Energy storage system configuration for offshore wind: tailored to China's needs

Xingru Ye[a,b,c], Ronghua Zhu[a,d,*], Chenghong Gu[c] and Haining Xing[d]

[a] *Ocean College, Zhejiang University, Zhoushan, 316000, China*
[b] *Interdisciplinary Student Training Platform for Marine areas, Zhejiang University, Hangzhou, 310027, China*
[c] *Department of Electronic and Electrical Engineering, University of Bath, Bath, BA2 7AY, UK*
[d] *Yangjiang Offshore Wind Energy Laboratory, Yangjiang, 529500, China*

ARTICLE INFO

Keywords:
Offshore wind
Power fluctuation
Battery energy storage
Hydrogen energy storage
China Certified Emission Reduction

ABSTRACT

Offshore wind has become an important part of China's national energy system. The fluctuating nature and strong reverse peaking characteristics of offshore wind power greatly challenge power systems' safe and economical operation. The Energy Storage System (ESS) is a key solution to address these challenges and avoid experiencing significant wind power curtailment or constraints. However, ESS configuration is still costly and needs a detailed cost-benefit analysis to ensure the rationality of the investment. This paper considers offshore wind development in China and systematically reviews theories, methodologies, and financial benefits of ESS configuration for offshore wind farms. The basic ESS requirements for offshore wind in China are first introduced. Then, the basic theories, methodologies, and financial benefits of battery energy storage systems are reviewed, including BESS control, utility constraints, and market returns. Another commercially available ESS, the hydrogen energy storage system, has been identified in terms of its technical and economic feasibility. Finally, the development trend of ESS configuration for offshore wind is prospected critically. This review aims to guide research and actual production activities on ESS configuration for offshore wind.

1. Introduction

Compared to onshore wind power, offshore wind power has higher wind speeds, more stable wind conditions, higher utilization rates, and larger unit capacities and does not occupy land resources (Hau, 2013; Foken, 2016; Wacker et al., 2020). It helps reduce the level of regional electricity prices through its merit-order effect(Sensfuß et al., 2008; Woo et al., 2011; Cludius et al., 2014; De Siano and Sapio, 2022) and also helps reduce the price variance compared to onshore wind (Hosius et al., 2023). Offshore wind contributes significantly to energy transition and mitigating climate change, making it favored by coastal countries. In China, benefiting from the construction of renewable-energy-generation-dominated power systems, offshore wind power has become an important part of national energy. As of the end of March 2024, the cumulative grid-connected capacity of offshore wind power nationwide reached 38.03GW.

Offshore wind power in China is mainly concentrated in energy-intensive economic zones along the eastern and southern coasts. Outside extreme weather conditions, offshore wind farms generally operate at total capacity. However, as a kind of intermittent energy resource, wind power's output fails to exceed 80% of its rated capacity for over 90% of the time. Wind resource uncertainty leads to power output fluctuations, resulting in issues such as flicker and harmonics and impacting regional power grids. Even worse, the degree and probability of strong reverse peaking in offshore wind surpass those in onshore wind, so the integration of offshore wind power can worsen peak-shaving difficulties in coastal economic zones with large variations in system load peaks and valleys, as well as increase the diversity of local grid currents. Furthermore, renewable energy's rapid growth and integration in coastal economic zones reduce thermal power proportion, which diminishes the power grid's voltage and frequency regulation capabilities and poses stricter challenges for fluctuation control.

The Energy Storage System (ESS) is a key solution to address the non-steady-state characteristics of renewable energy generation and avoid experiencing significant curtailment or constraint (McDonagh et al., 2020). The dynamic performance of ESS to rapidly absorb and release energy, coupled with its static energy storage capability, can effectively mitigate fluctuations in offshore wind power. These rapid and stable responses to fluctuations reduce the impact on the power system. Furthermore, the cooperation of wind power and ESS could provide frequency regulation in power markets (He et al., 2017). Introducing ESS could ensure a reliable power supply and reserve capacity, enhancing the system's ability to integrate offshore wind power. Consequently, formulating a rational ESS configuration plan becomes an essential task.

ESS configuration can have different optimization objectives. For example, Pandzic et al. optimize the system operation cost and daily operating cost of ESS. (Pandzic et al., 2015). Jannati et al. aim to protect the battery lifetime for Battery Energy Storage System (BESS) units by selecting an effective power allocation method (Jannati and Foroutan, 2020). Liu et al. consider characteristics of charging load and wind power fluctuations, aiming to optimize total costs when configuring ESS for electric vehicle fast charging stations (Liu and Feng, 2021). Dhiman et al. aim at minimizing penalty cost (Dhiman et al., 2021). In addition, ALAhmad et

---

*Corresponding author

12034049@zju.edu.cn (X. Ye); zhu.richard@zju.edu.cn (R. Zhu)

Table 1
ESS requirements for several major offshore wind provinces.

Province	Ratio of ESS to offshore wind (%)	ESS Duration (h)
Guangxi	20	2
Guangdong	10	1
Fujian	10	2
Zhejiang	10	2
Shanghai	20	2
Jiangsu	10	2
Shandong	20	2

al. construct a mixed integer non-linear optimization problem comprising three objective functions, including the total operation and planning cost of ESSs, the average voltage deviation, and average power losses (ALAhmad, 2023).

From an industrialization perspective, we suggest maximizing the profits of offshore wind farms over their life cycle as an objective for ESS configuration.

2. Configuration status

The framework of offshore wind with ESS is shown in Fig. 1. The grid-connected power P_G is generated by the output power of offshore wind farms P_W and ESS P_E. In China, different provinces have introduced various ESS configuration policies for renewable energy. Some with higher demands require that the ESS capacity be no less than 20% of the offshore wind for 2 hours, while regions with lower demands require no less than 10% for 1 hour. Additionally, some provinces stipulate that the grid connection time for ESS should not be later than that of offshore wind. Otherwise, the offshore wind plant will be fined, such as lowering the electricity price. The ESS requirements for several provinces engaged in offshore wind are shown in TABLE 1.

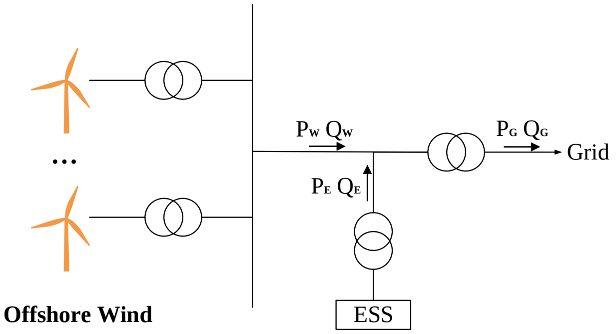

Fig. 1. The combined power transmission of offshore wind and ESS to the grid.

New ESS technologies continue to increase. While the Lithium Battery Energy Storage System (LBESS) remains overwhelmingly dominant, technologies such as compressed air energy storage, flow battery energy storage, and flywheel energy storage are rapidly advancing. Since 2023, China has commenced the construction of 300-MW-scale compressed air energy storage projects, 100-MW-scale flow battery projects, and MW-scale flywheel energy storage projects. Additionally, new technologies such as gravity energy storage, liquid air energy storage, and carbon dioxide energy storage are being implemented, reflecting an overall trend toward diversified development. As of the end of 2023, the proportion of operational LBESS was 97.4%, lead-acid BESS was 0.5%, compressed air energy storage was 0.5%, flow battery energy storage was 0.4%, and others accounted for 1.2%. LBESS has been extensively adopted on a large scale due to its cost-effectiveness. Most offshore wind energy storage projects under construction or proposed to be built also use LBESS. In addition, benefiting from the seawater resources, some projects have also turned their attention to the Hydrogen Energy Storage System (HESS), which uses offshore wind power to electrolyze seawater to produce hydrogen for storage.

This paper explores the current status and prospects of commercialized ESS deployment in China's offshore wind. It primarily discusses BESS in Section 3 and HESS in Section 4. The future outlook of ESS configuration in offshore wind is presented in Section 5.

3. Offshore wind with BESS

This section introduces the control strategies, technology constraints of BESS, and revenues in detail.

3.1. BESS control

BESS is expensive for a large-scale wind farm, and a control strategy is crucial to optimize the BESS's capacity and cost (de Siqueira and Peng, 2021). Generally, the first step of a control strategy is to get BESS target output power determined by wind farm power predictions or real-time wind farm power tracking. This step always uses techniques such as moving average(Yu et al., 2022; Lin et al., 2024), filtering (Qin et al., 2023), signal decomposition (Shi et al., 2019; Guo et al., 2020), neural network (Jannati et al., 2014, 2016; Jannati and Foroutan, 2020), fuzzy control and its hybrid(Yang et al., 2023a; Huixiang et al., 2022; Roy et al., 2023), etc. The second step is to allocate the target output power to the BESS. The research on single BESS has limited Depth of Discharge (DoD) and experiences frequent switching, which can significantly reduce battery lifespan. So it is proposed to allocate power to batteries with supercapacitors or battery groups and regulate energy between them based on their state of charge (SoC). Supercapacitors are too costly to be widely adopted for commercial use (Wieczorek et al., 2019; Ahmed et al., 2023), so we shall focus more on battery grouping power allocation for large-scale offshore wind farms.

A novel dual-battery energy storage system (DBESS) for wind power is proposed, where one group takes the charging role, and another handles the discharging task. The roles for each group switch when one group reaches either the fully charged or the deeply discharged state (Nguyen and Lee, 2016). Lin et al. introduce indicators for saturation capability and operation stability based on real-time battery conditions and power fluctuations. Additionally, it presents a control strategy to adaptively adjust the low-pass filter time constant, aiming to optimize and control the SoC of the DBESS in real-time, ensuring its long-term operational stability (Lin et al., 2021).

For multiple battery group control, the objective of maintaining the consistency of SoC is more prominent, which is beneficial for maintaining better group regulation for a long time. Li et al. compare three power allocation strategies to maintain SoC consistency (Li et al., 2022). However, it's still difficult to ensure the consistency of the SoC in all battery units at the end of the response. To solve this problem, Yu et al. try to maintain the consistency of SoC within the same group. They divide the BESS into two groups with stable capacity: one group with small capacity responds to a relatively high-frequency fluctuation, and the other is subdivided into three clusters responding to low-frequency fluctuation–one cluster is for charging, one is for discharging, and the left one depends on the situation. Dynamic grouping of battery units is completed according to two groups' capacities and SoC of all battery units (Yu et al., 2022). Similarly, Shi et al. divide the BESS into three groups: Group 1 and Group 2 can only be charged or discharged one at a time. Group 3 activates when another group reaches its upper or lower limit. Once Group 3 and another group reach their limits, Group 3 deactivates, and Group 1 and Group 2 exchange roles (Shi et al., 2024).

Adopting an appropriate power allocation strategy can significantly reduce the required BESS capacity and decrease the number of charge and discharge cycles, thus lowering both the investment cost and operation and maintenance (O&M) cost of BESS, which will be stated in Section 3.3.2 in detail.

3.2. Utility constraints of BESS

BESS configuration must consider limitations such as BESS energy capacity, charge/discharge capacity, SoC, etc.

3.2.1. Capacity and SoC constraints of BESS

Assume *n* battery groups are involved in BESS. Without considering the case of self-discharge, the charging dynamics for every battery group can be expressed as

$$SoC_i(t) = SoC_i(t-1) + \eta_i^{ch} P_i^{ch}(t-1)\Delta T \tag{1}$$

where $SoC_i(t)$ and unsigned scalar $P_i^{ch}(t)$ are respectively the SoC and charging power of the *i*-th battery group at time t, η_i^{ch} is the charging efficiency, and ΔT is the discrete time interval. Similarly, the discharging dynamics can be written as

$$SoC_i(t) = SoC_i(t-1) - P_i^{dis}(t-1)\Delta T / \eta_i^{dis} \tag{2}$$

where unsigned scalar $P_i^{\mathrm{dis}}(t)$ is the discharging power of the *i*-th battery group at time t and η_i^{dis} is the discharging efficiency. Consequently, the net output power of the *i*-th battery group during the time interval $[t, t+1)$ is written as

$$P_i(t) = \mu_i(t) P_i^{dis}(t) - (1 - \mu_i(t)) P_i^{ch}(t) \tag{3}$$

where $\mu_i(t)$ is a binary variable used to indicate whether charging or discharging is taking place. The maximum energy capacity of the *i*-th battery unit is $P_i^{\max}$:

$$|P_i(t)| \le P_i^{\max} \tag{4}$$

Table 2
Max. active power fluctuation limit for offshore wind (MW).

Installed Capacity	10 min	1 min
≤ 200	1/3 Capacity	1/10 Capacity
>200	66	20

It is always suggested that the greater the DoD is, the higher the utilization rate of batteries will reach (Koller et al., 2015; Sarker et al., 2017). However, existing studies indicate that a DoD of approximately 80% is optimal for maintaining the battery state while minimizing damage to battery longevity. Thus, in practical terms, to prevent overcharging or overdischarging, which would reduce the battery lifespan, we often set limits on upper and lower bounds of charging and discharging for batteries:

$$0 < SoC_{i,\mathrm{L}} \le SoC_i \le SoC_{i,\mathrm{H}} < 1 \tag{5}$$

where $SoC_{i,\mathrm{L}}$ and $SoC_{i,\mathrm{H}}$ are the lower and upper bounds of SoC. Eventually, the output of BESS is $P_{\mathrm{B}}(t) = \sum_{i=1}^{n} P_i(t)$.

3.2.2. Fluctuation mitigation constraints

In response to the problem of active power fluctuations for offshore wind connecting to the grid, the technical rule Q/GDW 11410-2015 formulated by the State Grid Corporation of China in 2016 specifies the maximum active power fluctuation limit for offshore wind farms under normal operating conditions. This includes two time scales: 10 minutes and 1 minute, as shown in TABLE 2. The grid-connected power can be calculated as $P_{\mathrm{G}}(t) = P_{\mathrm{W}}(t) + P_{\mathrm{B}}(t)$. According to the maximum limit standards in TABLE 2, the expressions for active power fluctuation mitigation constraints are expressed as follows:

$$\max_{j=0}^{k_1} P_{\mathrm{G}}(t-j) - \min_{j=0}^{k_1} P_{\mathrm{G}}(t-j) \le C_1 \tag{6}$$

$$\max_{j=0}^{k_{10}} P_{\mathrm{G}}(t-j) - \min_{j=0}^{k_{10}} P_{\mathrm{G}}(t-j) \le C_{10} \tag{7}$$

where $k_1 = 1\,\mathrm{min}/\Delta T$, $k_{10} = 10\,\mathrm{min}/\Delta T$; C_1 is the maximum active power fluctuation limit in 1 min for offshore wind farms; C_{10} is the maximum active power fluctuation limit in 10 min for offshore wind farms.

3.3. Market returns

The marginal cost of renewable energy is extremely low. Various provinces have introduced corresponding spot market rules, making renewable energy such as offshore wind power more advantageous for consumption in the medium and long-term power markets. Taking the Zhejiang spot power market rules as an example, since non-standalone BESS's frequency regulation capability of wind farms can be disregarded in studies, the revenue brought by BESS configuration for offshore wind farms mainly includes increased electricity generation revenue and increased zero-carbon revenue (Chen et al., 2022). The BESS configuration cost includes investment cost and O&M cost. The market returns of BESS configuration for offshore wind farms can be expressed as

$$M_r = \Delta R_{\mathrm{G}} + \Delta R_{\mathrm{CCER}} - C_{\mathrm{I}} - C_{\mathrm{OM}} \tag{8}$$

where ΔR_{G} is the increased electricity generation revenue, ΔR_{CCER} is the increased revenue from the sale of China Certified Emission Reduction (CCER), a type of zero-carbon revenue that is now considered more advantageous for promoting offshore wind development, C_{I} is the BESS investment cost, and C_{OM} is the BESS O&M cost.

3.3.1. Revenue from BESS configuration

Electricity generation revenue Electricity generation revenue consists of day-ahead full energy revenue R_{DA}, real-time deviation energy revenue R_{RT}, and medium- and long-term differential contract revenue R_{ML}. Electricity generation revenue can be expressed as

$$R_{\mathrm{G}} = R_{\mathrm{DA}} + R_{\mathrm{RT}} + R_{\mathrm{ML}} \tag{9}$$

$$R_{\mathrm{DA}} = \sum EG_{\mathrm{DA}} \times p_{\mathrm{DA}} \tag{10}$$

$$R_{\mathrm{RT}} = \sum (EG_{\mathrm{RT}} - EG_{\mathrm{DA}}) \times p_{\mathrm{RT}} \tag{11}$$

$$R_{\mathrm{ML}} = \sum EG_{\mathrm{C}} \times (p_{\mathrm{C}} - p_{\mathrm{ML}}) \tag{12}$$

where EG_{DA} is the day-ahead full energy generation, p_{DA} is the node marginal price of the day-ahead market; EG_{RT} is the actual energy generation, p_{RT} is the node marginal price of the real-time market; EG_{C} is the medium and long-term contract energy generation, p_{ML} is the day-ahead market price at the medium and long-term settlement reference point.

1. R_{DA}: Since EG_{DA} is the electricity generation declared by the offshore wind farm based on day-ahead wind speed and power forecasts, it is unrelated to BESS configuration for offshore wind farms.
2. R_{RT}: Without a BESS, electricity generation forecast errors cause discrepancies between actual power generation and the day-ahead planned curve. When the actual power generation of the offshore wind farm exceeds the planned curve, the wind farm shall rely on automatic adjustments, such as altering the pitch of the wind turbine blades, to reduce the power generation to the planned level. This adjustment is essentially to curtail wind power, which typically results in a negative R_{RT} for the offshore wind farm. However, if energy storage is configured for offshore wind power, the actual power generation can be adjusted more precisely to match the day-ahead planned curve without wind curtailment, minimize errors, and make R_{RT} as close to zero as possible. In addition, p_{RT} in the real-time market usually fluctuates greatly, the high-cost deviation electricity rate caused by high real-time market electricity price can be avoided by configuring BESS.
3. R_{ML}: EG_{C} is fixed, so it is not closely related to the BESS configuration for offshore wind farms.

Overall, ΔR_{G} mainly reflects in ΔR_{RT} .

CCER revenue CCER refers to a tradable certificate in China's carbon emission trading system. CCERs are issued to companies or projects that reduce greenhouse gas emissions below a certain baseline. These certificates can then be traded on the carbon market as a way for companies to comply with emission reduction targets or to generate revenue by selling excess credits.

For instance, replacing other power plants with grid-connected offshore wind projects can reduce carbon dioxide emissions.

Those projects located at least 30 kilometers offshore or in water depths greater than 30 meters are allowed to obtain CCER revenue. The CCER period begins when the offshore wind project owner registers emission reductions and shall not exceed 10 years, within the project's life cycle. Grid-connected offshore wind projects are shown in Fig. 2. Within the boundary of grid-connected offshore wind projects, there are three kinds of emissions–baseline, project, and leakage emissions(CDM - Executive Board, 2009). Baseline emissions refer to the emissions that would occur without the offshore wind project. Essentially, the offshore wind project intends to replace the emissions associated with conventional energy sources. This can include emissions from fossil fuel-based power generation, transportation of fuels, and other related activities. Project emissions of offshore wind mainly come from fossil fuels used by backup generators, maintenance vessels, and vehicles. However, considering their relatively low emissions, they are counted as zero to reduce project implementation and management costs. Leakage emissions of offshore wind result from fossil fuels used by operations such as extraction, processing, and transportation. However, due to their relatively small contribution compared to baseline emissions, they can be disregarded. Since greenhouse gases other than carbon dioxide account for a small proportion, only carbon dioxide is considered here(Ministry of Ecology and Environment of the People's Republic of China, 2023). BE_y, the baseline emission in year y, unit in $\mathrm{tCO_2}$, is calclulated as follows:

$$BE_y = EG_{PJ,y} \times EF_{\mathrm{G},CM,y} \tag{13}$$

where $EG_{PJ,y}$ is the net grid-connected electricity of the project in year y, unit in MWh. $EF_{\mathrm{G},CM,y}$ is the combined margin (CM) $\mathrm{CO_2}$ emission factor–a weighted average of operating margin (OM) $EF_{\mathrm{G},OM,y}$ and build margin (BM) emission factors $EF_{\mathrm{G},BM,y}$ for the project electricity system in year y, unit in $\mathrm{tCO_2/MWh}$, calculated as

$$EF_{\mathrm{G},CM,y} = EF_{\mathrm{G},OM,y} \times \omega_{OM} + EF_{\mathrm{G},BM,y} \times \omega_{BM} \tag{14}$$

where ω_{OM} is the weighting of operating margin emissions factor and ω_{BM} is the weighting of build margin emissions factor(Institute for Global Environmental Strategies (2024), 2024). United Nations Framework Convention on Climate Change suggests setting $\omega_{OM} = 0.75$ and $\omega_{BM} = 0.25$ for wind and solar power generation project activities owing to their intermittent and non-dispatchable nature for the first and subsequent crediting periods. For all other projects, it is suggested to set $\omega_{OM} = 0.5$ and $\omega_{BM} = 0.5$ for the first crediting period, and $\omega_{OM} = 0.25$ and $\omega_{BM} = 0.75$ for the second and third crediting period. Based on this, alternative weights can be proposed as long as $\omega_{OM} + \omega_{BM} = 1$. So offshore wind projects in China use weight values of 0.5 for both weights ω_{OM} and ω_{BM} (Lee and Lee, 2021). Thus,

$$\Delta R_{\mathrm{CCER}} = \sum_{y=1}^{\lambda} \Delta BE_y \times p_{\mathrm{CCER}} = \sum_{y=1}^{\lambda} \Delta EG_{PJ,y} \times EF_{\mathrm{G},CM,y} \times p_{\mathrm{CCER}} \tag{15}$$

where λ is the CCER period, p_{CCER} is the CCER price.

Overall, ΔR_{CCER} is determined by $\Delta EG_{PJ,y}$, which will be improved by BESS configuration.

3.3.2. BESS cost

BESS cost consists of investment cost and O&M cost.

Investment cost From the energy and power capacity perspective, power capacity takes precedence over power capacity when BESS is mainly employed to mitigate fluctuations.

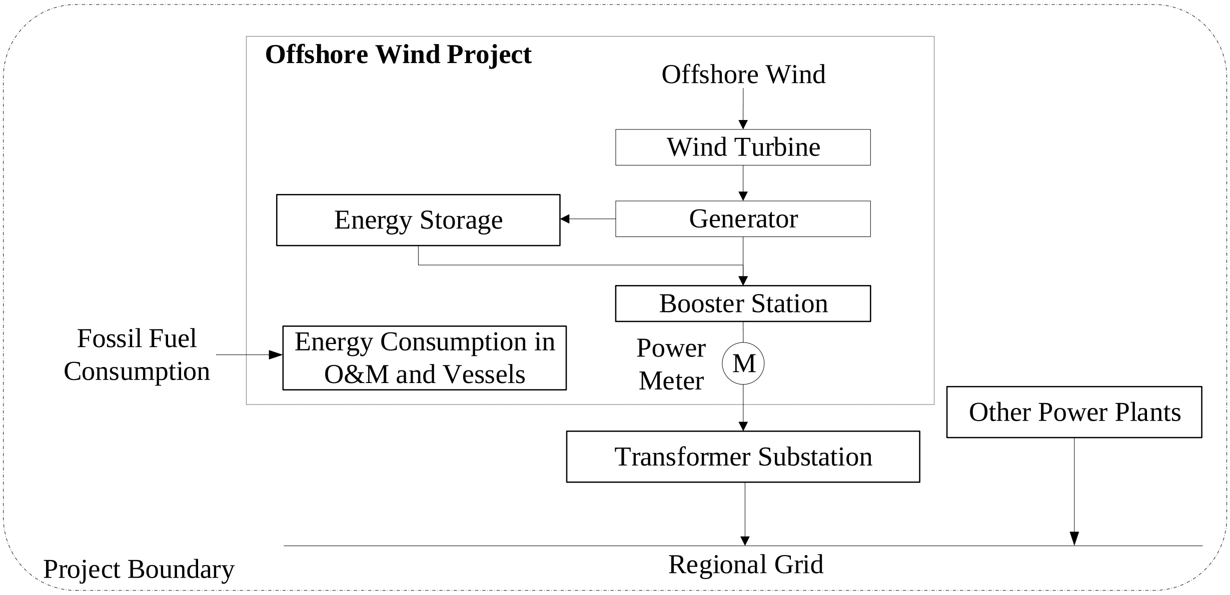

Fig. 2. Project boundary of grid-connected offshore wind power.

Conversely, when BESS is utilized for peak shaving, the total amount of storage is more important than the power capacity (Gao, 2022). For offshore wind, the main purpose of BESS configuration is to mitigate fluctuations, so power capacity is relatively more important.

For a specific offshore wind farm, the characteristics of its wind power fluctuations are suggested to be considered to determine the optimal BESS control method. Then mixed-integer linear programming (MILP) (Lamedica et al., 2018), stochastic optimization (Abdulgalil et al., 2019), P-graph (Mah et al., 2021; Ji et al., 2023) or other optimization methods (Jiang et al., 2020; Yu et al., 2020) are employed to determine the optimal BESS capacity configuration. The BESS investment cost of P_B MW and E_B MWh for an offshore wind farm can be simply calculated as

$$C_I = c_P \times P_B + c_E \times E_B \tag{16}$$

where c_P and c_E are the unit power and capacity cost of BESS, P_B and E_B are the configured power and energy of BESS, respectively. In 2021, c_P in China is nearly 1.1 RMB per watt, and c_E is nearly 1.5 RMB per watt hours (Shi et al., 2022). Some of the on-grid offshore wind farms with BESS connected to the grid are shown in TABLE 3, and the relationship between BESS investment cost and configured power and energy is fitted in Fig. 3. In BESS, the most critical and core component is the battery, whose cost is greatly influenced by raw material price.

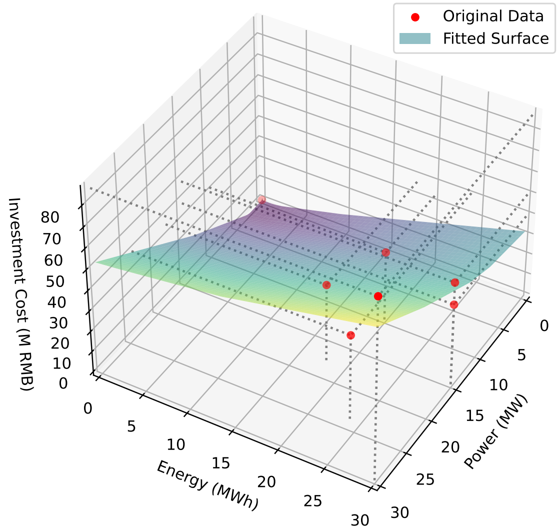

Fig. 3. Relationship between BESS investment cost and configured power and energy.

BESS O&M cost BESS O&M cost primarily involves battery replacement costs. When batteries experience severe degradation or reach the end of their cycle life, replacement is necessary. Currently, most regions require that the capacity degradation rate of BESS during their service life should not exceed 20%, the AC-side efficiency should not be lower than 85%, the DoD should not be less than 90%, and the station availability should not be lower than 90% (Tianjin Development and Reform Commission, 2023).

The battery life is influenced by several factors, including charge-discharge conversion numbers, DOD, charge rate, and battery temperature (Stroe et al., 2017). After choosing the optimal BESS control approach to avoid frequent charging or discharging (illustrated in 3.1), many methods remain to prolong BESS life and ensure BESS stability and

Table 3
LBESS Configuration Investment Cost for Offshore Wind Farms in China.

Year	Offshore Wind Project	Project Capacity /MW	BESS Power /MW	BESS Energy /MWh	Cost /M RMB
2021	Guohua Zhugensha H1#	200	10	20	33.5
2021	South of Shandong Peninsula No.3	302	15	30	39.3
2021	South of Shandong Peninsula No.4	300	15	30	49.9
2023	Zhejiang Energy Taizhou No.1	300	18	18	37.3
2024	Three Gorges Yangxi Shapa (Phase 1) -Xia An BESS	300	30	30	87.3
2024	CR Power Cangnan 1#	400	24	24	41.1

Notice: Competitive configuration for offshore wind is not included.

reliability during the operation period, such as battery health monitoring, preventive maintenance, regular calibration of the control system, and replacement of degraded batteries.

Windey Co., Ltd has proposed distributed BESS, equipping each wind turbine with a six-percent-installed-capacity BESS for one hour and placing it on the wind turbine tower platform (Windey, 2023). But compared to the centralized O&M, distributed BESS configuration causes frequent charging and discharging, shortens battery life, reduces cost-efficiency, requires more management and coordination to ensure timely and effective execution at each wind turbine, and takes longer to identify issues and dispatch personnel for repairs or replacement (Tao et al., 2024; Feng et al., 2024). In addition, some offshore wind farms use leasing instead of construction for BESS configuration. Taking the 306MW Huadian Daishan No.1 offshore wind farm as an example, its leased capacity is 30.6MW/61.2MWh. The annual price for grid-side BESS service is 2.99 million CNY. The leasing mode of BESS reduces upfront costs, financial pressure, and operational risks while providing professional maintenance, but it also involves dependence on the leasing provider and limited control over the system.

4. Offshore wind with HESS

Unlike BESS, HESS is more suitable for long-term energy storage, so the primary purpose of using HESS is to utilize excess wind energy that would be wasted rather than to smooth out offshore wind power. Converting excess electricity into hydrogen is a viable option to mitigate losses when unable to connect to the grid. This process involves electrolysis, where electricity is used to split water into hydrogen and oxygen(Jacobson and Delucchi, 2011; Davis et al., 2018). The generated hydrogen can then be stored and sold as a valuable commodity for various industrial applications, including fuel cells, transportation, and energy storage. By converting electricity into hydrogen, wind farm owners can still extract value from their renewable energy assets, even if they cannot immediately connect to the grid. But at present, offshore wind-powered hydrogen production and energy storage are only considered as an economic remedial measure for offshore wind farms to address issues such as substandard electricity quality and wind curtailment (Bechlenberg et al., 2024).

4.1. Seawater electrolysis

Both direct seawater electrolysis and desalinated seawater electrolysis can be applied to produce hydrogen for storage. As the desalination process consumes energy and adds to the overall energy cost, it does not reflect the convenience and advantages of offshore wind-powered hydrogen production, so the direct seawater electrolysis method for hydrogen production is more attractive (Ahmad et al., 2020; Generous et al., 2021; Wang et al., 2022; Xie et al., 2022; Dokhani et al., 2023; Lin et al., 2023). In 2023, a Power-to-Gas (PtG) conversion test was conducted in Fujian, China to produce hydrogen using offshore wind power. The test used Dongfang Electric Xinghua Bay No.58 10-MW wind turbine for power supply, equipped with a 28kW output power ESS for direct seawater electrolysis. The production rate was 1.3 standard cubic meters of hydrogen per hour, with an energy consumption of 5kWh per standard cubic meter of hydrogen.

4.2. Hydrogen storage and transportation

Hydrogen storage technology can be divided into two types: physical-based and material-based. In physical-based storage technology, hydrogen is stored by changing its physical state, such as increasing pressure (compressed gaseous hydrogen storage, CGH_2) and liquefying hydrogen (liquid hydrogen storage, LH_2). Cryo-compressed hydrogen storage (CcH_2) is another physical-based way to store hydrogen, but it is not highly practical. In material-based storage technology, hydrogen is stored by forming metal hydrides or Liquid-organic Hydrogen Carriers (LOHCs) such as methanol and ammonia through reaction (Yang et al., 2023b).

Since CGH_2 is easier and more mature compared to LH_2 as liquefying hydrogen consumes more energy (Barthelemy et al., 2017; Smolinka and Garche, 2021), it is more attractive in HESS construction. There are different types of pressure vessels, including fully metallic pressure vessels (e.g. steel, Al), metallic pressure vessels hoop-wrapped with glass fiber composite, full composite wrap with metal liner, and fully composite (e.g. high-density polyethylene inner with glass or carbon fiber) and are applied in various fields (Elgowainy et al., 2014; Parks et al., 2014; Rivard et al., 2019). Among the vessels above, fully carbon fiber vessels have higher mass density and lower cost and are expected to replace other containers in the future (Cheng et al., 2024).

Currently, the average offshore distance for offshore wind farms in China is approximately 30-40km, with considerable space for development in nearshore areas. It is estimated that the average offshore distance for domestic offshore wind power in the future will be within 100-150 kilometers, which is still a short distance for hydrogen transportation. Therefore, for offshore wind-powered hydrogen, we suggest paying more attention to small-scale CGH_2 storage and tank shipping without the need for new hydrogen pipelines. Some studies also have proposed blending 3% to 25% of hydrogen into nearby underwater natural gas pipelines (Tian and Pei, 2023; Zhang et al., 2023a; Li et al., 2024), but it doesn't show much significance for offshore as the hydrogen production might be inadequate and inconsistent.

5. Prospects

5.1. Shared ESS

It would be best to mitigate offshore wind power fluctuations on site, so it is necessary to support the co-establishing and leasing of ESS in conjunction with renewable energy projects nearby to avoid excessive construction and haphazard maintenance of ESS. Shared ESS profit allocation can be inspired by Nash-Harsanyi Bargaining Solution(Chen et al., 2021), nucleolus theory, Shapley value theory(Fang et al., 2020; Zhang et al., 2023b), etc.

However, neighboring offshore wind farms sometimes belong to different power generation companies. Their commercial behavior of co-establishing may impact the progress of construction and O&M, so it is suggested that the power grid side take the lead on ESS construction. In this way, ESS can have better centralized coordination across different offshore wind farms, optimize the integration of renewable energy sources into the grid, and better assist regional frequency and peak regulation. From a financial perspective, the co-establishment led by the power grid side helps reduce construction costs, streamline O&M, and reduce energy loss during conversion, leading to a more concentrated energy infrastructure.

5.2. Coastal battery logistics

Developing coastal battery logistics based on offshore wind and BESS is also an excellent way to reduce overall expenditure. Take electric vehicles as an example, Hayajneh et al. design a logistics system where electric semi-trucks transport batteries between BESS and electric vehicle charging stations. This system aims to reduce the curtailment of renewable energy while limiting the public costs of BESS. It addresses challenges in renewable energy integration, limited investment appeal in large-scale ESS, and infrastructure constraints hindering the expansion of electric transportation charging networks (Hayajneh and Zhang, 2020). Electric vessels and their charging stations can also benefit from BESS. Vessels with battery/hybrid propulsion need to recharge the batteries due to battery size and energy density limitations (Kolodziejski and Michalska-Pozoga, 2023). BESS built on the coast can provide power to short-range ships, allowing them to charge or swap batteries from ESS while berthed. Additionally, vessel charging stations can be built on platforms such as offshore booster stations or small islands based on offshore wind infrastructure. Dedicated power delivery ships transport batteries between BESS and electric vessel charging stations. They provide battery replacement services for vessels engaged in offshore construction and operations, reducing the need for ships to return to port and thereby saving time and operational costs.

5.3. Pre-sale ESS

Offshore wind offers a more stable wind resource than onshore wind, often leading to reduced prices and fluctuations. However, the upfront investment for offshore wind and ESS is substantial. Although the construction cost for offshore wind is trending below 10,000 RMB/kW and its matched BESS cost is gradually declining towards 1 RMB/Wh, they remain relatively expensive. Due to more prolonged and costly post-construction processes than pre-planned configuration, it's generally not mandated to configure ESS for existing offshore wind projects.

Incentivizing consumers to purchase offshore wind and energy storage options could be explored, which has been put into practice in pre-sale properties. Those who opt for this solution could enjoy reduced electricity prices or other benefits through welfare policies in advance.

6. Conclusion

This paper provides a comprehensive review of ESS configuration for offshore wind tailored to China's needs. The first part presents the background, including the current status and requirements of ESS in China. It critically reviews existing technologies, academic works, and financial analyses of BESS and HESS for offshore wind. The challenges and opportunities of ESS configuration are also discussed. Finally, the prospects of three areas within this emerging research field are highlighted: shared ESS, coastal battery logistics, and pre-sale ESS. The main conclusions are as follows:

1. In terms of BESS control strategies, the key to BESS lies in efficiently allocating target output power and maintaining the battery group's state with considerations of energy capacity, charge-discharge capabilities, and DoD of batteries. Current research indicates that dynamic grouping and adaptive control strategies can maximize battery life and performance stability. From an economic perspective, the market benefits of offshore wind integrated with BESS primarily manifest in increased electricity generation revenue and CCER benefits. By increasing actual generation revenue, enhancing the real-time response capabilities of wind power, and participating in carbon emission trading markets, BESS significantly enhances the market competitiveness and profitability of offshore wind farms.

2. Integrating Hydrogen Energy Storage Systems (HESS) with offshore wind farms effectively manages excess wind energy by converting it into hydrogen, preventing waste and providing economic benefits. Direct seawater electrolysis is preferred for hydrogen production, and CGH_2 is more practical and efficient. Given the short offshore distances in China, small-scale CGH_2 storage and tank shipping are recommended over new hydrogen pipelines.

3. The future outlook of ESS configuration for offshore wind is shared energy storage led by the power grid side for better coordination, cost reduction, and energy efficiency. Coastal battery logistics can lower expenses, enhance offshore wind integration, and benefit electric vehicles. To avoid high upfront costs, pre-sale ESS projects can incentivize consumers with lower electricity prices and other benefits.

CRediT authorship contribution statement

Xingru Ye: Conceptualization, Methodology, Software, Formal analysis, Investigation, Validation, Writing – original draft. **Ronghua Zhu:** Supervision, Writing – review & editing. **Chenghong Gu:** Supervision, Writing – review & editing. **Haining Xing:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research is financially supported by the National Natural Science Foundation of China (Grant No. 52371293) and the Key-Area Research and Development Program of Guangdong Province (Grant No. 2021B0707030002).

References

Abdulgalil, M.A., Khalid, M., Alismail, F., 2019. Optimal sizing of battery energy storage for a grid-connected microgrid subjected to wind uncertainties. Energies 12. doi:`10.3390/en12122412`.

Ahmad, N.A., Goh, P.S., Yogarathinam, L.T., Zulhairun, A.K., Ismail, A.F., 2020. Current advances in membrane technologies for produced water desalination. Desalination 493. doi:`10.1016/j.desal.2020.114643`.

Ahmed, S., Flowers, D.L., Balducci, P.J., 2023. Technology Strategy Assessment - Flow Battery. DOE Energy Earthshots .

ALAhmad, A.K., 2023. Voltage regulation and power loss mitigation by optimal allocation of energy storage systems in distribution systems considering wind power uncertainty. Journal of Energy Storage 59. doi:`10.1016/j.est.2022.106467`.

Barthelemy, H., Weber, M., Barbier, F., 2017. Hydrogen storage: Recent improvements and industrial perspectives. International Journal of Hydrogen Energy 42. doi:`10.1016/j.ijhydene.2016.03.178`.

Bechlenberg, A., Luning, E.A., Saltık, M.B., Szirbik, N.B., Jayawardhana, B., Vakis, A.I., 2024. Renewable energy system sizing with power generation and storage functions accounting for its optimized activity on multiple electricity markets. Applied Energy 360. doi:`10.1016/j.apenergy.2024.122742`.

CDM - Executive Board, 2009. Methodological Tool to calculate the emission factor for an electricity system. Unfccc/Ccnucc Annex 14.

Chen, H., Yu, H., Yang, X., Lin, Y., Lou, S., Peng, S., 2022. Joint Planning of Offshore Wind Power Storage and Transmission Considering Carbon Emission Reduction Benefits. Energies 15. doi:`10.3390/en15207599`.

Chen, W., Qiu, J., Zhao, J., Chai, Q., Dong, Z.Y., 2021. Bargaining Game-Based Profit Allocation of Virtual Power Plant in Frequency Regulation Market Considering Battery Cycle Life. IEEE Transactions on Smart Grid 12. doi:`10.1109/TSG.2021.3053000`.

Cheng, Q., Zhang, R., Shi, Z., Lin, J., 2024. Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners. International Journal of Lightweight Materials and Manufacture 7. doi:`10.1016/j.ijlmm.2023.08.002`.

Cludius, J., Hermann, H., Matthes, F.C., Graichen, V., 2014. The merit order effect of wind and photovoltaic electricity generation in Germany 2008-2016 estimation and distributional implications. Energy Economics 44. doi:`10.1016/j.eneco.2014.04.020`.

Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., Benson, S.M., Bradley, T., Brouwer, J., Chiang, Y.M., Clack, C.T., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C.B., Hannegan, B., Hodge, B.M., Hoffert, M.I., Ingersoll, E., Jaramillo, P., Lackner, K.S., Mach, K.J., Mastrandrea, M., Ogden, J., Peterson, P.F., Sanchez, D.L., Sperling, D., Stagner, J., Trancik, J.E., Yang, C.J., Caldeira, K., 2018. Net-zero emissions energy systems. Science 360. doi:`10.1126/science.aas9793`.

De Siano, R., Sapio, A., 2022. Spatial merit order effects of renewables in the Italian power exchange. Energy Economics 108. doi:`10.1016/j.eneco.2022.105827`.

Dhiman, H.S., Deb, D., Muyeen, S.M., Abraham, A., 2021. Machine intelligent forecasting based penalty cost minimization in hybrid wind-battery farms. International Transactions on Electrical Energy Systems 31. doi:`10.1002/2050-7038.13010`.

Dokhani, S., Assadi, M., Pollet, B.G., 2023. Techno-economic assessment of hydrogen production from seawater. International Journal of Hydrogen Energy 48. doi:`10.1016/j.ijhydene.2022.11.200`.

Elgowainy, A., Reddi, K., Sutherland, E., Joseck, F., 2014. Tube-trailer consolidation strategy for reducing hydrogen refueling station costs. International Journal of Hydrogen Energy 39. doi:`10.1016/j.ijhydene.2014.10.030`.

Fang, F., Yu, S., Liu, M., 2020. An improved Shapley value-based profit allocation method for CHP-VPP. Energy 213. doi:`10.1016/j.energy.2020.118805`.

Feng, X., Lin, S., Liang, Y., Lai, X., Liu, M., 2024. Coordinated risk-averse distributionally robust optimization for maintenance and generation schedules of offshore wind farm cluster. International Journal of Electrical Power and Energy Systems 159. doi:`10.1016/j.ijepes.2024.109993`.

Foken, T., 2016. Angewandte Meteorologie. doi:`10.1007/978-3-642-25525-0`.

Gao, Z., 2022. Research on the energy storage configuration strategy of new energy units. Energy Reports 8. doi:`10.1016/j.egyr.2022.03.091`.

Generous, M.M., Qasem, N.A., Akbar, U.A., Zubair, S.M., 2021. Techno-economic assessment of electrodialysis and reverse osmosis desalination plants. Separation and Purification Technology 272. doi:`10.1016/j.seppur.2021.118875`.

Guo, T., Liu, Y., Zhao, J., Zhu, Y., Liu, J., 2020. A dynamic wavelet-based robust wind power smoothing approach using hybrid energy storage system. International Journal of Electrical Power and Energy Systems 116. doi:`10.1016/j.ijepes.2019.105579`.

Hau, E., 2013. Wind turbines: Fundamentals, technologies, application, economics. volume 9783642271519. doi:`10.1007/978-3-642-27151-9`.

Hayajneh, H.S., Zhang, X., 2020. Logistics design for mobile battery energy storage systems. Energies 13. doi:`10.3390/en13051157`.

He, G., Chen, Q., Kang, C., Xia, Q., Poolla, K., 2017. Cooperation of Wind Power and Battery Storage to Provide Frequency Regulation in Power Markets. IEEE Transactions on Power Systems 32. doi:`10.1109/TPWRS.2016.2644642`.

Hosius, E., Seebaß, J.V., Wacker, B., Schlüter, J.C., 2023. The impact of offshore wind energy on Northern European wholesale electricity prices. Applied Energy 341. doi:10.1016/j.apenergy.2023.120910.

Huixiang, L., Caixue, C., Zhigang, X., 2022. A wavelet packet-dual fuzzy control method for hybrid energy storage to suppress wind power fluctuations. Renewable Energy and Power Quality Journal 20, 470–475. doi:10.24084/repqj20.343.

Institute for Global Environmental Strategies (2024), 2024. List of Grid Emission Factors, version 11.4 URL: https://pub.iges.or.jp/pub/iges-list-grid-emission-factors.

Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 39. doi:10.1016/j.enpol.2010.11.040.

Jannati, M., Foroutan, E., 2020. Analysis of power allocation strategies in the smoothing of wind farm power fluctuations considering lifetime extension of BESS units. Journal of Cleaner Production 266. doi:10.1016/j.jclepro.2020.122045.

Jannati, M., Hosseinian, S.H., Vahidi, B., Li, G.J., 2014. Mitigation of windfarm power fluctuation by adaptive linear neuron-based power tracking method with flexible learning rate. IET Renewable Power Generation 8. doi:10.1049/iet-rpg.2013.0258.

Jannati, M., Hosseinian, S.H., Vahidi, B., Li, G.j., 2016. ADALINE (ADAptive Linear NEuron)-based coordinated control for wind power fluctuations smoothing with reduced BESS (battery energy storage system) capacity. Energy 101, 1–8. doi:10.1016/j.energy.2016.01.100.

Ji, M., Zhang, W., Xu, Y., Liao, Q., Jaromír Klemeš, J., Wang, B., 2023. Optimisation of multi-period renewable energy systems with hydrogen and battery energy storage: A P-graph approach. Energy Conversion and Management 281. doi:10.1016/j.enconman.2023.116826.

Jiang, Y., Kang, L., Liu, Y., 2020. Optimal configuration of battery energy storage system with multiple types of batteries based on supply-demand characteristics. Energy 206. doi:10.1016/j.energy.2020.118093.

Koller, M., Borsche, T., Ulbig, A., Andersson, G., 2015. Review of grid applications with the Zurich 1 MW battery energy storage system. Electric Power Systems Research 120. doi:10.1016/j.epsr.2014.06.023.

Kolodziejski, M., Michalska-Pozoga, I., 2023. Battery Energy Storage Systems in Ships' Hybrid/Electric Propulsion Systems. Energies 16. doi:10.3390/en16031122.

Lamedica, R., Santini, E., Ruvio, A., Palagi, L., Rossetta, I., 2018. A MILP methodology to optimize sizing of PV - Wind renewable energy systems. Energy 165. doi:10.1016/j.energy.2018.09.087.

Lee, K.M., Lee, M.H., 2021. Uncertainty of the electricity emission factor incorporating the uncertainty of the fuel emission factors. Energies 14. doi:10.3390/en14185697.

Li, J., Song, F., Zhang, X., 2024. A review on hazards and risks to pipeline operation under transporting hydrogen energy and hydrogen-mixed natural gas. Science and Technology for Energy Transition (STET) 79. doi:10.2516/stet/2024004.

Li, X., Geng, G., Jiang, Q., Ma, J., Ni, Q., Guo, K., 2022. Case study of power allocation strategy for a grid-side lead-carbon battery energy storage system. IET Renewable Power Generation 16. doi:10.1049/rpg2.12318.

Lin, K., Xie, H., Peng, Q., Zhang, Y., Shen, S., Jiang, Y., Ni, M., Chen, B., 2023. Hydrogen production from seawater splitting enabled by online flow-electrode capacitive deionization. Renewable and Sustainable Energy Reviews 183. doi:10.1016/j.rser.2023.113525.

Lin, L., Cao, Y., Kong, X., Lin, Y., Jia, Y., Zhang, Z., 2024. Hybrid energy storage system control and capacity allocation considering battery state of charge self-recovery and capacity attenuation in wind farm. Journal of Energy Storage 75. doi:10.1016/j.est.2023.109693.

Lin, L., Jia, Y., Ma, M., Jin, X., Zhu, L., Luo, H., 2021. Long-term stable operation control method of dual-battery energy storage system for smoothing wind power fluctuations. International Journal of Electrical Power and Energy Systems 129. doi:10.1016/j.ijepes.2021.106878.

Liu, X., Feng, T., 2021. Energy-storage configuration for EV fast charging stations considering characteristics of charging load and wind-power fluctuation. Global Energy Interconnection 4, 48–57. doi:10.1016/j.gloei.2021.03.005.

Mah, A.X.Y., Ho, W.S., Hassim, M.H., Hashim, H., Ling, G.H.T., Ho, C.S., Muis, Z.A., 2021. Optimization of photovoltaic-based microgrid with hybrid energy storage: A P-graph approach. Energy 233. doi:10.1016/j.energy.2021.121088.

McDonagh, S., Ahmed, S., Desmond, C., Murphy, J.D., 2020. Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment. Applied Energy 265. doi:10.1016/j.apenergy.2020.114732.

Ministry of Ecology and Environment of the People's Republic of China, 2023. Voluntary greenhouse gas emission reduction project methodology for grid-connected offshore wind.

Nguyen, C.L., Lee, H.H., 2016. A Novel Dual-Battery Energy Storage System for Wind Power Applications. IEEE Transactions on Industrial Electronics 63. doi:10.1109/TIE.2016.2570721.

Pandzic, H., Wang, Y., Qiu, T., Dvorkin, Y., Kirschen, D.S., 2015. Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network. IEEE Transactions on Power Systems 30. doi:10.1109/TPWRS.2014.2364257.

Parks, G., Boyd, R., Cornish, J., Remick, R., 2014. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration. Technical Report. URL: https://doi.org/10.2172/1130621.

Qin, L., Sun, N., Dong, H., 2023. Adaptive Double Kalman Filter Method for Smoothing Wind Power in Multi-Type Energy Storage System. Energies 16. doi:10.3390/en16041856.

Rivard, E., Trudeau, M., Zaghib, K., 2019. Hydrogen storage for mobility: A review. Materials 12. doi:10.3390/ma12121973.

Roy, P., Liao, Y., He, J.B., 2023. Economic Dispatch for Grid-Connected Wind Power With Battery-Supercapacitor Hybrid Energy Storage System. IEEE Transactions on Industry Applications 59. doi:10.1109/TIA.2022.3203663.

Sarker, M.R., Murbach, M.D., Schwartz, D.T., Ortega-Vazquez, M.A., 2017. Optimal operation of a battery energy storage system: Trade-off between grid economics and storage health. Electric Power Systems Research 152. doi:10.1016/j.epsr.2017.07.007.

Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36. doi:10.1016/j.enpol.2008.03.035.

Shi, J., Wang, L., Lee, W.J., Cheng, X., Zong, X., 2019. Hybrid Energy Storage System (HESS) optimization enabling very short-term wind power generation scheduling based on output feature extraction. Applied Energy 256. doi:10.1016/j.apenergy.2019.113915.

Shi, L., Duanmu, C., Wu, F., He, S., Lee, K.Y., 2024. Optimal allocation of energy storage capacity for hydro-wind-solar multi-energy renewable energy system with nested multiple time scales. Journal of Cleaner Production 446. doi:10.1016/j.jclepro.2024.141357.

Shi, S., Wu, H., Huang, D., Hu, A., Song, W., 2022. Energy storage capacity configuration of an offshore wind farm considering the influence of complex ocean climate conditions. Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control 50, 172–179. doi:10.19783/j.cnki.pspc.210931.

de Siqueira, L.M.S., Peng, W., 2021. Control strategy to smooth wind power output using battery energy storage system: A review. doi:10.1016/j.est.2021.102252.

Smolinka, T., Garche, J., 2021. Electrochemical Power Sources: Fundamentals, Systems, and Applications Hydrogen Production by Water Electrolysis. doi:10.1016/C2018-0-05096-3.

Stroe, D.I., Knap, V., Swierczynski, M., Stroe, A.I., Teodorescu, R., 2017. Operation of a grid-connected lithium-ion battery energy storage system for primary frequency regulation: A battery lifetime perspective. IEEE Transactions on Industry Applications 53. doi:10.1109/TIA.2016.2616319.

Tao, Z., Liu, H., Si, Y., Wang, C., Zhu, R., 2024. An opportunistic joint maintenance strategy for two offshore wind farms. Ocean Engineering 304. doi:10.1016/j.oceaneng.2024.117890.

Tian, X., Pei, J., 2023. Study progress on the pipeline transportation safety of hydrogen-blended natural gas. Heliyon 9. doi:10.1016/j.heliyon.

2023.e21454.

Tianjin Development and Reform Commission, 2023. Tianjin new energy storage development implementation plan. URL: https://fzgg.tj.gov.cn/zwgk_47325/zcfg_47338/zcwjx/fgwj/202308/t20230801_6367348.html.

Wacker, B., Seebaß, J.V., Schlüter, J.C., 2020. A modular framework for estimating annual averaged power output generation of wind turbines. Energy Conversion and Management 221. doi:10.1016/j.enconman.2020.113149.

Wang, M., Zhang, P., Liang, X., Zhao, J., Liu, Y., Cao, Y., Wang, H., Chen, Y., Zhang, Z., Pan, F., Zhang, Z., Jiang, Z., 2022. Ultrafast seawater desalination with covalent organic framework membranes. Nature Sustainability 5. doi:10.1038/s41893-022-00870-3.

Wieczorek, M., Lewandowski, M., Jefimowski, W., 2019. Cost comparison of different configurations of a hybrid energy storage system with battery-only and supercapacitor-only storage in an electric city bus. Bulletin of the Polish Academy of Sciences: Technical Sciences 67. doi:10.24425/bpasts.2019.131567.

Windey, 2023. Customized One WTGS, One Storage, How Can Windey Solve the Problem of Large-Scale Offshore Wind Power Energy Storage? URL: https://windeyenergy.com/en/news_show?id=104.

Woo, C.K., Horowitz, I., Moore, J., Pacheco, A., 2011. The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. Energy Policy 39. doi:10.1016/j.enpol.2011.03.084.

Xie, H., Zhao, Z., Liu, T., Wu, Y., Lan, C., Jiang, W., Zhu, L., Wang, Y., Yang, D., Shao, Z., 2022. A membrane-based seawater electrolyser for hydrogen generation. Nature 612. doi:10.1038/s41586-022-05379-5.

Yang, J., Yang, T., Luo, L., Peng, L., 2023a. Tracking-dispatch of a combined wind-storage system based on model predictive control and two-layer fuzzy control strategy. Protection and Control of Modern Power Systems 8. doi:10.1186/s41601-023-00334-6.

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., Wang, B., 2023b. A review of hydrogen storage and transport technologies. Clean Energy 7. doi:10.1093/ce/zkad021.

Yu, X., Zhang, W., Dong, X., Liu, S., Pang, S., Zang, H., 2020. Optimization of wind farm self-discipline interval and energy storage system configuration. IEEE Access 8. doi:10.1109/ACCESS.2020.2989306.

Yu, Y., Chen, D., Wang, B., Wu, Y., Lu, W., Mi, Z., 2022. Control scheme to extend lifetime of BESS for assisting wind farm to track power generation plan based on wind power feature extraction. IET Power Electronics 15, 1629–1651. doi:10.1049/pel2.12333.

Zhang, H., Zhao, J., Li, J., Yu, B., Wang, J., Lyu, R., Xi, Q., 2023a. Research progress on corrosion and hydrogen embrittlement in hydrogen–natural gas pipeline transportation. Natural Gas Industry B 10, 570–582. doi:10.1016/j.ngib.2023.11.001.

Zhang, T., Qiu, W., Zhang, Z., Lin, Z., Ding, Y., Wang, Y., Wang, L., Yang, L., 2023b. Optimal bidding strategy and profit allocation method for shared energy storage-assisted VPP in joint energy and regulation markets. Applied Energy 329. doi:10.1016/j.apenergy.2022.120158.