB hybrid and standalone (or independent) PV technologies.

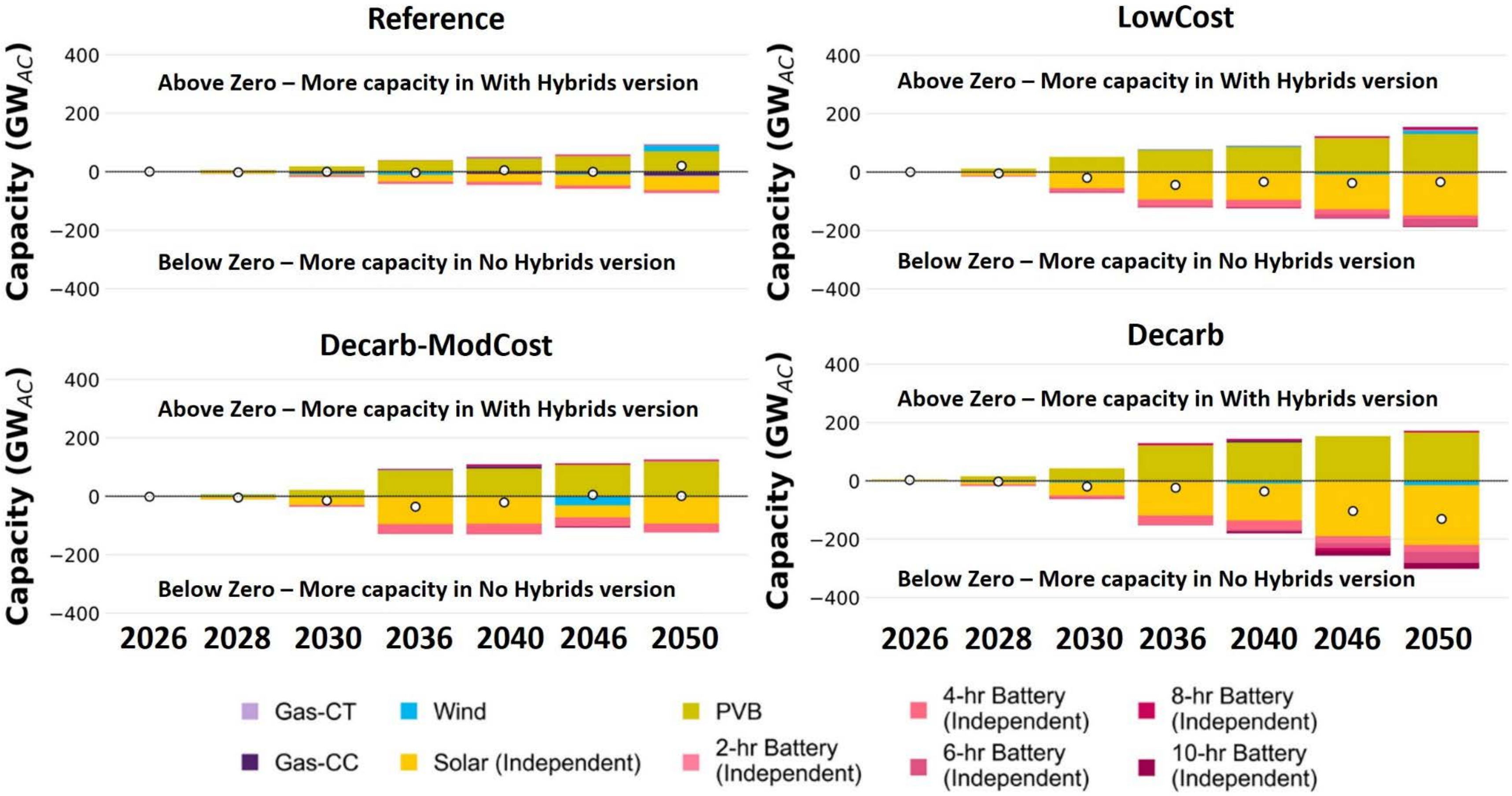

Figure 3. The change in cumulative installed capacity between the With Hybrids and No Hybrids versions of our Reference (top-left), LowCost (top-right), Decarb-ModCost (bottom-left), and Decarb (bottom-right) scenarios, with white circles indicating net changes in total installed capacity (based on the AC rating)

For scenarios with low-cost PV and battery technology assumptions (LowCost and Decarb), the tradeoff between the PVB hybrid and standalone PV capacities occurs on a largely one-for-one basis; this is because PV and battery technologies are among the least-cost options regardless of whether they can be deployed together as hybrids. For scenarios that involve default technology cost assumptions (Reference and Decarb-ModCost), the cost savings associated with our PVB hybrid configurations lead to additional forms of competition among resources—including modest impacts on wind and natural gas technologies—but the most prominent competition continues to be between hybrid and standalone PV capacities. Changes in total installed capacity (white circles in Figure 3) are explained by both the relative deployments of the Low-ILR and High-ILR PVB hybrid configurations *and* reporting of coupled battery capacity, as discussed in the remainder of this subsection.

3.1.1 PVB Hybrid Deployment

Across all scenarios explored, the economic deployment of both the Low-ILR and High-ILR PVB hybrid configurations begins in the late 2020s and continues throughout the analysis period. Cumulative PVB hybrid deployment and the relative shares of each configuration vary strongly based on technology cost and policy assumptions. Figure 4 presents cumulative deployment over time for our Low-ILR (solid lines) and High-ILR (dashed lines) PVB hybrid configurations across all scenarios explored, based on the AC (or inverter) rating (top row) and the DC (or PV array) rating (bottom row). Comparison across panels reveals the isolated (LowCost and Decarb-ModCost) and combined (Decarb) effects of technology cost and policy assumptions on the magnitude and mix of PVB hybrid deployment.

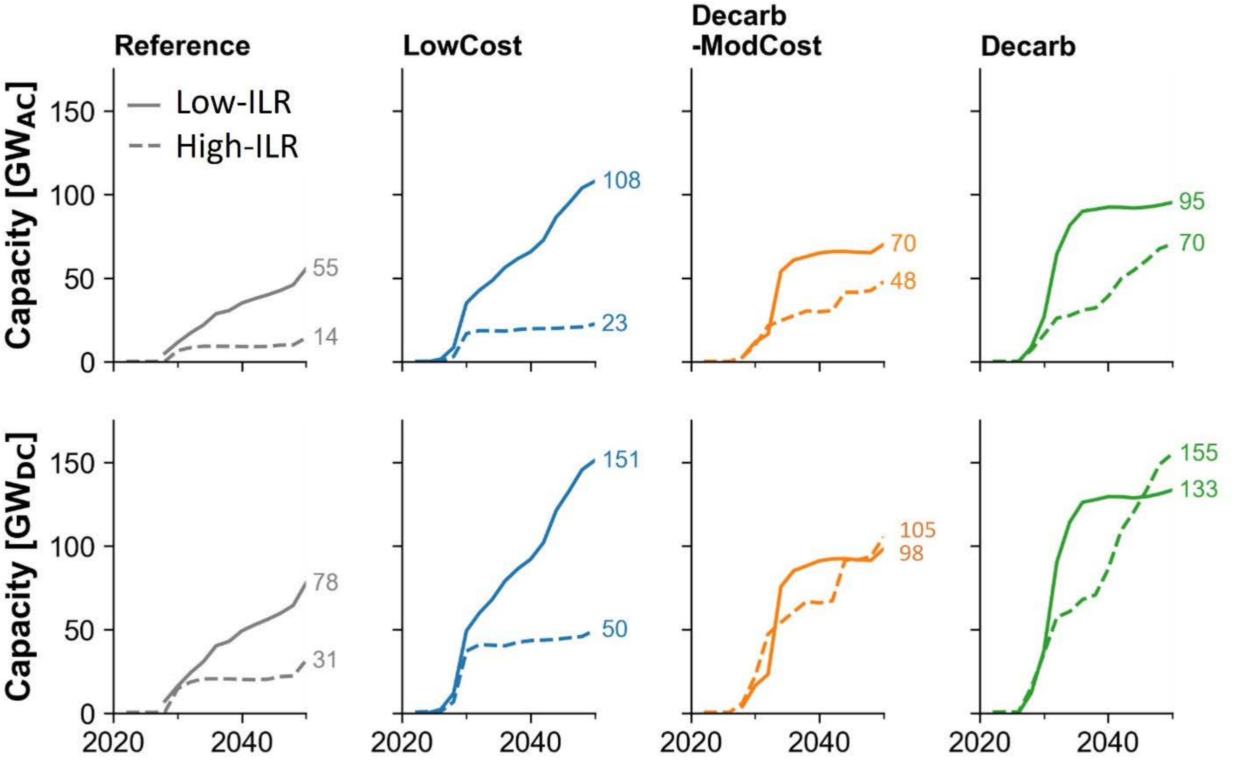

Figure 4. Cumulative installed PVB hybrid capacity over time across all scenarios

In the Reference scenario, most hybrid deployment takes the form of the Low-ILR PVB configuration. Deployment of this configuration grows steadily over time and is concentrated in regions with relatively high solar resources and demand for electricity (e.g., California, Texas, and Florida). The High-ILR PVB hybrid configuration experiences more modest deployment in the Reference scenario (Figure 4), reaching 14 GW_{AC} (31 GW_{DC}) by 2050. In turn, the Low-ILR PVB hybrid configuration accounts for 80% (71%) of PVB hybrid capacity based on the AC or inverter rating (DC rating) in 2050, where the different values reflect the significantly oversized PV array in the High-ILR PVB hybrid configuration. Given its similarities with standalone PV, the widespread deployment of the Low-ILR PVB hybrid configuration reflects the fact that deploying PV and battery together has the system cost benefits of lower capital costs (compared to separate PV and battery projects) and the battery component's eligibility for the ITC.[12]

The isolated effect of assuming aggressive cost-reduction trajectories for PV and battery technologies is an increase in the deployments of both the Low-ILR and High-ILR PVB hybrid configurations. In turn, installed PVB hybrid capacity in 2050 under the LowCost scenario is nearly double that observed in the Reference scenario (Figure 4). The Low-ILR PVB hybrid configuration continues to make up most of the total PVB hybrid capacity—83% based on the AC rating and 75% based on the DC rating—and its deployment expands into mid-latitude states in the Eastern Interconnection.

The implementation of a required emissions reduction target for the U.S. bulk power system drives an increase in the competitiveness of the more forward-looking High-ILR PVB hybrid configuration. Under the Decarb-ModCost and Decarb scenarios, deployment of the High-ILR PVB hybrid configuration grows in the near term and accelerates as the policy trajectory approaches 100% power sector decarbonization (during the 2040s). In a fully decarbonized grid, cumulative installed capacities of the High-ILR PVB hybrid configuration remain below that of the Low-ILR PVB hybrid configuration, based on the AC rating (top row of Figure 4). However, when accounting for PV array oversizing, the High-ILR PVB hybrid configuration accounts for the majority (52%–54%) of the DC-rated PVB capacity in 2050 (bottom row of Figure 4).

The deployment of coupled 4-hr battery capacity generally follows the discussion above, but it is further modified by the different BIRs: the coupled battery is 25% of the corresponding AC-rated capacity in the Low-ILR PVB hybrid configuration, compared to 50% in the High-ILR configuration. Combining these BIRs with the AC-rated PVB hybrid deployment (Figure 4) yields the coupled battery capacities presented in Table 4. The High-ILR PVB hybrid configuration hosts roughly one-third of total coupled battery capacity in the scenarios without a decarbonization policy, and it hosts the majority (58% and 60%) of coupled battery capacity in the scenarios with a decarbonization policy. However, cumulative installed capacity of coupled

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[12] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, only batteries in a PVB project could qualify for the federal ITC, and only if 75%–100% of their stored energy were derived from the coupled PV during the first 5 years of operation. The *Inflation Reduction Act* expanded ITC eligibility to standalone storage projects which will likely influence the relative competitiveness of standalone and coupled battery projects. However, the Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

batteries must be considered within the context of changes to the installed capacities of standalone batteries (of varying duration), which is discussed in more detail in Section 3.1.3.

Table 4. Cumulative Installed Capacity of Coupled Batteries in PVB Hybrid Configurations in 2050

	Coupled 4-hr Battery Capacity in the Low-ILR PVB Hybrid Configuration	Coupled 4-hr Battery Capacity in the High-ILR PVB Hybrid Configuration
Reference With Hybrids	55 GWh	29 GWh
LowCost With Hybrids	108 GWh	45 GWh
Decarb-ModCost With Hybrids	70 GWh	96 GWh
Decarb With Hybrids	95 GWh	141 GWh

3.1.2 Total PV Deployment

To provide context for the total PVB hybrid deployment results, Figure 5 presents a breakdown of PV capacities across scenarios, differentiating between hybrid and standalone capacity. The results presented in Figure 5 span all PV technology classes in ReEDS, including utility-scale PV[13], distributed (e.g., rooftop) PV, and PVB hybrids. The left panel presents AC-rated (or inverter) capacity, whereas the right panel presents DC-rated capacity to illustrate the oversizing of the PV arrays in the High-ILR PVB hybrid configuration. Comparison between neighboring bars reveals the impacts of enabling the PVB hybrid configurations within the ReEDS optimization on total installed PV capacity in 2050. Comparison of the green bars to the total bar height indicates the share of PV capacity that adopts a PVB hybrid configuration.

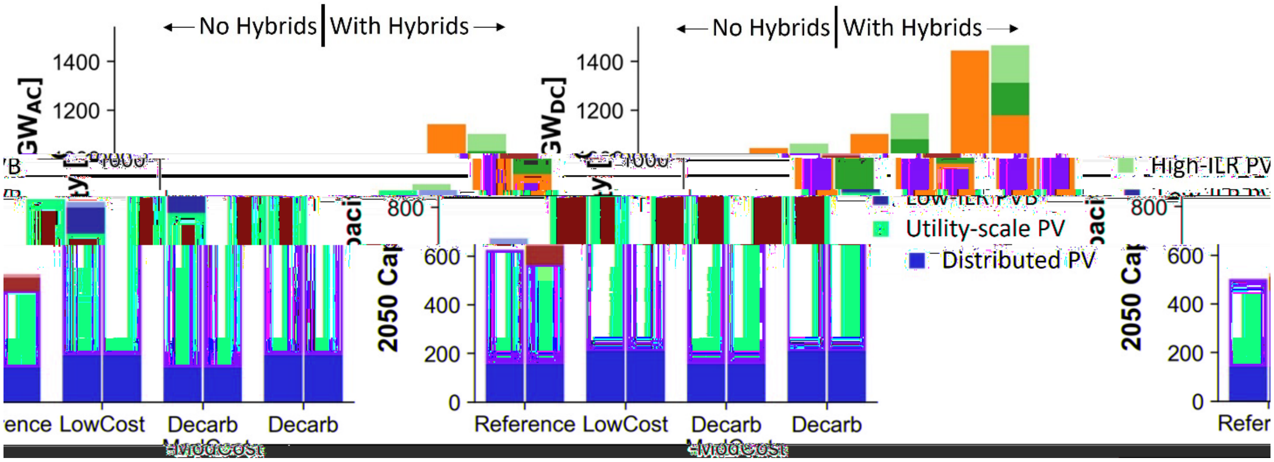

Figure 5. Installed PV capacity in 2050 for all No Hybrids (left bar) and With Hybrids (right bar) version of each scenario, including AC-rated (left panel) and DC-rated (right panel) capacities

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[13] Orange bars include both the utility-scale PV and distribution-sited utility-scale PV technologies from ReEDS.

Considering the DC-rated PV capacity first, the right panel of Figure 5 reveals that enabling the PVB hybrid configurations increases the number of deployed PV panels. The availability of the PVB hybrid configurations leads to the greatest increases in total installed DC-rated PV capacity under scenarios with default cost and performance assumptions, including 49 GW_{DC} and 83 GW_{DC} increases under the Reference and Decarb-ModCost scenario definitions (respectively). More modest increases are observed under scenarios that involve low-cost assumptions for PV and battery technologies, because standalone PV and battery technologies were already part of the least-cost solution. The PVB hybrid configurations' share of total DC-rated PV capacity in 2050 is comparable across scenarios and ranges from 16% to 20%.

Considering the AC-rated PV capacity, the left panel of Figure 5 indicates that the impacts of enabling the PVB hybrid configurations similarly vary based on the assumed PV and battery cost trajectories. Under default technology cost assumptions, PVB hybrid configurations capture 13% of the AC-rated PV capacities in 2050 (Figure 5). In addition, the availability of PVB hybrids drives a 3%–5% increase in total AC-rated PV capacity in 2050, which reflects the greater impact of cost savings associated with the hybrid configurations (i.e., shared component and balance-of-system costs) under default technology cost assumptions.

In scenarios that assume aggressive cost reductions for PV and battery technologies, PVB hybrids capture a slightly larger (15%–16%) share of AC-rated PV capacity in 2050, but their availability drives modest (1%–3%) *reductions* in the AC-rated PV capacities in 2050 (compared to the corresponding No Hybrids versions). The total AC-rated PV capacities in 2050 for our LowCost and Decarb scenarios are comparable to those reported in the *Solar Futures Study* (869 GW and 1050 GW, respectively) in both the No Hybrids and With Hybrids versions. Moreover, these trends are related since the AC-rated PV capacities in Figure 5 mask the greater oversizing of PV arrays in our PVB hybrid configurations (Table 3).

Finally, we observe regional variation in the deployment patterns of standalone and hybrid PV systems. Figure 6 demonstrates this regional variation for the Decarb scenario via state-level capacities for standalone utility-scale PV (left), the Low-ILR PVB hybrid (middle), and the High-ILR PVB hybrid (right) technologies in 2050. The common color scale across technologies illustrates that standalone utility-scale PV continues to make up the majority of installed PV capacity; this standalone PV deployment is concentrated in regions with relatively high-solar-resource quality and demand for electricity (e.g., California, Texas, and the South-Atlantic and Mid-Atlantic regions), but it extends into higher latitudes by 2050 under the Decarb scenario.

PVB hybrid deployment is more modest but still visible on this scale, with similar levels of deployment as standalone utility-scale PV in select locations. Among the candidate hybrid systems, the Low-ILR PVB configuration dominates in the Texas Interconnection, whereas the High-ILR PVB configuration makes up the majority of PVB deployment in the Western Interconnection. Outside of Texas, state-level results should be interpreted as regional trends, since balancing area-level capital cost multipliers can have a strong influence on deployment of a given technology in one state versus a neighboring state.

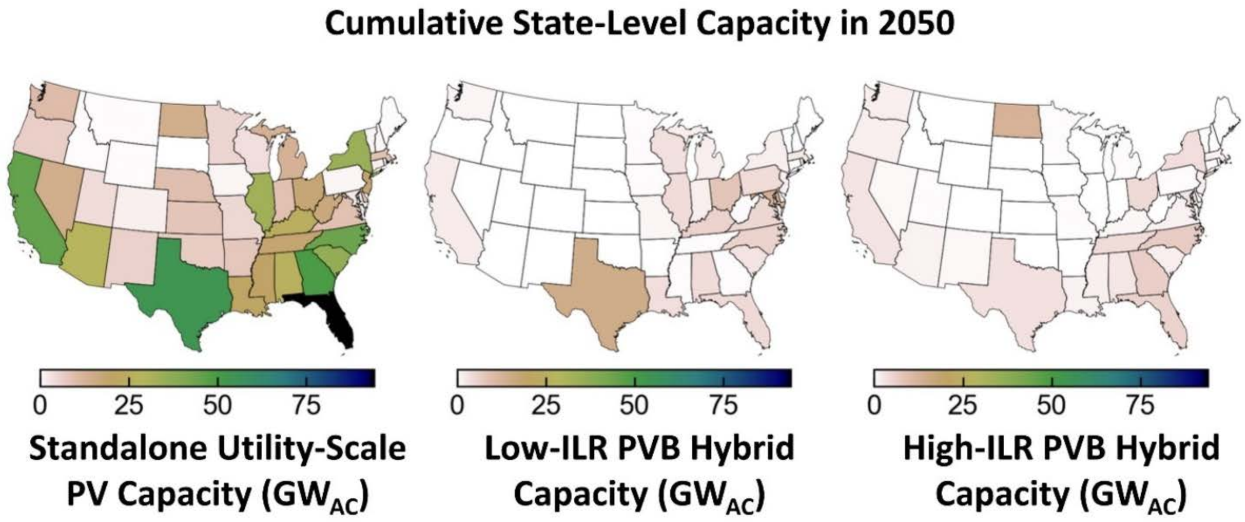

Figure 6. Installed capacity in 2050 for utility-scale PV (left), the Low-ILR PVB hybrid (middle), and the High-ILR PVB hybrid (right) configurations under the Decarb scenario

Both PVB hybrid configurations experience widespread deployment in the Eastern Interconnection, albeit with different regional patterns. The Low-ILR PVB hybrid configuration experiences the greatest deployment in mid-latitude states, including those that border the load centers of New England. Deployment of the High-ILR PVB hybrid configuration is more prevalent in the South Atlantic region, which may reflect that this region tends to be winter peaking, so the High-ILR PVB hybrid configuration can better contribute to the planning reserve margin. Deployment of the High-ILR PVB hybrid configuration in the northernmost latitudes likely reflects its greater output potential in this relatively low-solar-resource region.

3.1.3 Total Battery Deployment

The availability of PVB hybrid configurations also has a sizable impact on the amount and mix of battery capacity, in terms of both power (GW_{DC}) and energy (GWh) ratings (Figure 7). Introducing the PVB hybrid configurations systematically drives an increase in the battery type included in our exogenously defined PVB hybrid configurations (i.e., 4-hr duration batteries). This hybrid-induced increase in installed 4-hr battery capacity is illustrated by the sum of coupled (green) and standalone (light blue) capacity in Figure 7, and it is driven by the coupled batteries' ability to reduce component and balance-of-system costs and qualify for the federal ITC[14] in the hybrid configurations. The magnitude of impact depends most strongly on technology cost assumptions, which define the percentage savings associated with these drivers.

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[14] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, only batteries in a PVB project could qualify for the federal ITC. The *Inflation Reduction Act* expanded ITC eligibility to standalone storage projects which will likely influence the relative competitiveness of standalone and coupled battery projects. However, the Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

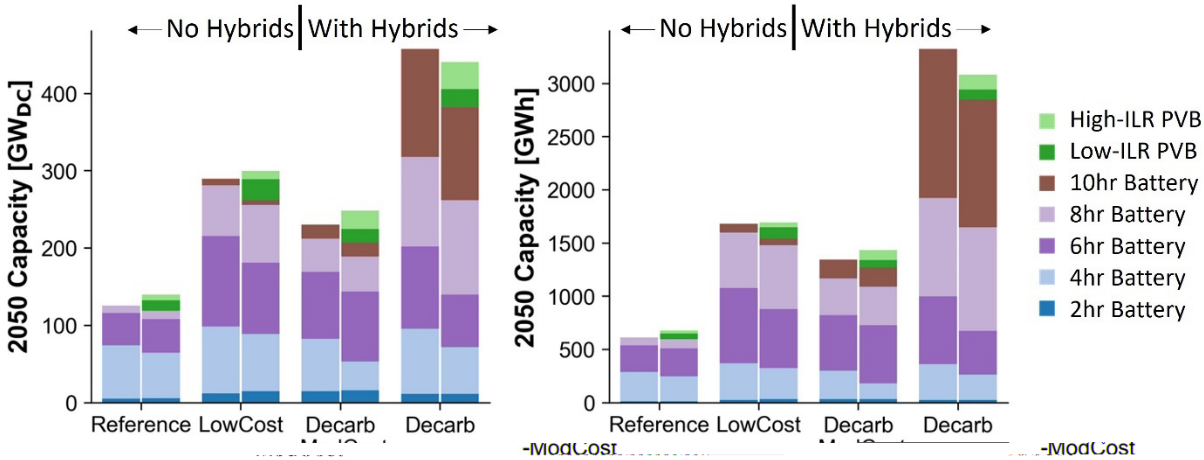

Figure 7. Total installed battery capacity for all scenarios (top) and the difference between With Hybrids and No Hybrids versions of each scenario (bottom) in 2050

Under default cost assumptions (Reference and Decarb-ModCost scenarios), introducing the PVB hybrid configurations drives a 15%–16% increase in 4-hr battery capacity. When combined with modest increases in longer-duration (6-hr to 10-hr) batteries (Figure 7), this result indicates that the introduction of our PVB hybrid configurations drives a net increase in the role of battery technologies under default cost assumptions, considering both power and energy ratings.

Scenarios that involve aggressive cost-reduction trajectories for PV and battery technologies indicate more complex interactions among different battery durations. Under our LowCost and Decarb scenarios, introducing the PVB hybrid configurations drives the pronounced expansion of 4-hr duration batteries, considering the sum of coupled (green) and standalone (light blue) batteries. On an energy (GWh) basis, this hybrid-induced expansion amounts to 29% and 10% increases in 4-hr battery capacity between the No Hybrids and With Hybrids versions of the LowCost and Decarb scenarios (respectively). However, this expansion in 4-hr battery capacity is largely or entirely offset by reductions in longer-duration batteries. Therefore, on an energy basis, the availability of PVB hybrid configurations has a more modest impact on the role of battery technologies under scenarios with low-cost PV and battery technology assumptions.

3.2 Generation Mix

To understand how the availability of PVB hybrid configurations impacts solar PV's share of U.S. electricity supply in 2050, we report the share of total generation that is provided by PV technologies (including standalone and hybrid, as well as distribution-sited and utility-scale projects). Consistent with the original *Solar Futures Study,* we find that the role of PV[15] in the future U.S. electricity mix depends strongly on the underlying scenario definitions (Table 5):

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[15] Note that the *Solar Futures Study* results typically include the joint contributions of solar PV and concentrating solar power technologies. We report only PV technology results here, due to the emphasis on PVB hybrid systems. The share of total generation provided by *solar* technologies is typically within 1 percentage point of the share of total generation provided by *PV* technologies. The one exception is the Decarb-ModCost scenario, in which concentrating solar power provides approximately 4% of total U.S. electricity generation in 2050 (under both the No Hybrids and With Hybrids versions).

comparing results from the Reference and Decarb scenario definitions reveals a 26 percentage point difference in PV's share of total generation in 2050.

Table 5. The Share of U.S. Electricity Generation in 2050 that Is Provided by PV (all) and PVB (only) Across all Scenarios

	PV's Share of Total Generation		**Hybrid Systems' Share of PV Generation**
Scenario	**No Hybrids Version**	**With Hybrids Version**	
Reference	20%	22%	18%
LowCost	36%	37%	20%
Decarb-ModCost	34%	36%	18%
Decarb	46%	48%	19%

Despite the wide-ranging results for PV's share of total generation, the isolated impact of introducing PVB hybrid configurations as an investment option is a consistent 1–2 percentage point increase in PV's share of total generation (Table 5). For most scenarios, this isolated effect does not produce a meaningful distinction compared to the results of the original *Solar Futures Study*. However, results for the With Hybrids version of our Decarb scenario indicate that the availability of PVB hybrid configurations could allow PV to provide nearly one-half (48%) of U.S. electricity generation in 2050. This result represents an expanded role for PV beyond that previously envisioned in the original *Solar Futures Study*, which reported a maximum share of generation provided by solar technologies of 44%–45%.

Within the context of this pronounced role for PV generation overall, the contributions of PVB hybrids are more modest. PVB hybrids provide 4%–9% of total generation across all scenarios explored, which corresponds to 18%–20% of total PV generation (Table 5). These metrics largely follow the varying levels of deployment presented in Sections 3.1, but they also reflect differences in the capacity factors among standalone PV, Low-ILR PVB, and High-ILR PVB configurations.

Considering only utility-scale projects (which typically involve higher ILRs and capacity factors than distribution-scale projects), standalone PV capacity factors range from 24%–29% across scenarios. The standalone PV capacity factors depend on regional deployment and curtailment rates, but they are independent of whether PVB hybrid configurations are available as investment options. Our Low-ILR PVB hybrid configuration exhibits similar but slightly higher capacity factors (29%–33%) because of the modest oversizing of PV arrays in this configuration. The significantly higher capacity factors observed for our High-ILR PVB hybrid configuration (38%–42%) reflect the oversizing of PV arrays and the larger battery sizes, the combination of which allows the DC-coupled battery to more efficiently store and shift excess PV generation for use during non-solar hours.

3.3 Other Impacts

As was reported in the original *Solar Futures Study,* the required level of transmission expansion varies strongly across scenario definitions. To illustrate this, Figure 8 presents new transmission capacity over time for all No Hybrids (dashed lines) and With Hybrids (solid lines) versions of each scenario. Scenarios that include the emissions reduction requirement involve the most pronounced growth in transmission expansion (Figure 8), which is required to connect large volumes of wind and solar resources (Figure 2) to load centers. The transmission expansion results presented in Figure 8 are highly consistent with those presented in the original *Solar Futures Study,* and they should be interpreted within the context of the existing U.S. transmission network, which amounts to 147 TW-miles in the ReEDS formulation.

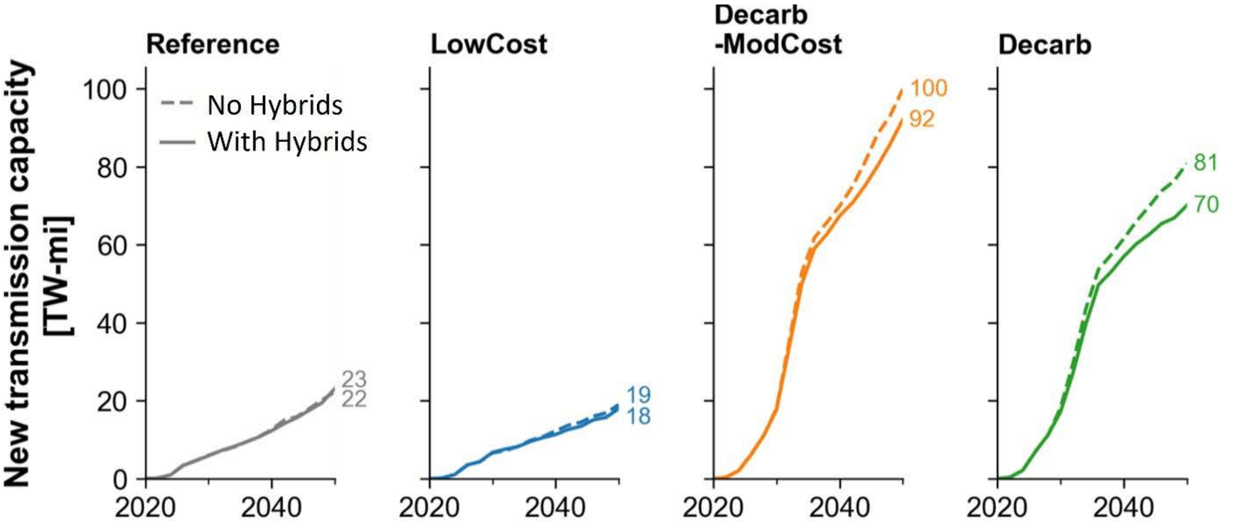

Figure 8. New transmission capacity over time across all scenarios explored

Introducing the PVB hybrid configurations has a modest (3%–5%) impact on transmission expansion by 2050 in the Reference and LowCost scenarios, but its impacts are more pronounced under scenarios that involve the *Solar Futures Study* emissions reduction requirement. Introducing the PVB hybrid configurations drives an 8%–12% (or 8–11 TW-mile) reduction in transmission expansion between the No Hybrids and With Hybrids versions of the Decarb-ModCost and Decarb[16] scenarios, respectively (Figure 8). This pronounced hybrid-induced reduction in transmission expansion reflects multiple impacts associated with the availability of PVB hybrids, but it is primarily rooted in their higher capacity factors (and, therefore, higher transmission utilization rates) compared to standalone PV.

Intuitively, the reduced transmission expansion drives a reduction in bulk power system costs associated with transmission investments under the With Hybrids version of each scenario. However, transmission investment is just one system cost category and accounts for no more than 3% of total bulk power system costs (on a cumulative but discounted basis across the simulation period of 2022–2050). Considering all system cost categories, the availability of PVB hybrids consistently reduces overall bulk power system costs, but the impact is very modest (0.1%–0.2%) across most scenarios. Introducing the PVB hybrid configurations under the Decarb scenario settings results in slightly larger bulk power system cost savings of 0.7% (or $21 billion), primarily due to avoided transmission and generation capital costs.

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[16] The Decarb scenario involves a smaller amount of new transmission capacity than the Decarb-ModCost scenario because the former involves less wind capacity (and transmission expansion typically scales with wind deployment).

4 Key Findings

Based on the full set of scenario results presented in the previous section, we identify five key findings regarding the potential impacts of PV-battery hybridization on the future role of PV across the *Solar Futures Study* scenarios explored in this report. Note that these findings are based on the previously described scenario results, which do not include provisions of the *Inflation Reduction Act* (U.S. Congress 2022) that expanded ITC eligibility to standalone storage projects.

4.1 PVB Hybrids Displace a Share of Standalone PV Capacity

Across the scenarios explored, deployment of candidate PVB hybrid configurations begins in the late 2020s and continues throughout the simulation period. The dominant effect of this growing PVB hybrid deployment is the displacement of standalone PV capacity, such that the total installed PV capacity is comparable across No Hybrids and With Hybrids versions of each scenario (e.g., Figure 5 above). PVB hybrid deployment increases under low-cost and/or decarbonization policy assumptions, but so does the deployment of standalone PV. Therefore, the share of PV capacity that is captured by hybrid configurations in 2050 (13%–16%) is similar across all scenarios explored.

Despite the widespread deployment of our PVB hybrid configurations over time and across scenarios, our simulation results are somewhat inconsistent with current U.S. interconnection queue data. As of the end of 2021, PVB projects accounted for 285 GW (42%) of proposed PV capacity (Rand et al. 2022), all of which would come online during the 2020s. Not all of these proposed projects will be built, and how many of them would adopt a full hybrid configuration is unclear. However, the large discrepancy between U.S. interconnection queue data and our simulation results could indicate that our selected PVB hybrid configurations do not represent the most competitive sizing of PV and battery components in the near term. Alternatively, there may be additional sources of cost savings and/or value that are not captured in our representation of the PVB hybrid technology in ReEDS.

4.2 The Highest-Net-Value PVB Hybrid Configuration Depends on Carbon Policy

The relative deployment of our two exogenously defined PVB hybrid configurations (e.g., Figure 4) provides new insights regarding the highest-net-value hybrid configuration across a range of technology and policy assumptions. The vast majority of PVB hybrid deployment takes the form of the Low-ILR configuration in the absence of a decarbonization policy. Given its similarities with standalone PV, deployment of the Low-ILR PVB hybrid configuration reflects the fact that PV and battery were already part of the least-cost solution in many regions, and deploying them together has the system cost benefits of lower capital costs (due to shared inverter and balance-of-system costs) and the battery component's eligibility for the ITC.[17] Deployments of the Low

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[17] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, only batteries in a PVB project could qualify for the federal ITC. The *Inflation Reduction Act* expanded ITC eligibility to standalone storage projects which will likely influence the relative competitiveness of standalone and coupled battery projects.

ILR PVB hybrid configuration are generally concentrated in regions with relatively high solar resource and demand for electricity, including California, Texas, and Florida (see Figure 6).

The introduction of an emissions reduction requirement increases the value proposition of the more forward-looking High-ILR PVB hybrid configuration, which involves significantly oversized PV arrays and larger batteries. Under this policy assumption, the Low-ILR PVB hybrid configuration experiences greater deployment leading up to 2035, when the scenario definition dictates that power sector emissions must be reduced by 95% compared to 2005 levels. Thereafter (along the path from 95%–100% decarbonization), the High-ILR PVB hybrid configuration experiences greater deployment, resulting in comparable levels of installed capacity for each PVB hybrid configuration by 2050. Compared to the Low-ILR PVB hybrid configuration, the High-ILR PVB hybrid configuration is preferentially deployed throughout the Western Interconnection and in the northernmost latitudes.

4.3 The Availability of PVB Hybrid Configurations Expands PV's Share of U.S. Electricity Supply in 2050

Solar PV's share of total generation varies strongly across technology cost and policy assumptions, ranging from 22% under the Reference scenario to 48% under the Decarb scenario. Despite the wide-ranging PV generation results, the isolated effect of introducing the PVB hybrid configurations is a consistent 1–2 percentage point increase in PV's share of total generation in 2050 (compared to corresponding No Hybrids scenarios). This hybrid-induced increase in the role of PV reflects the increased production from the PVB hybrid configurations, primarily because of the recovery and shifting of otherwise clipped energy into non-solar hours.

Under the Decarb scenario, the availability of PVB hybrids allows PV to provide 48% of U.S. electricity generation in 2050, which exceeds any of the estimates produced in the original *Solar Futures Study*. This outsized role of PV in the 2050 U.S. electricity mix reflects the fact that PVB deployment under the Decarb scenario is dominated by the more forward-looking High-ILR PVB hybrid configuration, which has a higher capacity factor (38%–42%) than standalone PV (24%–29%) and the Low-ILR PVB hybrid configuration (29%–33%).

4.4 PVB Hybrids Influence the Future Mix of Battery Technologies

Beyond the direct competition between hybrid and standalone deployments of PV (described in Section 4.1), the introduction of candidate PVB hybrid configurations also leads to the increased deployment of the battery type included in our exogenously defined PVB hybrid configurations (i.e., 4-hr duration batteries). While this effect is observed across all scenarios explored, its absolute and relative magnitudes depend strongly on technology cost assumptions.

Under low-cost assumptions for PV and battery technologies, the introduction of PVB hybrid configurations drives a 10%–29% increase in 4-hr battery capacity (compared to the corresponding No Hybrids scenarios). However, this hybrid-induced expansion of 4-hr battery capacity is partially offset by the reduced deployment of longer-duration (6-hr to 10-hr) batteries. When accounting for both power rating and duration, the introduction of PVB hybrid configurations has a modest effect on the role of battery technologies (i.e., on an energy or GWh basis). Therefore, the introduction of PVB hybrid configurations with low-cost assumptions for

PV and battery technologies simply shifts the relative competitiveness of different battery durations in favor of 4-hr duration batteries.

Under default cost assumptions, the availability of PVB hybrid configurations drives more modest (15%–16%) increases in 4-hr duration batteries, but this is accompanied by the expansion of longer-duration batteries as well. Therefore, introducing the PVB hybrid configurations systematically expands the role of battery technologies under default technology cost assumptions, which reflects the more pronounced system cost benefits associated with hybridization. In other words, the shared costs and the battery component's ability to qualify for the ITC[18] are more impactful under default technology cost assumptions, both in terms of their absolute effect and the resulting relative competitiveness with other resources.

4.5 PVB Hybrids Reduce Transmission Buildout, Particularly in Scenarios That Involve a Power Sector Decarbonization Policy

Introducing our candidate PVB hybrid configurations has a negligible effect on the required level of transmission expansion in the absence of a power sector decarbonization policy, regardless of technology cost assumptions. However, in scenarios that involve an emissions reduction requirement, introducing the PVB hybrid configurations reduces transmission expansion by 8%–12% (or 8–11 TW-miles) compared to the corresponding No Hybrids version of a given scenario. This hybrid-induced reduction in transmission expansion reflects multiple impacts associated with the availability of PVB hybrids, but it is primarily rooted in their higher capacity factors (and therefore higher transmission utilization rates) compared to standalone PV.

In turn, the avoided transmission expansion contributes to a consistently observed reduction in bulk power system costs under scenarios that include PVB hybrids as a candidate investment option. Across most scenarios, the bulk power system cost impacts associated with the availability of PVB hybrid configurations are modest (0.1%–0.2%), which reflects the fact that standalone PV and battery technologies were already part of the least-cost solution. The largest-magnitude system cost impact is observed in the Decarb scenario, where the availability of PVB hybrid configurations drives a 0.7% (or $21 billion) reduction in bulk power system costs, primarily due to avoided transmission expansion and generation capital costs.

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[18] This scenario analysis was performed prior to the *Inflation Reduction Act* (U.S. Congress 2022) being signed into law in August 2022. Therefore, at the time of this analysis, only batteries in a PVB project could qualify for the federal ITC. The *Inflation Reduction Act* expanded ITC eligibility to standalone storage projects which will likely influence the relative competitiveness of standalone and coupled battery projects.

5 Conclusions and Future Research

In this paper, we explore the potential impacts of growing industry interest in hybrid systems comprising PV and battery technologies on the results and findings of the *Solar Futures Study* (DOE 2021). We employ similar scenario definitions in the same ReEDS capacity expansion model, but we perform two versions of each scenario: one in which PV and battery technologies must be deployed separately (No Hybrids), and one in which the model has the option of deploying them together as PVB hybrids (With Hybrids). By comparing the No Hybrids and With Hybrids versions of each scenario, we isolate the impacts of hybridization on the outcomes and findings of the *Solar Futures Study*.

We find that PVB hybrids capture a sizable share of PV deployment, and the highest-net-value hybrid configuration depends strongly on policy conditions. A power sector decarbonization policy generally increases the value proposition of a more forward-looking PVB hybrid configuration that involves significant oversizing of the PV arrays, a larger battery (which facilitates greater recovery and utilization of otherwise clipped energy), and a higher capacity factor. The growing deployment of PVB hybrid configurations primarily displaces standalone PV capacity, such that total installed PV capacity is largely unaffected by the availability of PVB hybrid configurations. However, the higher capacity factors associated with PVB hybrid configurations drive a modest (1–2 percentage point) increase in PV's share of U.S. electricity supply in 2050. Finally, introducing the PVB hybrid configurations influences the future role and makeup of battery storage technologies, and it reduces the required transmission expansion, particularly under scenarios that involve a power sector decarbonization policy.

The results in this study point to several future research directions. First, when the *Inflation Reduction Act* (U.S. Congress 2022) was signed into law in August 2022, it expanded eligibility for the federal ITC to standalone storage technologies. In this analysis, one of the primary drivers of the economic deployment of PVB hybrid technologies is their battery component's unique ability to qualify for the federal ITC. The addition of federal ITC eligibility for standalone storage systems could have a pronounced influence on the results and findings of this analysis.[19]

In addition, scenarios explored in this report involve default electricity demand profiles, which means we do not evaluate the effects of changing load shapes. The *Solar Futures Study* found that load shapes associated with widespread electrification had a negligible effect on solar's share of the U.S. electricity supply, but that they could lead to significant increases in cumulative PV deployment (DOE 2021). The present results indicate that the availability of PVB hybrids can also expand cumulative PV deployment (based on the DC-rated capacity), although that result was not tested in scenarios with widespread electrification. If the effects of electrification and hybridization are additive, then it would be valuable to revisit the material supplies and land requirements of solar energy in a decarbonized U.S. grid (Heath et al. 2022).

Load profiles associated with electrification are also expected to involve a greater prevalence of winter-peaking regions (due to electrified space heading) (Mai et al. 2018), and they may introduce more flexibility in the timing of electricity demand (due to flexible vehicle charging)

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[19] The Internal Revenue Service has not issued guidance clarifying how the *Inflation Reduction Act* tax credits will be implemented, so there is still some uncertainty regarding their potential impact.

(Sun et al. 2020). The evolving shape and flexibility in the timing of electricity demand would likely influence the highest-net-value PVB hybrid configuration, but the static PVB hybrid configurations in ReEDS do not allow for an evolution in the available PVB hybrid configurations over time. Therefore, another suggested future research direction is the development of endogenous sizing capabilities for the PV, battery, and inverter components of PVB hybrid configurations in capacity expansion models. This more flexible representation of available PVB hybrid configurations would also advance the modeling community's ability to represent a commonly cited benefit of hybridization, which is its ability to enable more modular designs that can be tuned as the mix of generation (and high-value electricity services) evolves over time.

Finally, the capacity expansion results from the core *Solar Futures Study* scenarios were validated, and their operational characteristics were studied in more detail, using production cost simulations. Detailed operational modeling of capacity expansion results from the present study could provide valuable insights into the highest-value operational patterns for PVB hybrids (Durvasulu, Murphy, and Denholm 2021), especially in terms of variations by region and configuration.

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