Role of Pumped Hydro Storage in China's Power System Transition

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Executive Summary

China has pledged to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. Decarbonizing the power system is key to achieving these targets. Pumped hydropower storage (PHS) can play a crucial role in a greener power system, providing both short- and long-term energy storage, facilitating the integration of renewable energy, and maintaining grid stability.

This study aims to inform discussions around three questions. First, what is the role of PHS in China's power system? Second, what is the optimal amount of PHS capacity for China's evolving power system? Third, what are incentive policies and cost recovery mechanisms for encouraging energy storage?

To address the first two questions, we utilized GridPath, a power system capacity expansion model, focusing on the years 2025 to 2050. Our model is based on a detailed representation of China's electricity system, including hourly provincial loads, interprovincial and interregional transmission constraints, region-specific wind and solar profiles, and recent renewable energy and energy storage cost projections for the country. The analysis' electricity demand projections are the median values of several recent long-term energy scenario studies.

Our research indicates that China would not need to deploy additional PHS to build its lowest-possible-cost electricity system, assuming PHS costs remain at current level. Instead, PHS capacity stabilize at its base level of 32.5 GW (Table ES-1). In contrast, the capacity of battery storage witnesses a substantial increase from 21 GW to 858 GW between 2025 and 2050, emerging as a more economical solution to address the variability of renewable energy and accommodate demand growth. The scale of PHS installation is considerably influenced by its cost. Assuming a rate of cost reduction for PHS equivalent to that of batteries, which might be overly optimistic, PHS installed capacity experiences a marked increase from 120 GW in 2030 to 234 GW by 2050 (Table ES-1). However, increasing the capacity of PHS does not notably impact the total system costs. Our analysis reveals that the total system cost would only experience a modest rise of 0.6% to 2% if PHS installed capacity is increased from 200 to 400 GW, relative to the Base scenario.

Table ES-1. Key differences among three scenarios

Metric	Year	Base scenario	Base_PHScost scenario	Low_PHScost scenario
PHS capacity (GW)	2025	32.5	62	62
	2030	32.5	120	120
	2040	32.5	120	143
	2050	32.5	120	234
Batter storage capacity (GW)	2025	21	21	21
	2030	31	23	23
	2040	292	220	217
	2050	858	742	632
Total system cost (US$ Trillion)	2025-2050	5.11	5.18	5.16

We also summarize US's experience with incentive policies and cost recovery mechanisms for energy storage, as a resource for relevant Chinese stakeholders. In the United States, energy storage policies include procurement targets, financial incentives, regulatory adaptation, and demonstration programs. These policies facilitated rapid development of energy storage. Especially noteworthy are financial incentives, such as the Investment Tax Credit (ITC), which significantly reduce costs for installing energy storage and thus accelerate their installation.

To foster the sustainable advancement of PHS and accelerate the decarbonization of China's power grid, we offer following recommendations, based on detailed scenario analyses and a review of international practices. First, it is crucial that PHS development policies and targets are integrated into the comprehensive planning of the electricity system. This involves a thorough comparison with other storage, generation technologies, and transmission solutions to avoid any mismatch in location and scale, thereby averting unnecessary increases in power system costs or tariffs. Second, it is prudent to re-evaluate the current PHS pricing mechanism and its potential impact on electricity tariff. Over-investment in PHS could lead to unnecessary electricity price inflation. Introducing market competition through an open and competitive bidding process for PHS developers can more effectively control project costs and, consequently, electricity tariffs. Lastly, fostering inter-provincial collaborations for PHS projects can offer substantial advantages in resource sharing and regional grid stability. If policymakers collaborate with their counterparts in neighboring provinces, they can create a cooperative framework and align regulations to encourage and facilitate cross-province endeavors, laying a solid foundation for the optimal deployment of PHS and other system resources.

1. Introduction

China's commitment to peaking its carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 underscores the urgent need for decarbonizing the country's power system. Transitioning to a decarbonized power system involves shifting from coal-dominated power generation to low-carbon energy sources such as renewable energy and nuclear power. This transition is essential not only for China's environmental responsibilities but also for its long-term energy security, economic growth, and global competitiveness.

Energy storage is crucial to enabling the economical and reliable operation of power systems that rely heavily on variable renewable energy (VRE) resources to achieve decarbonization goals. The transition to renewable energy resources, particularly variable wind and solar, requires storing energy to guarantee that electric demand can be met consistently. As utilization of VRE resources increases, considerable energy storage capacity will be required to support the grid (International Energy Agency [IEA], 2021, and International Renewable Energy Agency [IRENA], 2023). In addition to short-duration energy storage technologies, such as batteries, significant long-duration energy storage will be needed to provide power system resiliency in situations of prolonged extreme weather events or other disturbances.

This report focuses on evaluating the role of PHS in China's renewable-dominated power system and examining policy incentives and international experience with hybrid plants and other energy storage technologies. First, we describe PHS systems—their purpose, importance, and utilization worldwide (Section 1). Section 2 describes the methods and results of the analysis we performed to examine the role of PHS in China's evolving energy system. Section 3 examines hybrid power plants (those that combine renewable resources with energy storage, such as batteries). Section 4 describes incentive programs and market mechanism for expanding the use of energy storage, with a focus on the United States. Section 5 presents policy recommendations for expanding the use of PHS in China. Section 6 lists the references cited in the report. The Appendix presents an analysis of China's future installed energy storage capacity under a scenario involving extremely low costs for PHS.

1.1 History of pumped hydro energy storage

A pumped hydropower storage (PHS) system (also known as a pumped storage system) is a commercially available, proven technology that reliably meets the needs for both short- and long-duration energy storage. As an effective means of storing energy, PHS systems further decarbonize a power system, support integration of renewable energy, and maintain grid stability (IRENA, 2020, IIASA, 2020.).

Beginning in the 1960s, PHS facilities were built in various countries, such as the United States and Japan, to complement nuclear power plants and serve as fast-response peaking plants (Nikolaos et al., 2023). Because PHS facilities could ensure stable operating conditions for power plants, the number of PHS facilities increased along with that of nuclear power plants, particularly during the 1980s and into the 1990s. As a result, many PHS facilities are strategically located between nuclear power plants and areas having high electricity demand. Development of PHS facilities declined after the 1990s, however, largely in response to growing environmental concerns and a scarcity of suitable construction sites (Deane et al., 2010). As the most cost-effective locations were occupied and development of nuclear power waned, fewer PHS facilities were constructed. After 2000, a renewed interest in PHS emerged driven by the increasing demand for renewable energy sources and the liberalization of electricity markets, breathing new life into the relevance and development of PHS facilities (Rehman et al., 2015; Zakeri and Syri, 2015).

More recently, PHS systems have represented 3% of the total installed electricity generation capacity in the world and more than 90% of the world's electricity storage capacity (Schoenfisch and Dasgupta, 2022), which makes them the most extensively used mechanical storage systems. The worldwide PHS capacity in 2021 was about 165 GW, according to the 2022 Hydropower Status Report (International Hydropower Association [IHA], 2022) (Table 1). Most PHS capacity is located in Asia (primarily China and Japan), followed by Europe and North America. New PHS capacity is being constructed quickly, primarily in China and India, as well as in Europe. PHS generating units differ greatly in size, from small (about 1 MW) to large (hundreds of megawatts). The duration of discharge at rated power ranges from 1 to 24+ h. The units have a round-trip efficiency of 70% to 85% and a generally negligible self-discharge (Barbour et al., 2016; Luo et al., 2015).

Table 1 Global PHS capacity by region in 2021 (IHA, 2022)

Region	**PHS capacity (MW)**
Africa	3,377
East Asia and Pacific	75,540
South and Central Asia	7,751
Europe	55,050
North and Central America	22,089
South America	994
Total	**164,761**

1.2 Types of pumped hydro energy storage systems

PHS facilities generally are designed to consume electricity to pump water uphill into a reservoir when electricity demand and prices are low. The water is released to flow downhill through turbines to generate electricity when demand and prices are high (GE Power, 2017).

1.2.1 Hybrid pumped hydro storage

There are two categories of PHS systems (Figure 1): (1) conventional PHS, which provides rapid start-up and variable power output in response to demand, and (2) coupled schemes, in which PHS is combined with VRE to minimize curtailment of electricity derived from the variable renewables.

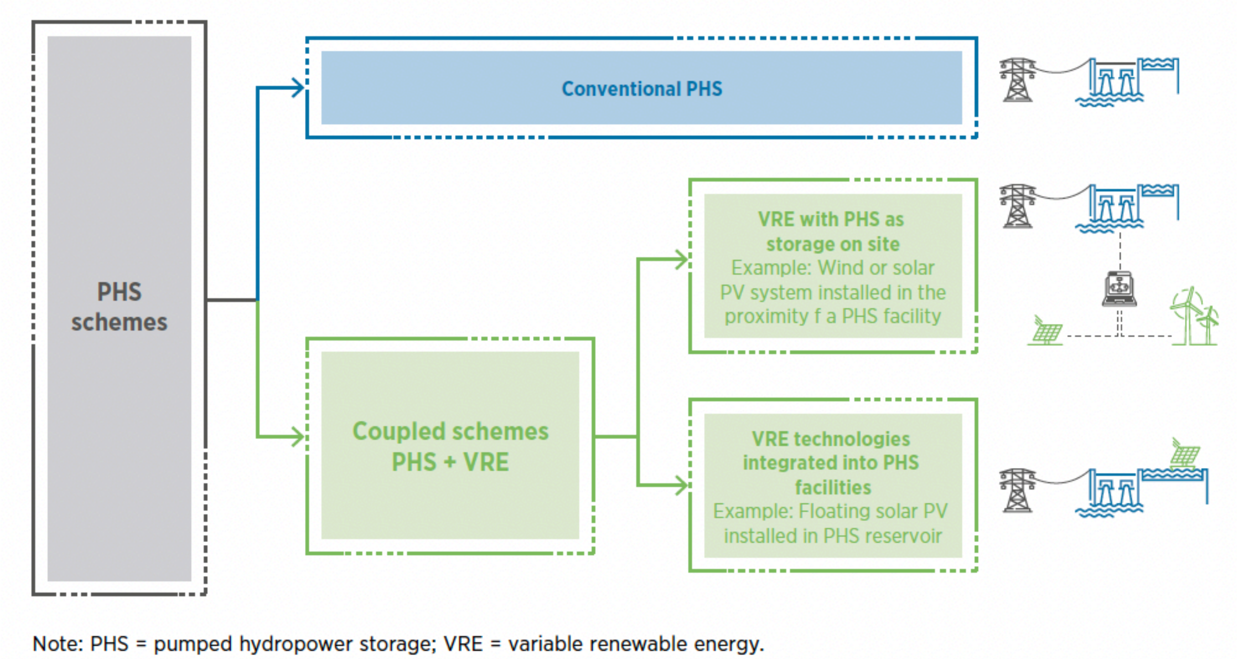


Figure 1. Configurations for pumped hydropower storage and renewables (IRENA, 2020).

Coupled systems include on-site VRE, where wind and solar facilities are installed near PHS, which compensates for the intermittent supply. Or VRE may be integrated into a PHS facility: floating photovoltaic (PV) systems can be installed in the upper and lower reservoirs of a PHS facility, creating a hybrid model that takes advantage of established high-voltage grid connections (IRENA, 2020). By supporting the integration of renewable energy into the power system, coupled schemes can play an important role in decarbonizing the system.

1.2.2 Fixed-speed and variable-speed PHS

Most PHS facilities throughout the world use fixed-speed (or single-speed) technology. Fixed-speed facilities employ a synchronous machine as a motor-generator, which operates in sync with the grid frequency. Today's fixed-speed PHS units can technically operate between 30% and 100%

of their rated power output in generating mode, but they typically do not operate below 60% to avoid accelerated turbine wear (Koritarov et al., 2022).

Adjustable-speed, also known as variable-speed, PHS technology was developed in Japan in the early 1990s. Studies have found that compared to fixed-speed PHS technology, variable-speed PHS systems allow for wider operating ranges and faster shifting between ranges, providing greater flexibility at lower system costs (IHA, 2018 and 2020; Simão and Ramos, 2020). Moreover, variable-speed PHS units can consume power from the grid to perform pumping operations if VRE resources are unavailable. Teng et al.'s study (2018) found that variable-speed PHS could lower total system costs in a scenario involving a high percentage of renewables. The increase in PHS systems' long-term economic benefits when combined with renewables has been estimated to be in the range of an additional about 10% to 20% compared to fixed-speed PHS. By the end of 2020, more than 18 power stations and about 40 variable-speed PHS units had been installed worldwide, particularly in Europe and Japan. Their popularity highlights the importance of variable-speed technology in achieving a more flexible and renewable-centric power system (National Hydropower Association [NHA], 2021).

1.2.3 Open- and closed-loop systems

Two categories of PHS are identified based on whether the system operates in an open or a closed loop. An open-loop PHS system maintains an ongoing hydrologic connection to a natural body of water. A closed-loop PHS is not "continuously connected to a naturally flowing water feature" (U.S. Department of Energy [DOE], 2016).

Open-loop systems have the advantage of using available water resources and infrastructure, thus lessening the need for additional land and construction. In cases where the lower reservoir is constrained by a dam, constructing the powerhouse eliminates the need for excavation. Such systems can raise environmental concerns, however, because of their potential impacts on water quality, aquatic life, and local ecosystems. Furthermore, open-loop systems rely on the availability of water resources, which could be affected by seasonal changes and drought conditions.

Closed-loop PHS systems typically consist of an upper and lower reservoir located away from a large water source and receiving limited water input. The systems can be constructed in small artificial lakes filled either by precipitation or water transported from off site. Some PHS projects are considered closed-loop even though they might initially draw water from naturally flowing surface water to fill their reservoirs and periodically replenish evaporative and seepage losses (International Hydropower Association [IHA], 2022; Saulsbury, 2020). Closed-loop systems have fewer environmental impacts than do open-loop systems because they minimize water usage and avoid disrupting natural water bodies. Additionally, they can be established in areas where limited water resources make open-loop systems unfeasible. Closed-loop systems require considerable initial investment in reservoir construction and water supply, however, making them potentially more costly than open-loop systems.

In conclusion, PHS, initially used to support development of nuclear power plants and address energy security concerns, has evolved to become a valuable component of the ever-changing energy landscape. Their provision of additional services, such as load balancing, frequency stability, and black starts, underscores the vital role PHS can play in modern power system management within the ongoing pursuit of sustainable, robust, and efficient energy systems.

2. Role of PHS in China's evolving power system

To achieve carbon neutrality by 2060, China has increased its solar PV and wind energy capacity dramatically during the past decade, from 120 GW (80 GW solar and 40 GW wind) in 2012 to 760 GW (395 GW solar and 365 GW wind) in 2022. The rapid expansion of wind and PV installations, however, has brought challenges related to the variability of those natural resources.

Energy storage increases a system's flexibility and is important in balancing the grid. Among available technologies, PHS offers a reliable method of short-, medium-, and long-term energy storage. Currently, China is on the forefront of PHS development, having had a total installed capacity of 37 GW as of 2021, which is 15.6% more than in 2020 (NEA, 2021). China's installed capacity of PHS increased from 22.8 GW in 2015 to 45.7 GW in 2022. Especially noteworthy is the surge in installed PHS capacity after 2020 (Figure 2).

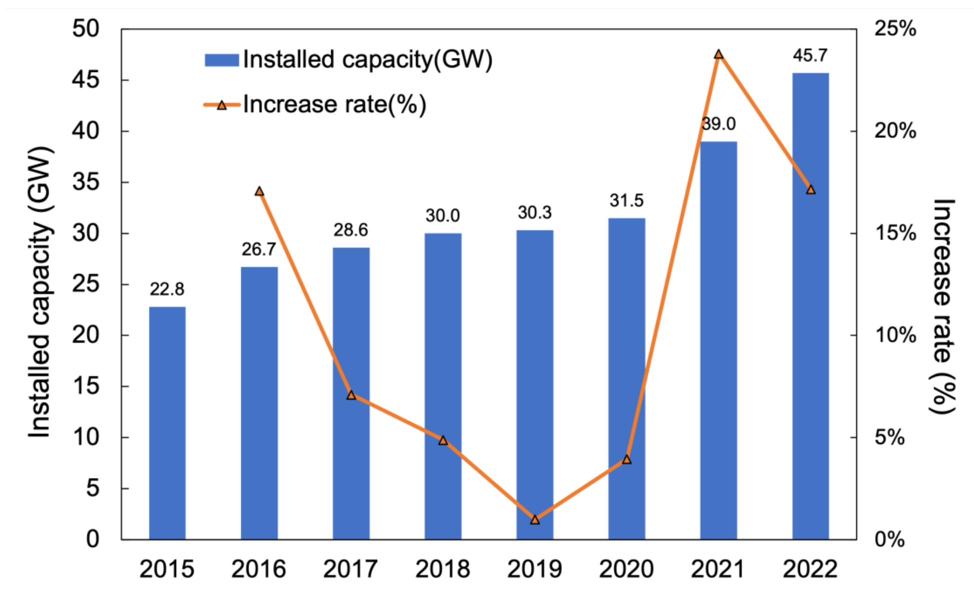


Figure 2. China's installed capacity and rate of increase in PHS, 2015–2022.

In September 2021, China's National Energy Administration (NEA) issued its Medium and Long-term Development Plan for Pumped Storage (2021–2035) (NEA, 2021). According to this plan, the installed capacity of PHS should reach at least 62 GW capacity by the end of China's 14^{th} Five-Year Plan (FYP), which would be 2025, and about 120 GW capacity by the end of the 15^{th} FYP (2030). It is worth noting, however, that the PHS targets for the 12^{th} and 13^{th} FYPs were not met, suggesting there are institutional and policy barriers to the development of PHS. A more recent survey by NEA identified more than 400 GW of potential PHS development in China. Nonetheless, it remains uncertain how well potential sites meet requirements for grid reliability and adherence to ecological guidelines. Research to understand the needs and challenges facing PHS development is critical to inform policymaking, enhance PHS development, and support China's evolving power system. We modeled China's power system to explore three issues related to the role of PHS in the power system: (1) how PHS will affect the need for battery and other storage methods needed to rely on a high penetration of renewables; (2) how much PHS capacity needs to be built to achieve system optimization; and (3) how installations of PHS should be distributed throughout China. Our analysis is intended to provide a scientific basis for sound policymaking in support of decarbonizing China's power system.

2.1 Methods

We utilized the GridPath power system optimization model (Blue Marble Analytics, 2023) to determine how various scenarios would affect the utilization of PHS in China's power system.

2.1.1 GridPath model

GridPath is an optimization model that solves for the ideal installed capacities of generators and transmission lines to meet a specific electrical demand. The optimal solution minimizes the cost of producing and delivering electricity while satisfying a set of operational requirements. In other words, given the electricity demand projected at a certain temporal and spatial resolution, GridPath optimizes the number of each type of generator, energy storage unit, and transmission line needed to balance projected demand with supply within each time step in each load zone. Figure 3 shows China's electricity demand projected from 2025 to 2050.

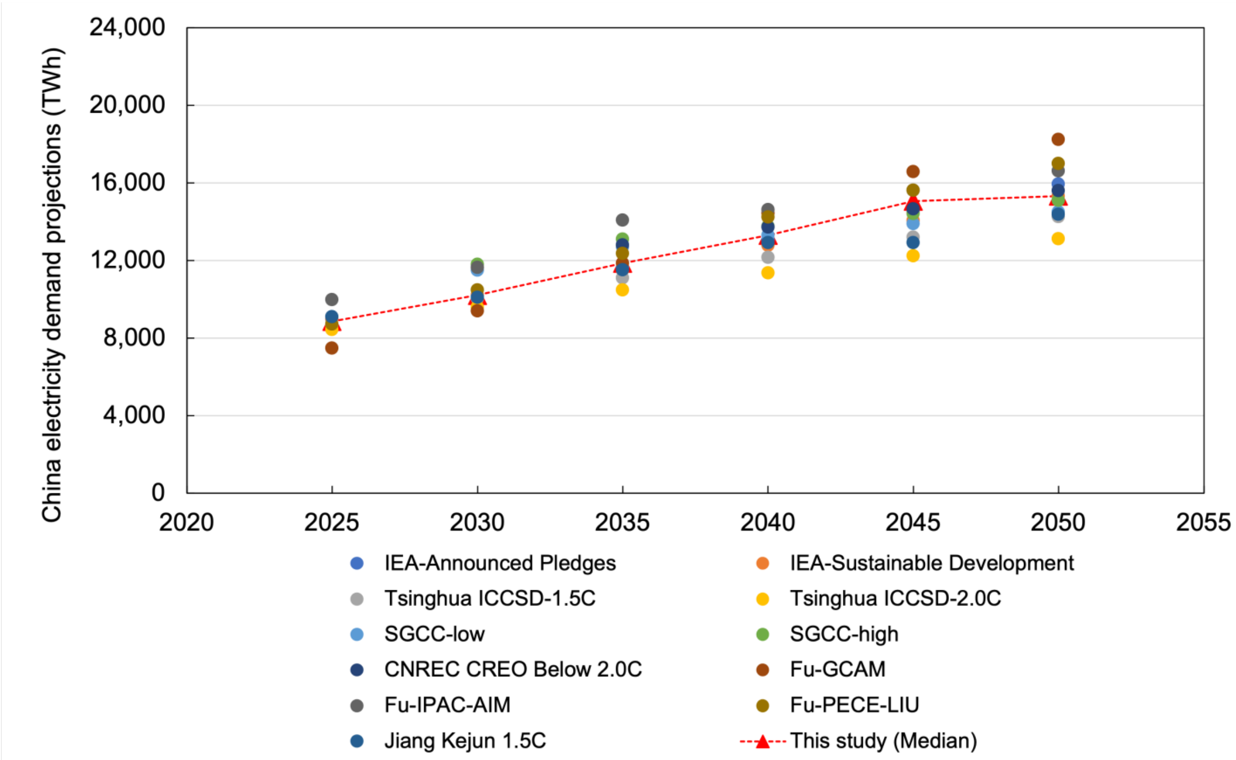


Figure 3. China's projected electricity demand, 2025–2050. Sources: IEA, 2021; State Grid Energy Research Institute (SGERI), 2020; ICCSD, 2022; CNREC, 2020; Fu et al. 2020 and Jiang et al. 2018.

Our model incorporates national system costs into the objective function: (1) capital costs of new power plants, battery storage, and transmission lines; (2) operation and maintenance (O&M) costs of existing and new power plants, battery storage, and transmission lines; and (3) variable costs incurred by power plants, such as costs of coal and gas. In our study, we use one hour as the time step and treat each provides as a load zone. The variable costs of wind, solar, pumped hydro storage, and battery storage are assumed to be zero. In general, those costs depend on both installed capacities within each province, which are model variables to be solved, and unit capital and O&M costs, which are model inputs. The cost information for renewable power generators, fossil fuel power generation, and energy storage (2- and 4-h batteries and PHS) are obtained from Bloomberg New Energy Finance (BNEF, 2022).

To model power system dynamics, GridPath employs four levels of temporal resolution: five-year investment periods, months, days, and hours. Our study divides the time span 2025–2050 into six five-year investment periods: 2021–2025, 2026–2030, 2031–2035, 2036–2040, 2041–2045, and 2046–2050. We use 12 months to characterize each investment period, two days to characterize each month (the median load days), and six hours to characterize each day. For each day, hourly sampling begins at midnight China Standard Time and includes the 0^{th}, 4^{th}, 8^{th}, 12^{th}, 16^{th}, and 20^{th} hours. This process results in: (6 investment periods) × (12 months/investment period) × (1 day/month) × (6 hours/day) = 432 study hours during which the power system is dispatched. Our figures show the results for 2025, 2030, 2035, 2040, 2045, and 2050 as representative years for the six investment periods.

2.1.2 Scenario design

Our study contains three primary scenarios (Table 2):

- a Base scenario, in which there are no constraints on PHS installation, and decisions regarding installations are based on model optimization;
- a Base PHS cost scenario, in which PHS costs stay consistent with the current situation, and we set a target of 62 and 120 GW PHS for 2025 and 2030 regarding NES's mid-to-long PHS plan, further PHS installation is based on model optimization;
- and a Low PHS cost scenario, in which PHS costs decrease at the same rate as those for batteries from 2025 to 2050 based on ATB 2022, and we again set targets of 62 and 120 GW PHS for 2025 and 2030, respectively. It's noted that this scenario is a highly aggressive assumption, which is difficult to implement in the real world since the PHS technology is mature today.

To comprehensively explore the impacts of various factors on PHS installation, we consider three factors—a carbon emission cap, a PHS capacity cap, and cost trajectories for renewable energy (RE). In particular, we examine two carbon emission caps (high and low), five PHS capacity caps (detailed in Table 2), and two RE costs (low and high), as well as PHS costs on installed capacity and total power system cost.

Table 2 Detailed scenario designs.

<table>
<tr><th>Scenarios</th><th>Carbon cap</th><th>PHS capacity cap</th><th>RE cost</th><th>PHS cost</th></tr>
<tr><td>1.Carbon_high_Base</td><td rowspan="6">High</td><td>No constraint</td><td>Low</td><td rowspan="9">Base</td></tr>
<tr><td>2.Carbon_high_cost_high</td><td rowspan="2">Set targets of 62 and 120GW for 2025 and 2030</td><td>High</td></tr>
<tr><td>3.Carbon_high_cost_low</td><td rowspan="5">Low</td></tr>
<tr><td>4.Carbon_high_cost_low_PHS200</td><td rowspan="3">Set sensitivity analysis from 200-400 GW for 2035</td></tr>
<tr><td>5.Carbon_high_cost_low_PHS300</td></tr>
<tr><td>6.Carbon_high_cost_low_PHS400</td></tr>
<tr><td>7.Carbon_low_Base (Base)</td><td rowspan="7">Low</td><td>No constraint</td></tr>
<tr><td>8.Carbon_low_cost_high</td><td rowspan="3">Set targets of 62 and 120GW for 2025 and 2030</td><td>High</td></tr>
<tr><td>9.Carbon_low_cost_low (Base_PHScost)</td><td rowspan="5">Low</td></tr>
<tr><td>10.Carbon_low_cost_low_LowPHScost (Low_PHScost)</td><td>Decrease rate as same as batteries</td></tr>
<tr><td>11.Carbon_low_cost_low_PHS200</td><td rowspan="3">Set sensitivity analysis from 200-400 GW for 2035</td><td rowspan="3">Base</td></tr>
<tr><td>12.Carbon_low_cost_low_PHS300</td></tr>
<tr><td>13.Carbon_low_cost_low_PHS400</td></tr>
</table>

The implementation of each factor in the scenarios is explained below.

Carbon emissions cap. We developed two scenarios related to carbon emissions caps. First, a high cap, which assumes decarbonization of the power system aligns with China's 2060 carbon neutrality target. In this scenario, the power system's carbon emissions peak in 2030, then in 2050 decrease by 90% compared to 2020 levels. Second, a low carbon emissions cap, which assumes a more aggressively decarbonized power system that achieves zero emissions in 2045. Figure 4 shows the carbon emissions trajectories for the two scenarios.

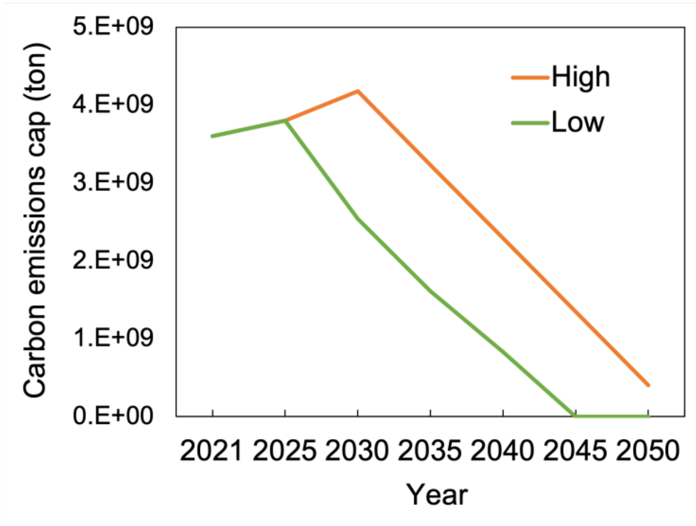


Figure 4. Carbon emission trajectories under high and low emissions caps.

PHS capacity cap. The Chinese government has issued plans for developing PHS facilities from 2021 to 2035 (NEA, 2021). Based on available literature and government plans, we expect total PHS capacity to increase to 62 GW by 2025, to 120 GW by 2030, and possibly to 421 GW by 2035. In our study, we established five PHS capacity caps. Under the base scenario, we place no restrictions on the construction of new PHS capacity. We then set the PHS capacity to reach 62 GW and 120 GW in 2025 and 2030, respectively. Additionally, we set the sensitivity analysis of PHS capacity to reach 200 GW, 300 GW, and 400 GW by 2035, respectively. The capacity for subsequent years is derived from the results of our optimization model.

Cost of renewable energy. We examined high and low cost scenarios for RE resources. The costs for other power generators and energy storage are also modeled based on the two scenarios. Figure 5 shows the cost data for renewable power generators, fossil fuel power generation, and energy storage (2- and 4-h batteries and PHS) from 2021 to 2050, which we obtained from BNEF 2022.

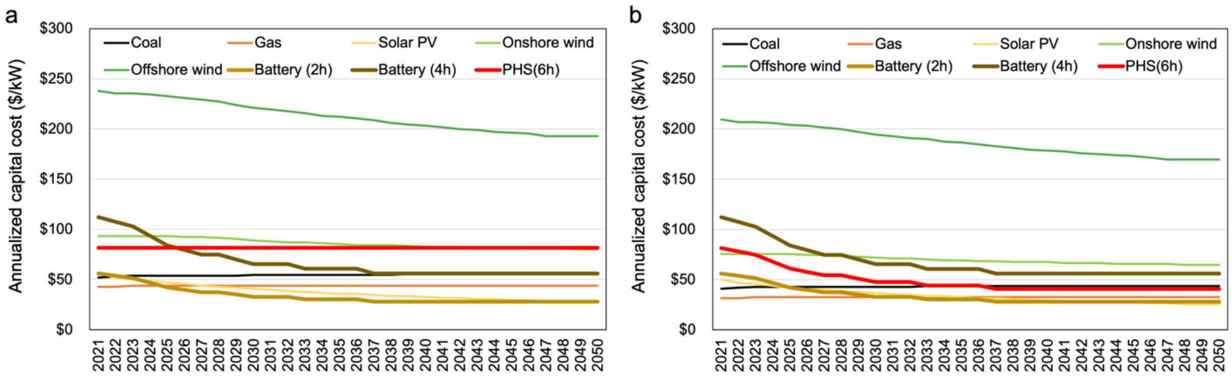


Figure 5. Annualized (a) high capital costs and (b) low capital costs for each type of power generation plus energy storage.

2.2 Results

This section presents the results of applying the GridPath model and selected parameters to our 14 scenarios.

2.2.1 Mix of installed capacity and power generation

The carbon emissions cap is a driving force for China's transition to RE power generation. Figure 6 presents the effects of low and high caps on the optimal mixes of installed capacity and power generation. As expected, under the high carbon emissions cap, the installed capacity of RE increases more gradually than under the low cap. On the other hand, under the high carbon emissions cap the installed capacity of coal-fired power plants increases from 2025 to 2030, peaking in 2030 (Figure 6a). The resulting higher level of coal-fired power generation in 2030 is shown in Figure 6b. Under the low carbon emission cap, all coal-fired power generation is phased out by 2045 and replaced by non-fossil fuel and coal with carbon capture and storage (CCS).

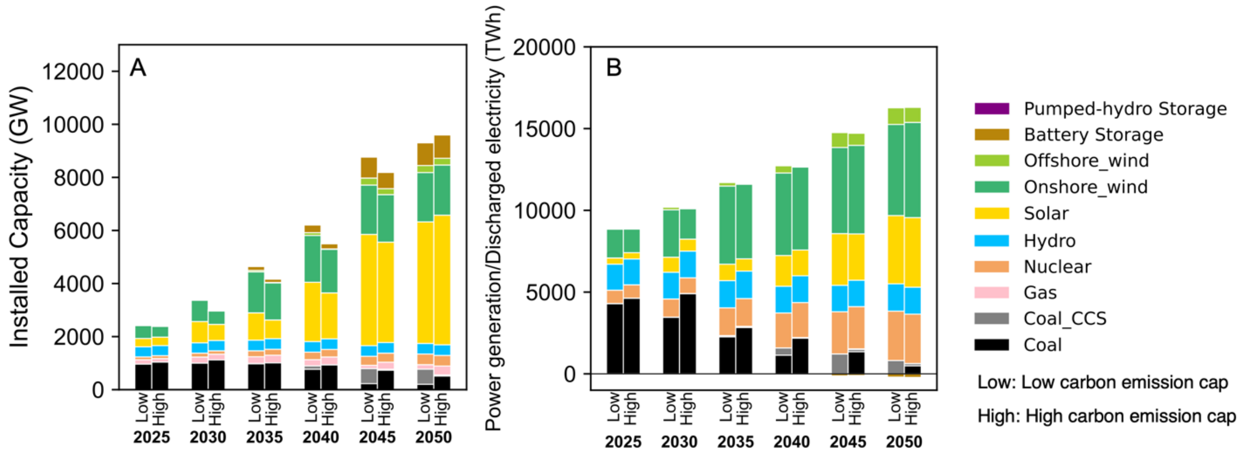


Figure 6. (A) Installed capacity and (B) power generation in the base scenarios given high and low carbon emissions caps.

Figure 7 shows the percentage of non-fossil fuel in total power generation from 2025 to 2050 under the two carbon emissions cap scenarios. The percentage of non-fossil fuel under the low cap always exceeds that under the high cap. It is feasible to achieve 80% non-fossil fuels by 2035 under the low carbon emissions cap, which is consistent with our previous research findings (Abhyankar et al., 2022).

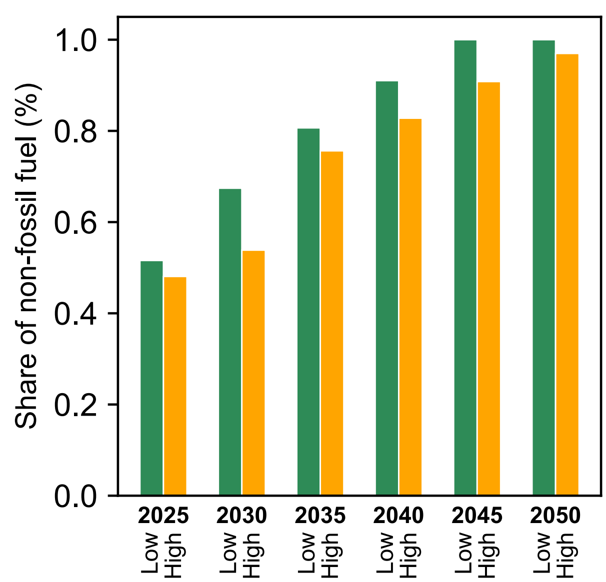


Figure 7. Percentage of non-fossil fuels in total power generation in the base scenario under high and low carbon emissions caps.

2.2.2 Installed capacity of PHS under three cost scenarios

We used GRIDPath to conduct sensitivity analysis of PHS costs on installed capacity. Our findings show that reducing PHS costs directly increases its installed capacity. Table 3 shows the installed capacity of PHS and corresponding system costs under various cost assumptions.

Table 3. Installed PHS capacity and total system costs under four PHS cost scenarios.

Scenario	**Carbon cap**	**RE cost**	**PHS cost**	**PHS capacity (GW)**						**Total cost ($)**
				2025	**2030**	**2035**	**2040**	**2045**	**2050**	
Base	Low	Low	Base	32.5	32.5	32.5	32.5	32.5	32.5	5.06E+12
BasePHScost			Base	62	120	120	120	120	120	5.15E+12
LowPHScost			Rate of decrease same as batteries	62	120	143	148	149	234	5.13E+12

Our analysis indicates that under the base scenario, no new PHS is installed. If the rate of PHS cost reduction mirrors that of batteries, as cited in the BNEF report (2022) (Low_PHScost scenario), installed PHS will increase substantially, from 62 GW in 2025 to 232 GW in 2050. Coinciding with the lower PHS costs and increased capacity under this scenario, total system costs decrease by 0.4%.

We further analyze the effects of PHS cost on the installed capacity of total energy storage (Figure 8). As the capacity of PHS storage increases, the installed capacity of battery storage declines. Under the low PHS cost scenario the installed capacity of batteries decreases from 858 to 632 GW in 2050. This result suggests that PHS storage and battery storage may be interchangeable within the power system, and PHS storage can substitute for battery storage.

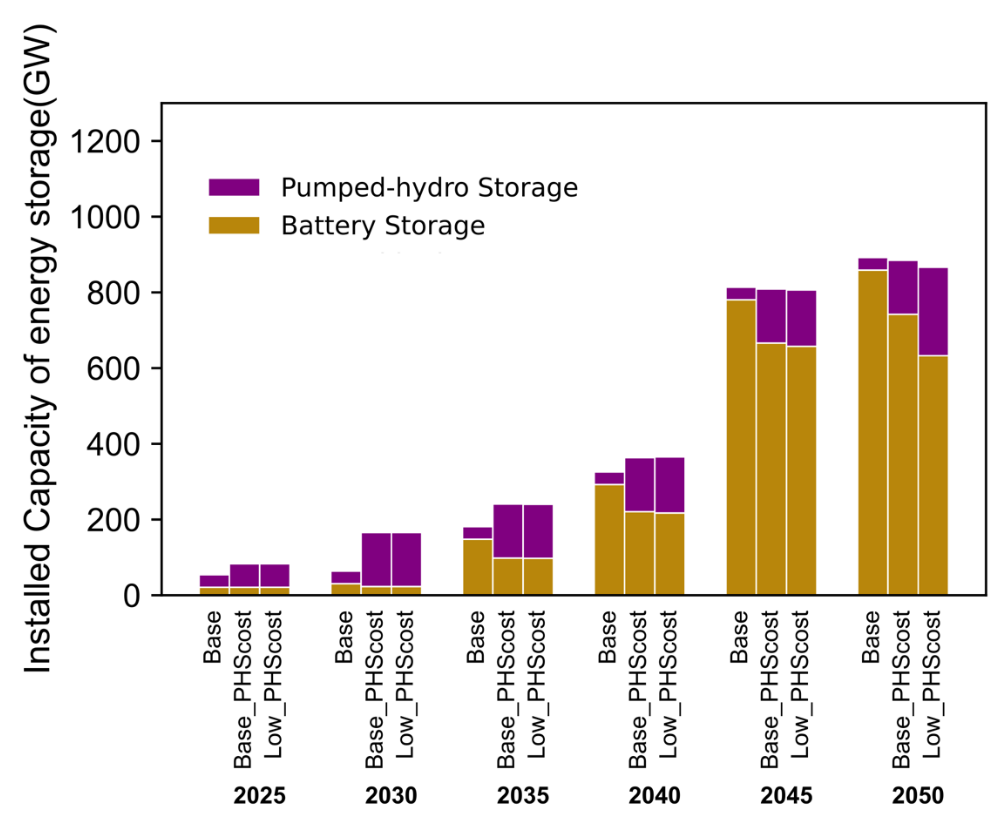


Figure 8. Energy storage capacities under three cost scenarios.

2.2.3 Distribution of installed capacity by province

Figure 9 shows the distribution of PHS installed capacity by province in China under three scenarios. In the base scenario, approximately 50% of PHS capacity is installed in Guangdong, Zhejiang, and Anhui provinces. With a slight decrease in PHS cost (Low_PHScost scenario), additional PHS facilities are established in Hebei, Shanxi, Zhejiang, Xizang, Qinghai, and Guizhou provinces.

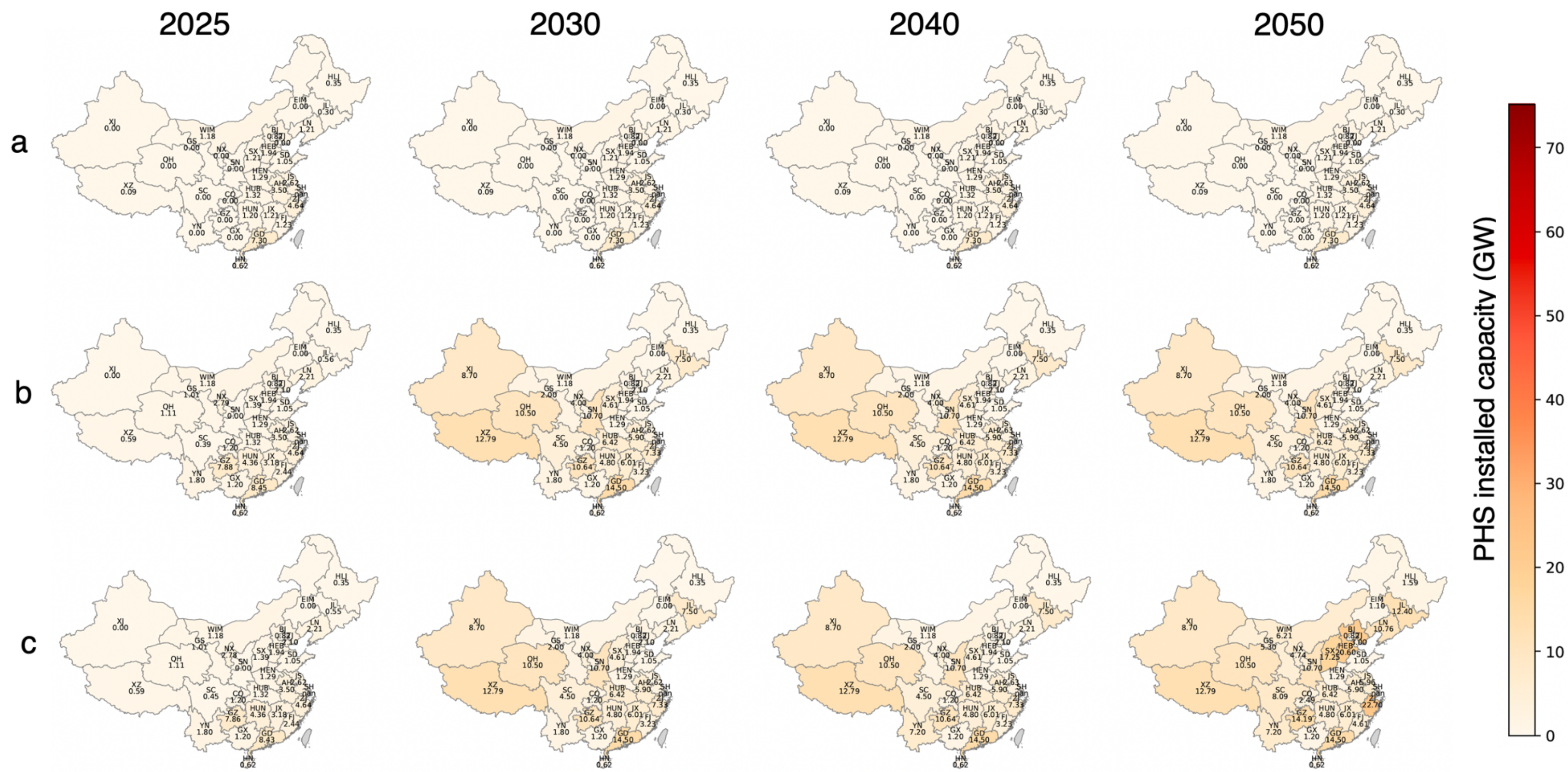


Figure 9. Installed PHS capacity by province given various PHS costs: (a) base scenario, (b) PHS capacity cap with existing PHS cost, and (c) PHS capacity cap with low PHS cost.

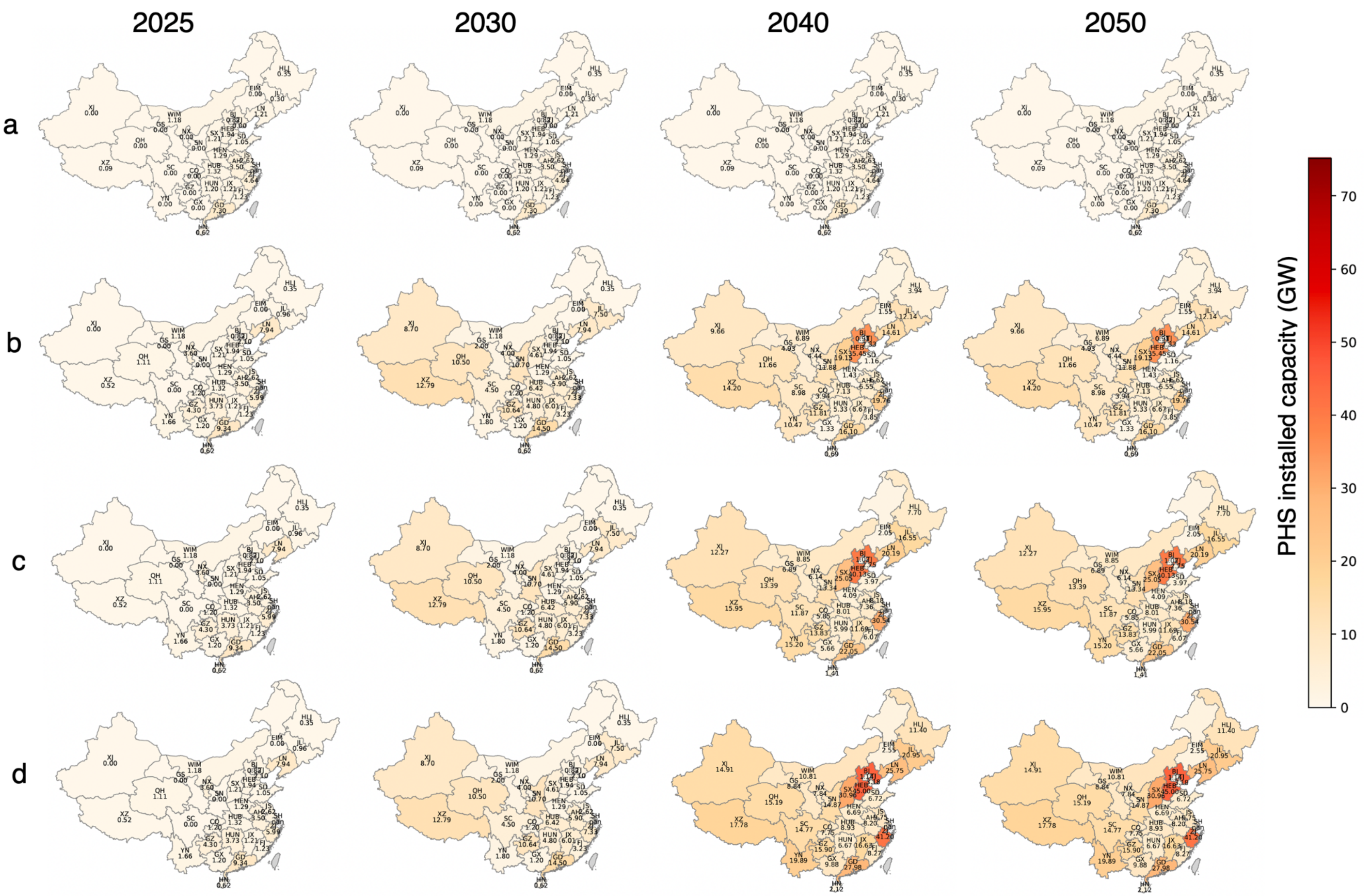


Figure 10. Installed PHS capacity by province under various PHS capacity caps: (a) base scenario, (b) 200 GW capacity cap, (c) 300 GW capacity cap, and (d) 400 GW capacity cap.

As depicted in Figure 10, our findings suggest that the distribution of installed PHS would not change significantly even given a slight increase in PHS installed cap from 200 to 400 GW. Table 4 lists the provinces that likely would have high installed capacities of PHS under various PHS cost scenarios.

Table 4. Provinces having high installed capacity of PHS under six scenarios.

Province	**Installed capacity in 2050 (GW)**					
	Base	PHS200	PHS300	PHS400	BasePHScost	LowPHScost
Zhejiang	4.6	35.4	38.8	49.7	6.5	17.8
Guangdong	7.3	17.3	20.9	35	14.4	14.5
Shanxi	1.2	3.4	17.3	19.1	1.2	17.3
Liaoning	1.2	16.3	16.3	21.2	12.7	13.2
Jiangxi	1.2	6.9	9.0	8.1	1.2	6.0
Hebei	1.9	31.9	31.9	34	27.3	31.9
Yunnan	0	9.2	13.1	17.6	5.0	9.4
Guangxi	0	6.0	13.4	21.3	3.7	1.2

2.3 Discussion

Our study reveals that our base scenario, which involves minimizing costs of the power system, does not favor additional installation of PHS, and its capacity plateaus at 32.5 GW, due to relative higher costs compared with batteries. Conversely, the installed capacity of battery storage increases significantly from 21 to 858 GW from 2025 to 2050, offering a more cost-effective means of mitigating the intermittency of renewable energy and meeting growing demand. As the installed capacities of PHS increase, the need for battery storage capacities decreases since they are substituted by PHS.

The scale of PHS installation is influenced significantly by its cost. If the rate of decrease in cost for PHS is equivalent to that for batteries, which is likely to be overly optimistic, the installed capacity of PHS increases significantly from 120 GW in 2030 to 232 GW by 2050.

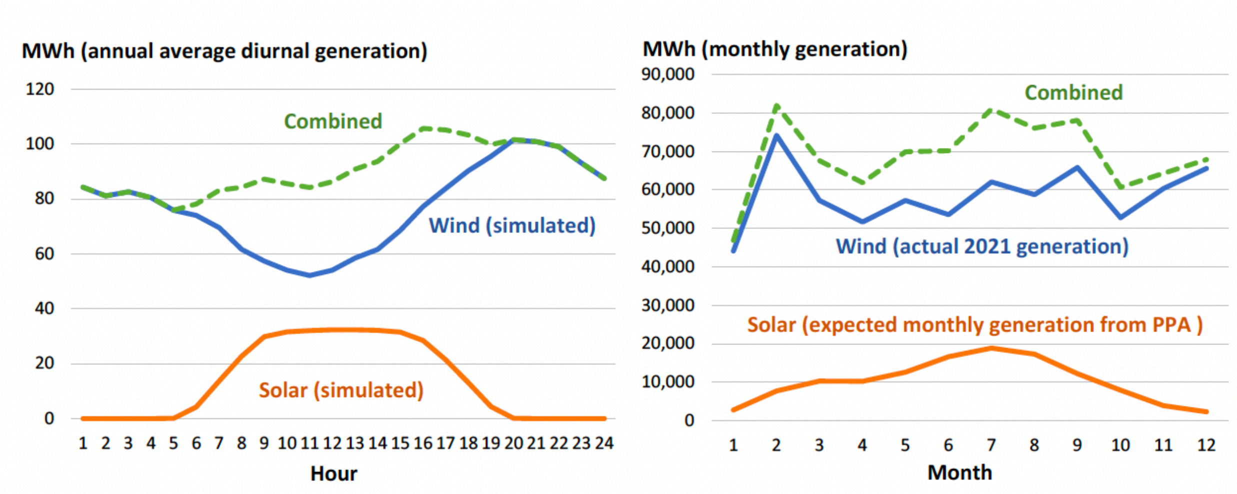
Increasing the capacity of PHS does not, however, affect total system costs significantly. Our findings indicate that if PHS installed capacity increases from 200 to 400 GW, total system cost would increase by only 0.6% to 2% based on the projected costs of PHS in 2035. As much, other factors such as local grid conditions may play a major role in determining the appropriate extent of PHS.

3. Hybrid power plants

Hybrid power systems combine two or three renewable energy (RE) sources, thermal power generation, and energy storage technologies. RE resources, although essential for a sustainable future, have several shortcomings. They are intermittent and variable, as solar and wind energy depend on weather conditions, leading to fluctuations in production and difficulty maintaining a consistent energy supply. Coupling renewables with storage increases the system's ability to monetize the VRE stream. Hybrid systems minimize the risks of RE variability and maximize the utility of interconnected resources. By coupling traditional and emerging energy technologies, plant operators increase the stability and reliability of power generation and boost power output while avoiding an investment in new infrastructure.

Studies show that combining technologies to leverage the interchangeable nature of different resources can lower the overall cost of energy to the power plant or increase the value of that energy within the electricity system (Dykes et al., 2020). In the United States the electricity market includes capacity markets, energy markets, and ancillary service markets. Historically, the inherent variability and uncertainty of renewables meant that they either could not participate or could claim only a small capacity credit in the capacity and ancillary service markets. As the need to ensure sufficient capacity and ancillary services increases, market structures may shift toward increasing revenue from those services while reducing revenues from energy markets.

Solar energy, regardless of its location on the globe, has a diurnal cycle (Lewis, 2007). The season of year and latitude of the location dictate the profile of that diurnal cycle. Figure 11 shows an example of the temporal profiles (diurnal and seasonal) for solar and wind power in Wheatridge, Oregon, USA.



Note: PPA = power purchase agreement.

Figure 11. Annual average diurnal and monthly generation of Wheatridge wind+PV+storage plant (Bolinger et al., 2023). Results do not include battery charging or discharging.

As shown in Figure 11, solar energy potential increases in the morning after sunrise, peaks in the middle of the day, and declines until it stops after sunset. In addition, the summer months have higher maximum potential irradiance (Bolinger et al., 2023). Wind energy resources vary widely depending on location. In every location (Figure 11), there is much more variability in wind than in solar resources, with a slight trend toward lower production in the middle of the day and higher production at night, plus higher overall production in the winter than in the summer. Combining solar and wind energy increases the complementary nature of renewables and decreases overall variability of RE resources, thereby increasing the predictability and controllability of power generation.

Some markets, many of which have a high penetration of wind and/or solar sources, are already shifting toward models such as that of the PJM Interconnection, in which the proportion of hybrid plant revenues from energy has declined, while a larger percentage of revenue is allocated to capacity payments (PJM Interconnection, 2017). In an electricity market dominated by capacity and ancillary services, which is likely to reflect future energy systems that incorporate a high proportion of renewable generation, the profitability of a plant depends primarily on its ability to (1) maximize the capacity value it provides to the electricity system and (2) provide ancillary services on demand. Hybrid power plants, for instance, PV plus storage systems, are able to fully monetize the federal investment tax credit (ITC) for solar, as long as the batteries are charged entirely from electricity produced by solar (Elgqvist et al., 2018).

Starting January 1, 2025, the 2022 federal Inflation Reduction Act (IRA) (U.S. Congress, 2022) will replace the previous Production Tax Credit (PTC) with the Clean Energy Production Tax

Credit, and the former ITC with the Clean Electricity Investment Tax Credit. Those tax credits function similarly to the ITC/PTC and generally are calculated as for the ITC and PTC but are not tied to specific technologies. They are applicable to any type of generation facility (including energy storage systems eligible under ITC) that are projected to produce zero greenhouse gas emissions. The new IRA credits will be phased out as the United States achieves its targets for reducing greenhouse gas emissions.

At the end of 2021, there were nearly 300 hybrid plants (>1 MW) operating across the United States, providing nearly 36 GW of generating capacity and 3.2 GW/8.1 GWh of energy storage. Hybrid PV+storage plants are by far the most common (140) and have the greatest storage capacity (2.2 GW/7.0 GWh). On average, operational PV+Storage plants provide significantly higher storage ratios (53%) and longer durations (3.2 h) than other hybrid types. By co-locating PV and batteries, the batteries are eligible for the federal investment tax credit for solar; can save on shared equipment, interconnection, and permitting costs; capture otherwise curtailed energy; and facilitate intraday energy shifting. Furthermore, using variable-speed generators paired with batteries provides greater dispatch flexibility, making them more attractive for grid operations. Although PV hybrids have become the most common, the 2022 IRA gave standalone storage access to the investment tax credit (ITC) starting in 2023, which might affect future choices regarding hybridization.

There are nearly 20 hybrid plant configurations in addition to PV+storage, including several fossil hybrid categories (each dominated by the fossil component) and others including wind+storage, wind+PV, wind+PV+storage, and geothermal+PV (Bolinger et al., 2023) (Figure 12).

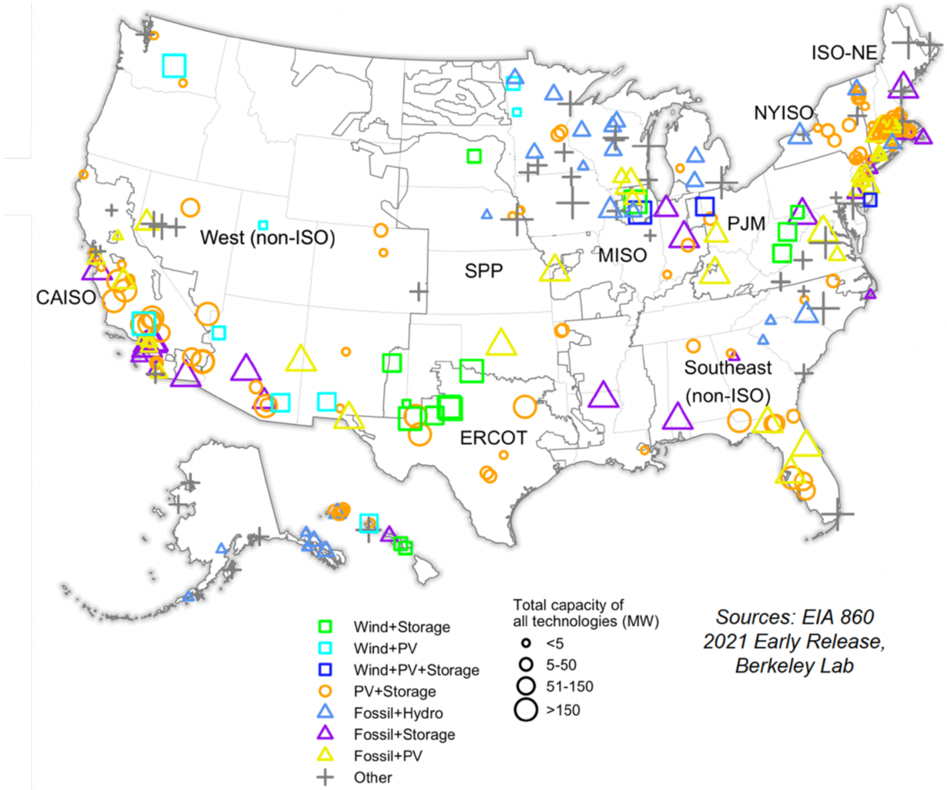


Figure 12. Distribution of hybrid plants across the United States at the end of 2021 (Bolinger et al., 2023).

At the close of 2021, 42% (285 GW) of all solar and 8% (19 GW) of all wind in interconnection queues were proposed as hybrids (up from 34% and 6% in 2020). Solar+Storage is the dominant hybrid type in queues, with nearly 20 times the proposed capacity of Wind+Storage. California, through the California Independent System Operator Corporation (CAISO), and the West are biggest contributors, but other regions are increasing capacity (Figure 13).

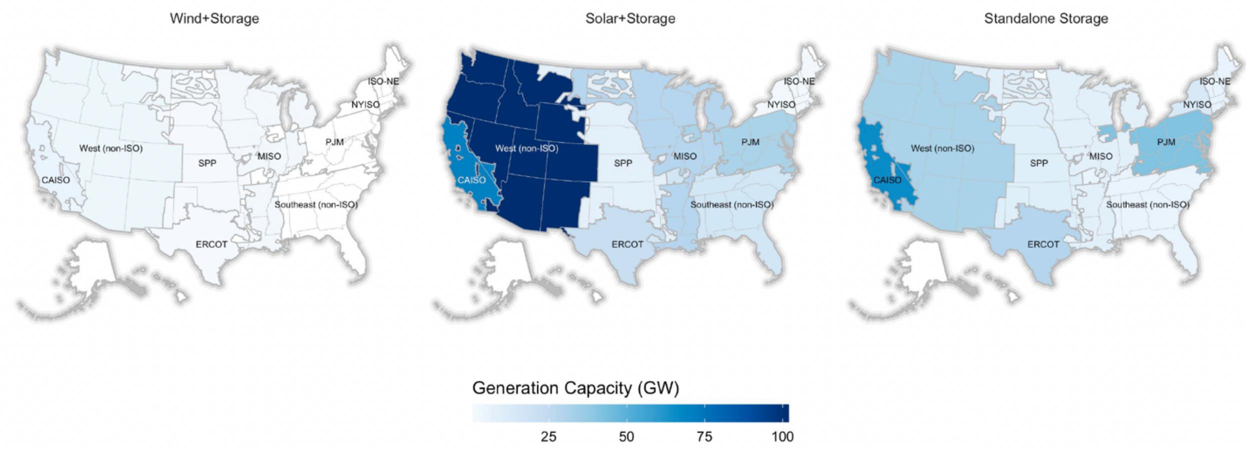


Figure 13. Generation capacity of hybrid power plants and standalone storage by electricity market (Bolinger et al., 2023). Not all of this capacity will be built.

Some studies have focused on how to maximize the benefits of hybrid power plants and the effects of hybrid power plants on local transmission. For example, Montañés et al. (2022) found that the net value of solar and wind hybrids is affected primarily by the duration and capacity of the associated battery. Given the current tax incentives, the most appealing hybrids typically feature a 2-h battery duration, with 4-h a close second. Battery size is recommended to match either 25% or 100% of the solar generator nameplate capacity, depending on the location.

Kemp et al.'s 2023 study investigated the effects of hybrid power plants on local transmission in congested regions. They found that hybrid power plants alleviate congestion in all load centers within the study's scope. In VRE-rich areas, the congestion relief from hybrid power plants depends not only on their precise location, but on the degradation characteristics of the storage technology and whether charging from the grid is allowed. Storage technologies having lower degradation and those that utilize grid charging produce more congestion-friendly hybrids than those having higher degradation or that exclusively charge from the VRE generator. Therefore, technological advances in energy storage and policy decisions will affect the results.

In both load centers and VRE-rich areas, renewable power plants hybridized with a 4-h battery significantly increase revenue (Kemp et al., 2023). For hybrids in VRE-rich areas, expanding transmission capacity typically increases plant revenues, although in some cases decreases revenues, including cases in the Electric Reliability Council of Texas (ERCOT) and among those hybrids that utilize grid charging.

PHS, the most widespread and mature energy storage technology, can be adapted to support both a grid connection and a standalone hybrid hydro-wind-solar grid system (Vieira, 2009). Figure 14 shows a typical conceptual pumped hydro storage system with wind and solar power options for transferring water from a lower to an upper reservoir (Simão and Ramos, 2020).

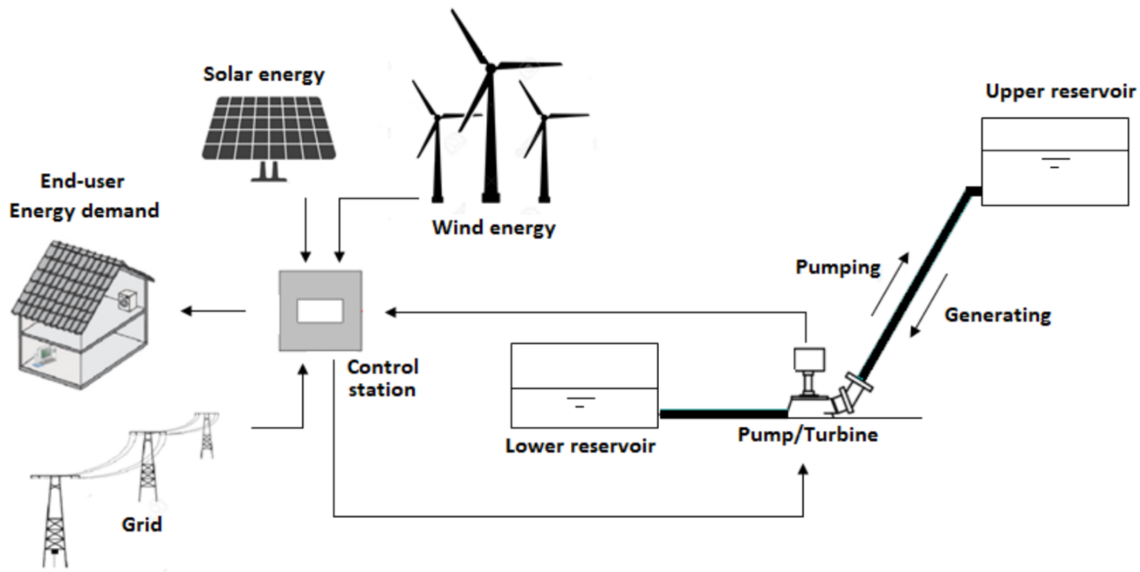


Figure 14. Hybrid hydro-wind-solar system with pumped hydro storage (Simão and Ramos, 2020).

Xu et al. (2019) explored the optimal operation and hydro storage sizing for a hybrid wind-hydro power plant, finding an annual profit of 11.91% if energy is purchased during low-demand periods and sold during high-demand periods. More detailed information on feasibility, optimal design, and operation of hybrid pumped-hydro systems can be found in Kocaman and Modi (2017); Kapsali et al. (2012); and Deason (2018).

In addition, the joint probability distributions for different renewable resources at different geospatial and temporal scales are critical for the optimal planning of hybrid power plants, increasing the predictability and controllability of the joint assets. This area of study presents potential for valuable future research.

4. International policies and incentives

Pumped hydro storage (PHS) currently is receiving renewed interest from diverse stakeholders, including developers, utilities, investment firms, and regulators. Policymakers increasingly have recognized the need for flexible and reliable long-duration energy storage, including PHS. By providing stability, load leveling, and peak-shaving capabilities. PHS offers solutions to the challenges that arise when integrating VRE sources into the grid (Denholm and Kulcinski, 2004; Garcia-Gonzalez et al., 2008).

Several countries and regions have begun to encourage and support the development of PHS. For instance, the EU has funded several PHS research and innovation projects through its Horizon 2020 program. Those initiatives (European Commission, 2020; XFLEX HYDRO, 2023) aim to improve the efficiency, flexibility, and environmental performance of PHS, while also exploring innovative concepts, such as hybrid and offshore pumped storage systems.

According to the 2021 pumped storage report for the United States (NHA, 2021), the country currently has 43 PHS plants. Those facilities, having a total installed power capacity of 22 GW and approximately 553 GWh of energy storage, account for 93% of all utility-scale energy storage in the country. No significant additions to the PHS infrastructure have been made in the past two decades, however. The DOE's Hydropower Vision (DOE, 2016) report identified a potential increase of 16.2 GW in pumped hydro storage by 2030, and an additional 36 GW by 2050, totaling 57 GW of domestic pumped storage. The Infrastructure and Investment Jobs Act (IIJA) (U.S. Congress, 2021) allocated US$909 million for conventional hydropower, pumped storage, and the marine energy industry. Specifically, Section 40334 of the IIJA authorizes $10 million to be appropriated in $2-million increments in fiscal years 2022 through 2026 to provide financial assistance to any eligible entity for carrying out project design, transmission studies, power market assessments, and permitting for a PHS project to facilitate the long-duration storage of intermittent renewable electricity. Furthermore, the IIJA allocated US$75 million for efficiency upgrades to existing hydroelectric facilities, including targeting a minimum 3% efficiency improvement for pumped storage. The American Water Infrastructure Act of 2018 directed the Federal Energy Regulatory Commission (FERC) to introduce a swift licensing process—2 years from application to final decision—for qualifying non-powered dams and closed-loop PHS projects (Uria-Martinez et al., 2021).

Japan currently has a total installed PHS capacity of 27 GW. PHS operation, governed by the dispatch rule established by Japan's Organization for Cross-regional Coordination of Transmission Operators, has a first-order priority, similar to thermal power control. PHS production does not participate in Japan's electricity market, and the power generation discharged from PHS bears the costs not only for the power lost during pumping and generating but also for the grid tariff related to power loss.

China's rapid growth in electricity demand and renewable energy deployment has increased interest in PHS systems to support grid stability and integrate VRE resources. Chinese policymakers have recognized the strategic significance of PHS in their energy transition roadmap and have been implementing a suite of policies, regulations, and incentives to advance such systems. The NDRC of the People's Republic of China established and gradually has improved the mechanism for formulating pumped storage tariffs, a critical step toward supporting the sound development of PHS (Nibbi et al., 2022). In recent years, the Chinese government has outlined its vision for PHS development in several key policy documents, such as the 13th Five-Year Plan for Energy Development (covering 2016–2020). Provincial governments also have developed their own plans and strategies for deploying PHS based on local resource availability, grid conditions, and renewable energy targets. For instance, provinces that have abundant hydropower resources, such as Yunnan and Sichuan, have prioritized the development of large-scale PHS projects to facilitate integration of renewables and enhance regional grid stability (Katsaprakakis and Christakis, 2009).

Incentives for PHS development, although found worldwide, remain limited. The expansion of PHS also faces problems such as insufficient convergence with market development. To facilitate further PHS growth requires more supportive policy measures, such as expanded incentives and financial support, market design and compensation, and integration with RE policies. In this context, we analyze the incentives for energy storage that have been developed in the United States. This information can provide valuable insights for China to consider moving forward.

4.1 Incentives for energy storage in the United States

In response to a confluence of early market and state policies such as utility procurement mandates, the installation of utility-scale battery storage in the United States has been concentrated in the PJM Interconnection and CAISO markets. As of 2019, more than 60% of large-scale battery storage was in either the PJM Interconnection or CAISO region (U.S. Energy Information Administration [EIA], 2021). Although four markets (CAISO, ERCOT, NYISO, and ISO-NE) were expected to host 97% (approximately 3.3 GW) of new standalone storage capacity between 2021 and 2023, other states were also projected to develop significant solar-plus-storage facilities (approximately 2.5 GW) (EIA, 2021). About 15 states have adopted energy storage policies encompassing procurement targets, financial incentives, regulatory adaption, demonstration programs, and/or consumer protections (Pacific Northwest National Laboratory, ongoing).

4.1.1 Procurement targets

State-mandated procurement targets require utilities to obtain a stipulated amount of energy storage by a specific deadline. Procurement targets offer investors encouraging signals while minimizing regulatory uncertainty. Targets can range from broad requirements for a certain number of megawatts to mandates that emphasize the adoption of specific storage technologies. Procurement targets have been established by state utility commissions (such as in California, Colorado, Massachusetts, Nevada, and New York) and state legislatures (as in Oregon and New Jersey). Currently, 11 states (including Illinois, Virginia, Connecticut, and Maine) have adopted procurement targets. California was the first state to do so, requiring 1,825 MW of energy storage by 2020, limiting pumped storage to 50 MW of the total procurement goal and including 500 MW of distributed storage.

In 2015, Oregon directed its two largest investor-owned utilities to each install a minimum of 5 MWh of storage by 2020, up to a maximum of 1% of the 2014 peak load. In 2017, the Nevada legislature directed the public utility commission to establish targets for procuring 1,000 MW by 2030, setting an initial target of 100 MW by December 31, 2020.

New Jersey enacted its Clean Energy Act in 2018, setting a target of 2,000 MW of energy storage by 2030. Also in 2018, Massachusetts passed the Act to Advance Clean Energy, directing the Massachusetts Department of Energy Resources to set an energy storage target of 1,000 MWh by 2025. Virginia’s target was enacted by law in 2020: 3,100 MW of energy storage by 2035.

In 2021, Illinois passed a law directing the Illinois Commerce Commission to establish storage procurement targets by 2032 for utilities serving more than 200,000 customers. Connecticut established a goal to achieve 300 MW of storage by 2024, 650 MW by 2027, and 1,000 MW by 2030. Maine's goal is to achieve 400 MW of installed storage capacity by 2030, with an interim target of 300 MW by 2025. Initially, New York aimed to procure 3 GW of energy storage by 2030; however, Governor Kathy Hochul recently announced plans to double that target to reach 6 GW by the same year.

4.1.2 Financial incentives

Financial incentives typically take the form of direct subsidies or tax credits made available to utilities, the production industry, or end-use customers for developing energy storage resources.

Investment tax credit

U.S. Internal Revenue Service tax guidance identifies batteries connected to either wind or solar farms as potentially eligible for the federal ITC. Allowing utilities to deduct a quarter of the installation costs is one reason companies are investing heavily in hybrid resources for nearer-term capacity needs. The Arizona Public Service Corporation was among the first to choose solar plus storage over a natural gas peaker in 2018. Partly because of the ITC, solar/wind plus battery installations are expected to quadruple by 2023.

Production Tax Credit

With the passing of the IRA in 2022, a range of new and expanded tax credits were introduced to support the domestic manufacturing sector. We expect those tax incentives to encourage growth in the domestic manufacture of renewable energy components and to facilitate financing and joint ventures that leverage those incentives. The IRA (Section 45X) introduced a new production tax credit, the Advanced Manufacturing Tax Credit. This credit is aimed at manufacturers of eligible components produced within the United States and sold to unrelated parties. The eligible components encompass various elements found in wind, solar, and battery projects, including PV cells, PV wafers, solar modules, blades, nacelles, inverters, battery cells, and modules, among others. The credits differ depending on the component, with some credits tied to production costs and others to a capacity factor.

Sale of Tax Credits

The IRA provides that project owners who are unable to use refundable credits may sell all or part of their tax credits for cash. This novel feature has the potential to significantly transform the market for financing the green technology industry. Previously, tax-driven structures such as partnership flips, sale-leasebacks, and inverted leases were used to monetize tax credits for renewable energy if the sponsors were unable to use the credits themselves.

Time-of-Use Rates

Some jurisdictions have adopted time-of-use (TOU) rates, which pair higher energy rates with periods that experience high demand. TOU rates send an economic signal to customers, encouraging them to reduce usage or meet demand through customer-sited resources, such as battery storage, during periods of peak load.

Other Financial Incentives

California's Self-Generation Incentive Program, which represents the largest financial incentive policy in the United States, allocated $450 million for behind-the-meter storage. In 2022, Maryland became the first to offer a state income tax credit for energy storage: as much as $5,000 for residential customers and $75,000 for commercial and industrial customers, subject to a program total of $750,000 per year.

In September 2022, the New Jersey Board of Public Utilities (BPU) published its Storage Incentive Program (SIP), which includes incentives for standalone energy storage devices, both in front of and behind the meter. Thirty-eight percent of the funds represent a fixed annual incentive to be paid in dollars per kilowatt hour of energy storage capacity. The rest of the SIP takes a pay-for-performance structure in which front-of-meter storage equipment is compensated based on the amount of carbon emissions the device eliminates. Behind-the-meter storage resources are compensated based on the successful injection of power into the distribution system. The proposal also states that the BPU seeks to maximize private investment in energy storage systems by allowing private investors to own and operate the energy storage resources, collect revenue from the wholesale electricity market, use behind-the-meter resources to reduce electricity costs, or participate in a service that aggregates distributed energy resources.

4.1.3 Regulatory adaptation

Regulatory adaptation refers to state energy regulations that are revised to facilitate development of energy storage opportunities. All states that have a storage policy have a renewable portfolio standard or a nonbinding renewable energy goal. Competitive access to storage can be expanded by updating resource planning methods or enabling storage through electricity rate proceedings.

Many states require utilities to create integrated resource plans (IRPs) to demonstrate how projections of long-term demand will be met cost effectively through a combination of generation, transmission, and energy-efficiency investments. Recently, at least 20 states have incorporated energy storage in utility resource plans. Nonetheless, incorporating storage into IRPs can be challenging because of its unique operational constraints, varying points of interconnection, multiple applications, and policy and regulatory uncertainty that may affect system profitability.

4.1.4 Demonstration programs

A state sometimes explicitly authorizes, and even funds, energy storage projects to gather data and study operation. Incremental deployment through demonstrations enables states to examine the benefits and logistics of energy storage. Nine states have adopted programs that support storage demonstration projects. Washington state's Clean Energy Fund allocated $14.3 million to utilities to deploy four utility-scale projects that test various energy storage technologies and uses. Massachusetts granted $20 million to demonstrate various storage applications via its Advancing Commonwealth Energy Storage program. Utah law permits utilities to invest in storage resources. New York's Reforming Energy Vision Program facilitates interactions between developers and utilities, issuing requests for proposal, coordinating independent evaluations, and matching projects with utilities. Maryland has approved a pilot program for utilities to develop projects under various ownership frameworks.

4.1.5 Consumer protections

Two states have enacted legislation to safeguard the rights of customers who install energy storage. In 2017, Nevada prohibited utilities from assigning customers who own an energy storage resource to a separate rate class solely for that reason and mandated utilities to establish optional TOU rates. Colorado, in 2018, passed a law granting utility customers the right to install storage equipment and directed the Colorado Public Utility Commission to establish rules for efficient interconnection procedures.

4.2 Energy storage market—United States as example

We again refer to the United States, this time to summarize operation of an energy storage market mechanism and to provide valuable insights for China's consideration. In the United States, FERC Order No. 841 stipulated that energy storage resources may be sold on the capacity, energy, or ancillary service markets operated by regional transmission organizations/independent system operators (RTOs/ISOs) (excluding ERCOT) (FERC, 2018) (Table 5).

Table 5. Applications of utility-scale energy storage (National Renewable Energy Laboratory [NREL], 2019)

Application	Description	Duration of Service Provision	Typically Valued in U.S. Electricity Markets?
Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Hours	Yes
Firm Capacity	Provide reliable capacity to meet peak system demand.	4+ hours	Yes, via scarcity pricing and capacity markets, or through resource adequacy payments.
Operating Reserves			
• Primary Frequency Response	Very fast response to unpredictable variations in demand and generation.	Seconds	Yes, but only in a limited number of markets.
• Regulation	Fast response to random, unpredictable variations in demand and generation.	15 minutes to 1 hour	Yes
• Contingency Spinning	Fast response to a contingency such as a generator failure.	30 minutes to 2 hours	Yes
• Replacement/ Supplemental	Units brought online to replace spinning units.	Hours	Yes, but values are very low.
• Ramping/Load Following	Follow longer-term (hourly) changes in electricity demand.	30 minutes to hours	Yes, but only in a limited number of markets.
Transmission and Distribution Replacement and Deferral	Reduce loading on T&D system during peak times.	Hours	Only partially, via congestion prices.
Black-Start	Units brought online to start system after a system-wide failure (blackout).	Hours	No, typically compensated through cost-of-service mechanisms.

The current market-based business case for energy storage pertains primarily to price spreads between peak and off-peak periods. Battery storage systems can take advantage of the spread by recharging during low-price hours at night and discharging during high-price hours in the evening, a strategy known as price arbitrage. Arbitrage maximizes the potential of battery storage because the battery charges when prices of renewable resources are set at $0/MWh on the margin and discharges when expensive gas, coal, or oil are setting the price.

The potential for arbitrage revenues varies across the United States, from a strong potential in renewables-heavy California to a lower potential in the PJM Interconnection, located primarily in the Eastern United States. The EIA's 2021 report includes a survey of applications for battery systems, revealing a growing proportion of capacity dedicated to price arbitrage. In 2021, 59% of battery storage capacity was used for arbitrage, a significant increase from the 17% recorded in 2019. Notably, California saw the addition of 1,800 MW of new battery storage capacity in 2021, with more than 80% of the state's total capacity of 2,339 MW utilized for arbitrage. In contrast, in 2021, the states within the PJM Interconnection added only 7 MW to their 136 MW of battery storage capacity, with less than 1% capitalizing on arbitrage potential (EIA, 2021).

In 2021 93% of new battery storage in the United States was collocated with a renewable resource to charge directly from the zero-cost resource. In regions that anticipate little growth in renewables through 2030, such as PJM, there is little difference between low and high electricity prices during the day, with prices much lower than in markets that have a high penetration of renewables. As the penetration of renewable generating resources grows, the shape of day-ahead hourly price curves will change, and daytime prices will decline.

Figure 15 shows net load curves for the day of January 11, 2015 through 2023, from CAISO data. Four distinct ramp periods emerge. In the morning, starting at around 4:00 a.m., the first ramp of 8,000 MW (known as the "duck's tail") occurs as people wake up and go about their daily activities. The second, in the downward direction, occurs after sunrise, around 7:00 a.m., as solar generation replaces conventional resources, resulting in a downward shift in net load (creating the "belly of the duck"). As the sun begins to set around 4:00 p.m., solar generation ends, and the ISO must deploy other resources to meet the most significant daily ramp, which is a steep increase of 11,000 MW (forming the "arch of the duck's neck"). Following this rapid increase, as demand decreases during the evening hours, the ISO curtails generation to accommodate the final downward ramp.

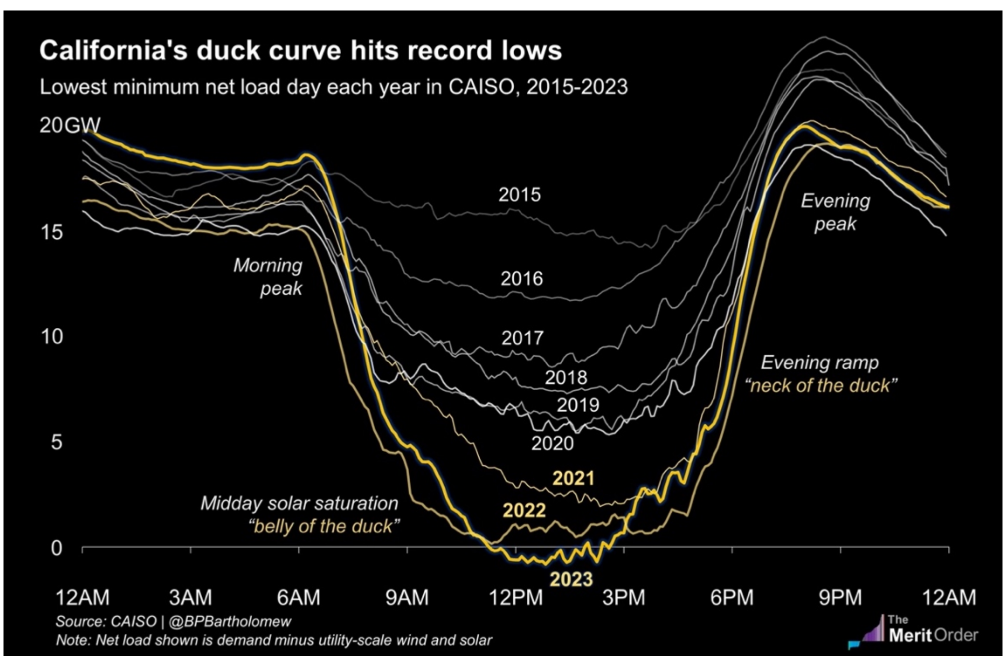


Figure 15. Net electric load curve in CAISO, 2015–2023.

Capacity markets have been used to compensate for available capacity. The market mechanisms typically are limited to brief capacity needs, 4 h or fewer, and provide guaranteed compensation only over short terms (e.g., 1-year capacity markets in many RTOs/ISOs) (Bhatnagar, 2022). There are other ancillary service markets that provide opportunities for shorter-duration battery systems. From products that regulate frequency, which can be activated in just seconds, to spinning reserve products, which require up to an hour, ancillary service markets support the deployment of fast-responding, short-duration battery systems (NREL, 2019).

Throughout the world, new compensation mechanisms for energy storage are emerging that involve long-term revenue guarantees through regulated returns or power purchase agreements. New agreement structures incorporate multipart payment schemes based on capacity availability, energy delivery, and performance. Such structures allow off-takers to mitigate market, technology, and renewable energy generation risks while providing project developers with revenue guarantees (subject to meeting performance requirements). Discussions also are taking place regarding new business models such as the storage-as-a-service model. Those models introduce a paradigm shift by recognizing energy storage as a distinct asset class separate from energy generation that requires its own compensation. Implementation can involve third-party resource owners or multi-utility ownership structures, drawing upon precedents from multiparty transmission ownership. The regulatory changes necessary to accommodate such business models require further development.

5. Policy recommendations

As part of its strategy to transition to a clean power system, China has established ambitious targets for expanding PHS. To evaluate the feasibility of this goal, our study explored a range of scenarios for PHS development in China’s power system by applying a capacity expansion model based on increasing penetration of renewables from 2020 to 2050.

In May 2023, China's NDRC released a Notice on the Capacity Price for Pumped Storage Power Plants and Relevant Matters. The notice proposed a new and comprehensive reform to the electricity pricing structure, further improving the two-part tariff mechanism. The two-part tariff includes energy prices and capacity prices. The energy price is the price charged based on the transaction volume; the capacity price represents the capacity cost in the cost structure of power industry enterprises, i.e., the fixed asset investment cost. The energy price reflects the value of the PHS power station that provides peak shaving services. The capacity price reflects the value of the pumped storage power station when providing ancillary services such as frequency regulation, voltage support, system backup, and black start. Through the capacity price, pumped storage power stations recover costs beyond pumping and generating operations to achieve reasonable returns. The new pricing structure includes ancillary service costs and PHS capacity price, both of which are listed separately from the prices for transmission and distribution. The capacity price for existing and new PHS ranges from 289 to 722 RMB/kW. The NDRC's notice is as an example of improved government policies for supporting the development of PHS.

Based on the results of our scenario analysis and the review of international practices, we offer following recommendations to support sustainable development of PHS in order to accelerate the decarbonization of China’s power grid. First, PHS development policy and targets should be integrated into the comprehensive planning of the electricity system. In particular, the development of PHS must be compared with other storage and generation technologies, as well as transmission solutions, to achieve the optimal scale and locations in support of a clean and reliable power system. Otherwise, a mismatch of PHS projects in terms of location and scale could unnecessarily increase power system cost or tariff.

Second, the current PHS capacity pricing mechanism, based on cost-recovery, could lead to inflated electricity prices. The pricing strategy currently is determined unilaterally by the relevant authorities based on investment costs. Introducing market competition—allowing various PHS developers to bid for PHS projects through an open and competitive process—would more effectively control project costs and, ultimately, electricity tariffs.

Last, fostering inter-provincial collaboration on PHS projects would offer substantial advantages, especially regarding resource/cost sharing and ensuring regional grid stability. If policymakers collaborate with their counterparts in neighboring provinces, they can create a cooperative framework and align regulations to encourage and facilitate cross-province endeavors, laying a solid foundation for the optimal deployment of PHS and other system resources.

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Appendix A: Effects of extremely low PHS cost

This study examined one very aggressive scenario, which assumed PHS cost is only one-fifth of that under the base scenario (1/5PHScost scenario). Comparing the installed capacity of total energy storage versus various PHS costs (Figure A1), we observe a significant surge in PHS installed capacity, from 32 GW in 2025 to 618 GW in 2050, when costs decrease to one-fifth of those in the base scenario. As the capacity of PHS storage increases under the 1/5PHScost scenario, the installed capacity of battery storage declines sharply: from 858 GW to 266 GW in 2050.

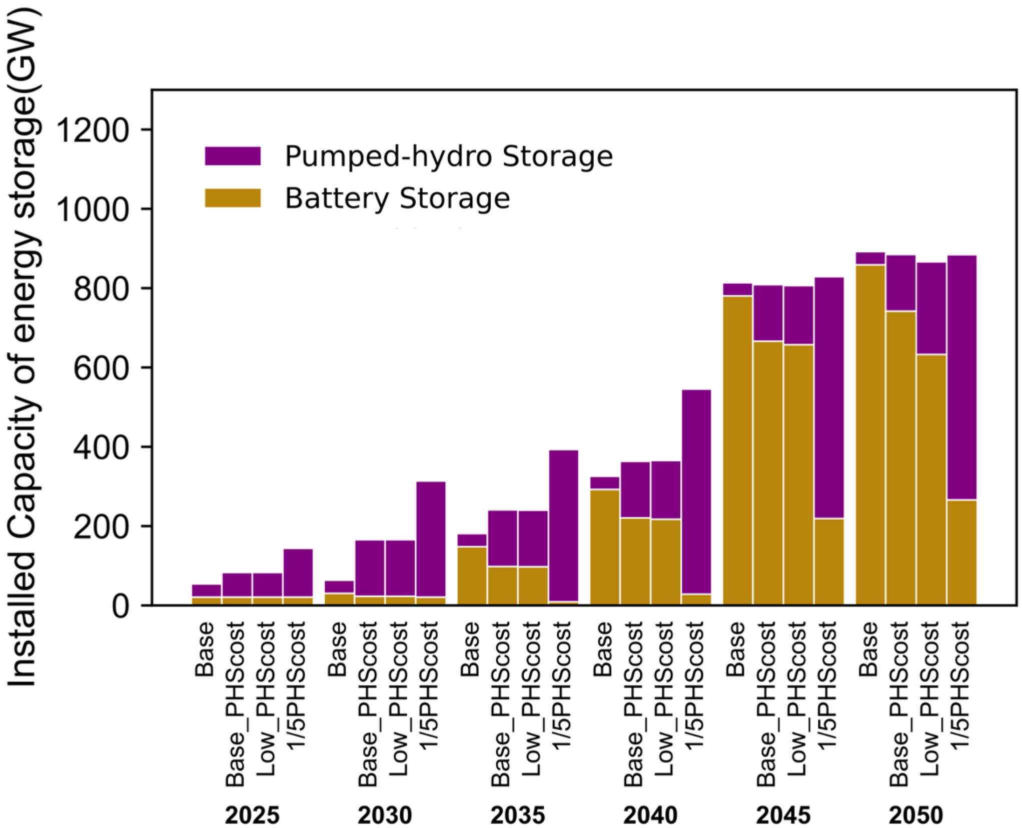

Figure A1. Energy storage capacities under four cost scenarios.

Figure A2 shows the distribution of PHS installed capacity by province in China under the 1/5PHScost scenario. We find that if PHS cost decrease substantially, additional PHS capacity is installed in Guangdong, Zhejiang, Liaoning, Jiangxi, and Yunnan provinces. Table A1 lists the provinces having high installed capacity of PHS given one-fifth of PHS base cost.

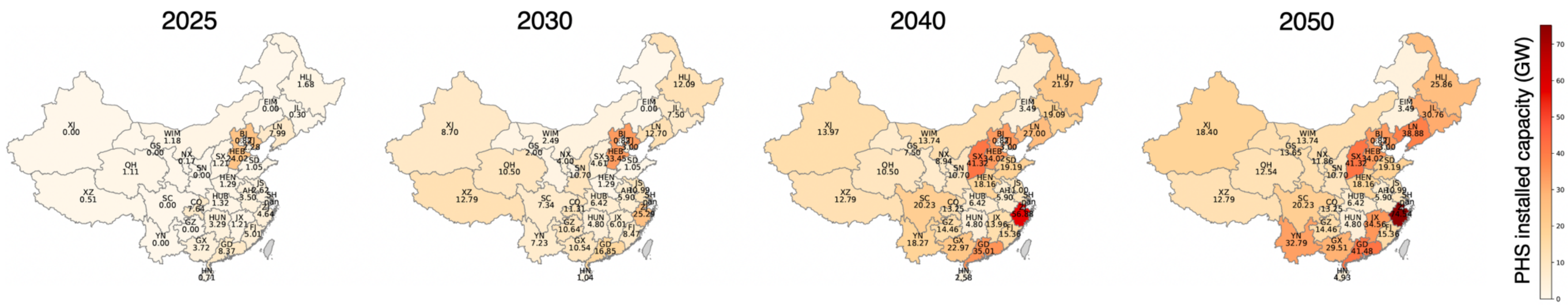

Figure A2. Installed PHS capacity by province under 1/5PHScost scenario.

Table A1. Provinces having high installed capacity of PHS under 1/5PHScost scenario

Province	**Installed capacity in 2050 (GW)**
Zhejiang	74.8
Guangdong	41.5
Shanxi	41.3
Liaoning	38.9
Jiangxi	34.5
Hebei	34.0
Yunnan	32.8
Guangxi	29.5

Appendix B: PHS installed capacities and total system costs under all scenarios

Table B1. Installed capacities of PHS and total system costs under all scenarios

Scenarios	Carbon cap	PHS capacity cap	RE cost	PHS cost	PHS capacity (GW)						Total costs ($)
					2025	2030	2035	2040	2045	2050	
1.Carbon_high_Base	High	No constraint	Low	Base	32.5	32.5	32.5	32.5	32.5	32.5	4.98E+12
2.Carbon_high_cost_high		Set targets of 62 and 120GW for 2025 and 2030	High		62	120	120	120	120	120	5.30E+12
3.Carbon_high_cost_low			Low		62	120	120	120	120	120	5.06E+12
4.Carbon_high_cost_low_PHS200		Set sensitivity analysis from 200-400 GW for 2035			62	120	200	200	200	200	5.07E+12
5.Carbon_high_cost_low_PHS300					62	120	300	300	300	300	5.10E+12
6.Carbon_high_cost_low_PHS400					62	120	400	400	400	400	5.13E+12
7. **Carbon_low_Base (Base)**	Low	No constraint			32.5	32.5	32.5	32.5	32.5	32.5	5.06E+12
8.Carbon_low_cost_high		Set targets of 62 and 120GW for 2025 and 2030	High		62	120	120	120	120	120	5.43E+12
9.Carbon_low_cost_low **(Base_PHScost)**			Low		62	120	120	120	120	120	5.15E+12
10. Carbon_low_cost_low_LowPHScost **(Low_PHScost)**				Decrease rate as same as batteries	62	120	143	148	149	234	5.13E+12
11. Carbon_low_cost_low_1/5PHScost **(1/5PHScost)**				1/5 of Base	122	293	384	517	610	618	5.03E+12
12.Carbon_low_cost_low_PHS200		Set sensitivity analysis from 200-400 GW for 2035		Base	62	120	200	200	200	200	5.16E+12
13.Carbon_low_cost_low_PHS300					62	120	300	300	300	300	5.19E+12
14.Carbon_low_cost_low_PHS400					62	120	400	400	400	400	5.22E+12