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Aligning offshore wind deployment with local priorities to accelerate power system decarbonization

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Abstract:

Accelerating offshore wind power deployment, a critical but underutilized resource for decarbonizing power systems, requires balancing national and local interests. Using China, the global leader in offshore wind, as a case study, here we evaluate how its deployment creates benefits, such as improved energy self-sufficiency, greater resource diversity, enhanced grid reliability, and increased local investments and employment. Our results show that offshore wind can bolster the energy self-sufficiency of coastal provinces, shifting them from net electricity importers to exporters. Furthermore, expanding offshore wind reduces the need for energy storage on a grid with high renewable penetration and drives substantial local investment and job creation. After quantifying uncertainties in policies, technology costs, and electricity demand, we find offshore wind could provide 3–18% of China's electricity by 2050. Aligning local interests with offshore wind development can facilitate more ambitious targets and accelerate power system decarbonization with limited increases in system cost.

Introduction

Limiting the global temperature rise to 1.5 °C requires rapid and large-scale deployment of renewable energy.[1] Offshore wind power is a critical component of this transition, with the World Bank estimating a

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global technical potential of over 71,000 gigawatts (GW).[2] The technology has attracted growing interest due to its high resource quality, proximity to coastal load centers, and substantial cost declines.[3,4] Accordingly, several major carbon-emitting countries have announced mid- to long-term offshore wind targets. For example, Europe aims for 109-112 GW by 2030, and 281–354 GW by 2050.[5] The U.S. seeks to install 30 GW by 2030.[6] China plans to reach 100 GW by 2025, according to several provincial-level "14th Five-Year Plans for Energy Development."[7-17] However, these policy targets remain conservative compared to offshore wind's enormous potential. Projections indicate that to achieve net zero by 2050, the world must install 2,000 GW of offshore wind, which could contribute one-third of the power sector's required emission reductions.[18]

Offshore wind enhances energy resource diversity and security through its high capacity factors and large power output.[18,19] It also helps avoid land use conflicts, a key advantage in regions with competing agricultural, industrial, or residential demands. While the global market has grown quickly, offshore wind development is still in its early stages, with a cumulative installed capacity of only 75 GW in 2023.[19] Its progress has been hampered by higher costs compared to land-based renewables, as well as complex permitting procedures, inflation, and supply chain bottlenecks that have slowed or canceled projects in the EU and U.S.. [20-22]

Previous studies have primarily evaluated offshore wind resource quality, optimal investment plans, and national-level economies, job creation, and grid impacts.[3, 23-28] For example, Beiter et al. estimated that offshore wind could supply 1–8% of U.S. power generation by 2050.[27] Sherman et al. estimated that offshore wind will be cost-competitive by 2030 and could provide China with 1,148–6,383 terawatt-hours (TWh) of electricity.[23] Guo et al. evaluated optimal investment plans for offshore wind and implications for long-distance transmission networks.[3] Some studies emphasize the role of policy support in offshore wind development. Dukan et al. proposed an enabling policy environment in Europe to ease market entry and provide revenue stabilization and government guarantees, thereby lowering investment risks and accelerating deployment.[24] O'Boyle et al. emphasized the role of federal and state governments in bolstering U.S. offshore wind deployment.[25] However, these research has not yet fully addressed how offshore wind development can be aligned with local interests and priorities, such as social acceptance and local economic impacts to motivate its accelerated deployment.

We use China as a case study to assess how accelerating offshore wind can generate local benefit in energy self-sufficiency, investments, employment, and grid stability. In this study, energy self-sufficiency is measured as the share of local generation in total demand for a given region, reflecting its reliance on

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imported electricity. As the world’s largest carbon emitter, China’s success in achieving carbon neutrality is crucial for global climate goals. Its coastal provinces, however, face considerable decarbonization challenges due to high electricity demand and a lack of local land-based renewables, which are concentrated in the country's southwest, northwest, and north.[29,30] With an estimated potential of 3,400–4,000 GW and high-quality resources,[3,23,31] rapid offshore wind development offers a promising solution to decarbonize China’s coastal regions.

China is the global leader in offshore wind, with 38 GW installed as of 2023, over half the global total.[19] Despite this, China’s investment in offshore wind pales in comparison to its spending on solar and onshore wind, and it has yet to set a national-level target. We argue that aligning local priorities with national decarbonization goals can motivate policymakers to set more ambitious offshore wind targets and better engage local stakeholders in its scale-up.

Ensuring a stable electricity supply is a paramount concern, and recent strains on China’s power system have intensified energy security anxieties.[32] This has led policymakers to revert to approving new coal-fired power plants, over 150 GW since early 2022,[33] a trend that endangers climate goals even as it assuages near-term security fears. In contrast, ramping up offshore wind would advance decarbonization while reducing local reliance on imported electricity, thereby avoiding risks like higher power costs, poor grid reliability, and lost economic opportunities.

Here, we develop a systematic assessment of how expanding China’s offshore wind deployment through 2050 aligns with local priorities. Using the GridPath model, we analyze the impacts on long-term grid planning and short-term grid operations across three key scenarios: a base scenario (Base), a moderate offshore wind scenario (MOSW), and accelerated offshore wind scenario (AOSW) (See Methods section and Supplementary Table 2 for scenario details). We also conduct sensitivity analyses on factors like energy sector policies, carbon emission caps, various technology capital and transmission costs, and future electricity demands to test the robustness of our results (See the sensitivity analyses in the Methods section and Supplementary Note 1.)

Our analysis shows that accelerating offshore wind can substantially enhance coastal provinces’ energy self-sufficiency, drive substantial local investments and job creation, and reduce the need for energy storage to maintain grid stability on a highly renewable grid. We estimate offshore wind could provide 3–18% of China’s electricity by 2050, a broad range that reflects large uncertainties in policies, technology costs, and electricity demand. These findings have global

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implications, as many countries face similar challenges with scaling offshore wind. Our analysis underscores the critical role of aligning with local priorities to accelerate offshore wind development. Prioritizing local needs and opportunities could increase social acceptance, promote efficient and sustainable deployment of offshore wind infrastructure, and ultimately contribute to broader national and global decarbonization goals.

Results and Discussion

Offshore wind supports energy self-sufficiency in coastal regions

The deployment of offshore wind diversifies clean energy resources and increases provincial energy self-sufficiency in the long term. We find that deploying offshore wind can substantially reduce coastal provinces' reliance on imported electricity, especially in Shandong, Jiangsu, Fujian, and Zhejiang provinces. Fig. 1 compares electricity demand and local power generation in 10 coastal provinces under three scenarios for 2030 and 2050. We select these two representative years because they mark crucial milestones in China's decarbonization pathway. China has pledged to reach its emission peak by 2030, and the power sector is expected to reach carbon neutrality by approximately 2050 to accomplish economy-wide decarbonization by 2060.

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In 2030, most coastal provinces will remain electricity net importers due to their high electricity demand and limited supply. Coastal provinces import 11% of their electricity from other regions in the AOSW scenario, 16% in the MOSW scenario, and 17% in the Base scenario in 2030. By 2050, however, under the AOSW scenario, key coastal provinces with relatively high electricity demand achieve energy independence and become electricity exporters. Zhejiang, Jiangsu, Shandong, Fujian, and Guangdong provinces export 409, 228, 123, 92 and 77TWh of electricity, respectively, in 2050, accounting for 44%, 17%, 10%, 20% and 6%, respectively, of their total electricity demand.

Expanding offshore wind changes coastal provinces' power generation profiles. Our findings suggest the share of offshore wind generation relative to total power generation in coastal provinces will increase from 20% in 2030 to 45% in 2050 under the AOSW scenario. Notably, in Jiangsu and Guangdong provinces, offshore wind power surpasses nuclear power and becomes the largest source of power generation. National optimal installed capacity and power generation results of different technologies are shown in Supplementary Figure 9 and Supplementary Table 5. National power dispatch for the two representative months, January and July, in 2050 is shown in Supplementary Figure 13.

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We analyze the overall impact of offshore wind deployment on net electricity transmission flows and energy self-sufficiency in coastal regions by aggregating all coastal provinces together. We find that under the Base and MOSW scenarios, the aggregate coastal region still imports electricity from central regions in 2050 (Fig. 2a). Increasing the offshore wind capacity from 213 GW in the Base scenario to 250 GW in the MOSW scenario can decrease coastal regions' electricity imports from 813TWh to 743TWh. However, under the AOSW scenario, which assumes 1,000 GW of installed offshore wind capacity by 2050, coastal regions will achieve energy self-sufficiency, and even export 88TWh of electricity.

Offshore wind deployment influences other provinces' net electricity transmission flows (Fig. 2b). For example, Inner Mongolia is China's main electricity exporter. Under the AOSW scenario, electricity exports from Inner Mongolia decrease by 318TWh compared to the Base scenario, and 271TWh compared to the MOSW scenario. This indicates moderate offshore wind deployment has limited impact on China's electricity transmission network, and that only large-scale offshore wind deployment would substantially affect regional electricity flows and transmission infrastructure needs. Thus, the energy independence and energy security of China's coastal provinces are achieved only if the country's power sector decarbonization efforts include accelerated offshore wind deployment similar to that described in the AOSW scenario.

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Accelerated offshore wind deployment also increases the average energy self-sufficiency of coastal regions. We find that the average energy self-sufficiency index of coastal regions, calculated as average power generation divided by total electricity demand, are 26% and 20% greater in the AOSW scenario than in the Base and MOSW scenarios, respectively, in 2050, as shown in Fig. 2c. Additionally, the results show that accelerated offshore wind development will decrease the installed capacity of energy storage on the power system (Supplementary Figure 12).

Investment in offshore wind benefits local economies and employment

Offshore wind development attracts investment capital to local communities, creates jobs in coastal provinces, and stimulates new regional energy innovation hubs. In the AOSW scenario, the highest levels of investment in the coastal region are Jiangsu, Shandong, Guangdong, and Zhejiang provinces (Fig. 3a). There's also a notable divergence in investment trends for most coastal and inland provinces under the AOSW scenario: coastal provinces generally see increased investments, while inland provinces experience reductions. Despite lower costs for offshore wind in the AOSW scenario (20% lower average capital costs compared to the Base scenario), total investments are still 6–74% higher in all but two coastal provinces (Liaoning and Tianjin).

As offshore wind deployment expands, investments in China's power system shift from inland provinces to coastal provinces (Fig. 3b). This shift is driven by a decreased need for power transmission from inland areas as offshore wind capacity grows. By 2050, some coastal provinces (e.g., Shandong, Jiangsu, Zhejiang, and Fujian) could become electricity exporters, further reducing inland power system investments. Cumulative investment in the inland region is projected to decrease by 2% in the MOSW and 6% in the AOSW scenario, compared to the Base scenario. Conversely, investment in the coastal region is expected to rise by 4% in the MOSW and 15% in the AOSW scenario, compared to the Base scenario.

Investments in power technologies are expected to create local jobs. We find that cumulative jobs related to power generation in the 10 coastal provinces from 2025 to 2050 are projected to increase from 41.7 million in the Base scenario to 48.3 million in the AOSW scenario, an increase of about 16%. Fig. 3c shows cumulative jobs for different power sector technologies in each coastal province from 2025 to 2050. On average, over half of these jobs (61%) are associated with solar and wind power plants, 15% with thermal power plants, 8% with hydro or nuclear plants, and 16% with energy storage.

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Offshore wind largely improves grid system reliability and resiliency

Accelerating offshore wind deployment improves grid reliability, thereby reducing the need for discharge from energy storage systems to balance short-term fluctuations. By 2050, accelerated offshore wind deployment substantially reduces energy storage discharge in most coastal provinces (Fig. 4). The most substantial reduction is in Jiangsu (43%) under the AOSW scenario compared to the Base scenario. This is attributed to the substantial difference in Jiangsu's installed offshore wind capacity (220 GW) between the two scenarios (Fig. 1b). Similarly, in the AOSW scenario, annual average energy storage discharge in Zhejiang, Guangdong, and Shandong decreases by 41%, 19%, and 14%, respectively, compared to the Base scenario. Substantial reductions in energy storage discharge are concentrated in February, August, September, and December. By 2050, accelerated offshore wind deployment is expected to reduce energy storage discharge by 54 TWh for batteries and 29 TWh for pumped hydro storage.

Increasing offshore wind energy can substantially reduce the net load of China's power system in 2050. Reducing net load can improve grid stability by minimizing the need for backup power sources, such as thermal power and energy storage, and enabling the grid to better accommodate fluctuations in energy supply. Fig. 5 shows load and net load over all 8,760 hours of 2050 in Shandong, Jiangsu, Zhejiang, and Guangdong provinces, which have the highest offshore wind deployment in that year. In the AOSW

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scenario, net load decreases substantially compared to the Base scenario at all times in Jiangsu, Zhejiang, and Guangdong. For Shandong, during the first 80th percentile of time, net load in the AOSW scenario is substantially lower than in the Base scenario; however, it becomes higher in the final 20th percentile of time. This is due to Shandong's large amount of solar power, and the fact that its solar generation is higher in the Base scenario than in the AOSW scenario. These results show that integrating more offshore wind energy not only supports a more sustainable energy mix, but also contributes to greater grid stability.

Factors shaping offshore wind deployment

Our sensitivity analysis highlights a wide variation in China's projected installed offshore wind capacities in 2050 (Fig. 6a), but only modest variations in system costs (Fig. 6b). We find that the presence of a policy target is the primary driver of offshore wind installations among all uncertainty factors, underscoring the importance of setting ambitious deployment targets aligned with local priorities. Notably, adopting a robust policy target (e.g., 1,000 GW of offshore wind by 2050 under the AOSW scenario) increases total system costs by 1.9% relative to the no-target MOSW scenario (~250 GW by 2050). This increase ranges from 1.4% to 2.5% when accounting for the empirical variation in grid connection costs (8–24% of total offshore wind capital expenditure; see Supplementary Table 8).

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Electricity demand is the second-largest driver of offshore wind capacity expansion, followed by technology costs, carbon emission caps, and transmission costs (Fig. 6a). In contrast, system costs show less variation (1–74%) compared to offshore wind capacity outcomes (20–205%). For example, high electricity demand will increase offshore wind capacity by 86% and system costs by 70%, compared to scenarios with low electricity demand. Additionally, scenarios with low RE costs can yield an extra 28 GW of offshore wind, compared to those with high RE costs. A rapid decrease in offshore wind costs (i.e., a 43% decrease from 2025 to 2050) will result in an additional 37 GW of offshore wind, compared to a scenario where costs decrease slowly (i.e., a 12% decrease over the same period). These effects can be even more pronounced at the provincial level. For instance, a rapid decrease in offshore wind costs by 2050 could increase deployment by 106 GW in Shanghai and 37 GW in Guangdong.

Conclusions and policy implications

Despite recent rapid growth in the global offshore wind market, offshore wind energy is still in its early stages, with only 75 GW of installed capacity in 2023,[19] compared with 2,000 GW needed to achieve net zero by 2050.[18] Policy incentives are critical to accelerating offshore wind energy deployment and decarbonizing power systems. Addressing local priorities and aligning them with the development of offshore wind energy provides a new perspective for local stakeholders and communities to consider

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supporting offshore wind.

Our study fills this need by providing a systematic assessment of the impacts of offshore wind deployment on local priorities, using China as a case study. Offshore wind has both higher capacity factors and fewer land use limitations than solar and onshore wind energy. More importantly, offshore wind resources are located near China's load centers in coastal provinces. Exploring benefits of offshore wind deployment for local communities will not only promote offshore wind energy in China, but also yield broader insights that are applicable worldwide.

We develop a framework to evaluate the implications of different offshore wind deployment scenarios on local priorities, including energy self-sufficiency, job creation, investments, and grid stability requirements. To evaluate the impacts of offshore wind energy on power system planning and detailed operations, we run both long-term capacity expansion and short-term production cost modeling.

Our findings emphasize the substantial benefits of accelerated offshore wind deployment on energy self-sufficiency and economic development in coastal provinces under deep decarbonization pathways. We find that accelerating offshore wind deployment substantially reduces coastal provinces' reliance on imported electricity, with provinces such as Zhejiang, Jiangsu, Shandong, and Guangdong able to achieve full energy self-sufficiency and even become electricity exporters by 2050. Furthermore, the rapid development of offshore wind brings substantial investments into related infrastructure and workforce development. We find that in the AOSW scenario, coastal provinces' cumulative investments in power generation technologies are expected to reach $2.6 trillion USD from 2025 to 2050, with related jobs growing to 48.3 million over the same timeframe. Offshore wind generation in the AOSW scenario could largely satisfy national electricity demand during peak load periods, reducing battery discharge by 54 TWh and pumped hydro storage discharge by 29 TWh in 2050.

Our model results indicate that power generation from offshore wind is projected to reach 918TWh in the MOSW scenario and 3,044TWh in the AOSW scenario by 2050, aligning with prior estimates.[23] We validated the reduced temporal sampling by comparing the capacity expansion results with a full 8,760-hour production cost model (hourly dispatch simulation with unit commitment) for 2050. As shown in Supplementary Table 7 and Supplementary Figure 14, system level generation differs by about 1% at the system level and technology-level results generally remain within ±10–15%. Policy and supporting actions play crucial roles in driving offshore wind growth. These findings suggest that policymakers have ample scope to set ambitious mid- to long-term offshore wind targets and to send clear signals to industry

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stakeholders.

In addition to capacity targets, Europe and the U.S. have developed supportive policies, such as long-term auctions, maritime spatial planning, and coordinated offshore transmission development, that could serve as useful references for China as it scales up offshore wind[34-35]. By situating China's pathway within the broader global offshore wind landscape, our findings also provide lessons for other emerging markets seeking to balance rapid scale-up with cost-effectiveness and system integration.

Inter-provincial electricity trading in China mainly relies on local governmental agreements, which do not adequately capture market dynamics and can create barriers to trade. Limitations around trading can lead to concern among provincial governments about the risks of overdependence on imported electricity (e.g., higher electricity costs, poorer electric system reliability, and foregone local economic development opportunities). Market-oriented reform could both enhance confidence in China's power markets and expand capabilities for inter-provincial electricity trading. Since 2018, provincial pilots for spot electricity markets have been implemented, but with limited success: by April 2023, provinces representing 80% of China's total electricity consumption had initiated spot market trials, but the permitted amounts of spot trading remained small.[36] Accelerating wholesale electricity market reform in China is crucial for developing a more efficient electricity trading system and allowing provinces to leverage diverse resources to achieve improved grid reliability. Our findings offer an approach to enhancing energy security and reducing outage-related losses in China's coastal provinces that is both distinct from and complementary to much-needed power market reforms.

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Deploying offshore wind near coastal load centers could dramatically reshape China's power grid by reducing reliance on long-distance transmission (Supplementary Note 2). China's major solar and onshore wind resources are located in its northern and western regions, and its transmission infrastructure is now characterized by a long-distance, high-voltage system extending from west to east. Offshore wind could satisfy a large share of coastal provinces' electricity demand, thereby reducing the need for ultra-high voltage (UHV) lines originating in the West. In our AOSW scenario, total transmission capacity in 2050 is 13% lower than in the Base scenario. East and Southern China shift to electricity exporters, while the Northwest and North China power regions play diminished exporting roles. These potential shifts in China's transmission system have profound implications for the strategic planning and layout of the national power system. Our findings suggest policymakers consider incorporating high offshore wind development scenarios into transmission planning and pursue a more robust, coordinated process that fully values China's vast but underutilized offshore wind resource when directing future infrastructure

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investment.

Emerging technologies in offshore wind present important opportunities for future system optimization and scientific advancement. Floating wind turbines, for example, can substantially expand accessible offshore wind resources by enabling deployment in deeper waters where fixed-bottom foundations are not feasible[37]. Advanced grid integration techniques, such as hybrid AC/DC systems, offshore hubs, and grid-forming converters, can improve the reliability and flexibility of power transmission from offshore wind farms to onshore grids[38,39]. In addition, innovations in energy storage technologies, including large-scale batteries and hydrogen production coupled with offshore wind[40-41] can enhance system stability and facilitate the integration of variable renewable generation. Incorporating these technological developments into future modeling efforts will provide a more comprehensive understanding of the evolving role of offshore wind in China's power system transition, and offer practical lessons and policy references for offshore wind development and grid optimization in other countries.

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Offshore grid connection constitutes an important component of offshore wind deployment and investment. In this study, we adopt an empirically grounded CAPEX-share approach to estimate of export-link and electrical infrastructure costs associated with connecting offshore wind generators to the onshore transmission network. Assuming grid-connection costs equal to 16% of total offshore wind capital expenditure (the midpoint of the 8–24% empirical range), the accelerated offshore wind scenario (AOSW) increases total system costs by approximately 1.9% relative to the MOSW scenario (~250 GW by 2050). While this approach captures observed project-level cost structures, uncertainties remain regarding future cost trajectories, technological standardization, and potential innovation in offshore transmission systems. More spatially explicit modeling of grid-connection infrastructure could further improve cost precision as additional data become available.

Although we have conducted sensitivity analyses across multiple uncertainty dimensions and examine the system-level implications of large-scale offshore wind development, inherent modeling limitations remain. Future research could enhance robustness by comparing results across different power system modeling frameworks. While our model results cannot perfectly represent future real-world conditions, our results provide valuable insights into potential system dynamics, technology deployment pathways, and the relative effects of different policy and investment strategies.

This study provides a quantitative assessment of offshore-wind deployment and its implications for provincial energy security and local economic outcomes, several socioeconomic and environmental

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uncertainties remain beyond our modeling scope. Factors such as public acceptance, permitting and regulatory delays, marine spatial conflicts, and localized ecological impacts can substantially influence deployment trajectories but are difficult to quantify due to limited data and context-specific variation across coastal provinces. While some of these risks are indirectly reflected in our sensitivity analyses, such as through cost variations and policy targets, a comprehensive evaluation would require targeted empirical research involving stakeholder engagement, institutional analysis, and site-level ecological assessments. We therefore acknowledge the importance of these dimensions and highlight their integration into future interdisciplinary energy-planning research as a valuable direction to enhance the robustness and policy relevance of long-term offshore wind strategies. At the same time, offshore wind has potential to generate long-term economic benefits by strengthening domestic supply chains, supporting industrial upgrading, and creating stable employment in coastal regions. These broader effects can enhance regional economic resilience and contribute to China's low-carbon transition, making this valuable for further quantitative research.

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Methods

Scenario design

We examine three core scenarios. The Base scenario uses BloombergNEF (BNEF) technology cost trends[42] and sets no constraints on offshore wind (OSW) installations in the model. However, recent studies indicate that installed costs of OSW in China declined by ~40% between 2021 and 2024[43-44]suggesting that BNEF's projection of only a 10–12% reduction by 2050 relative to 2021 are overly conservative. To reflect this faster observed cost declines, we define a moderate offshore wind scenario (MOSW) that applies a 43% decline in OSW costs over 2025-2050, consistent with the advanced scenario in the 2022 Annual Technology Baseline (ATB) database from the National Renewable Energy Laboratory (NREL)[45] (Supplementary Table 2 and Supplementary Figure 2). Finally, the accelerated offshore wind deployment scenario (AOSW) applies the same 43% decrease as in the MOSW scenario, while also assuming the achievement of designed policy targets. These targets incorporate existing national plans, projection studies, and ambitions in China and elsewhere. The AOSW scenario assumes that 80 GW of OSW will be installed by 2025, thereby meeting 80% of China's goal for new installed renewable energy capacity by 2025 as set forth in its 14th Five-Year Energy Plan. It further assumes that OSW installed capacity reaches 400 GW by 2035, based on Abhyankar et al.[31] and 1,000 GW by 2050.[3,23,46]

Although China has not yet announced long-term offshore wind targets, other major carbon emitting economies have done so, including the U.S. (30 GW by 2030)[5] and Europe (109–112 GW by 2030, 281–

354 GW by 2050).[18] If China adopted targets similar to Europe's on a proportional basis, scaled by electricity demand, it would set a target of approximately 700 to 1,000 GW of offshore wind by 2050. Existing studies[47,48] show that China's offshore wind potential exceeds 1,000 GW even after accounting for constraints such as nature reserves, fisheries, and leisure activities, with a range of 993-2678GW. Thus, a 2050 target of 1,000 GW is feasible and aligned with international trajectories. The Base, MOSW, and AOSW scenarios all utilize the same assumptions of technology and fuel costs, except offshore wind technology costs. Additional model inputs are provided in Supplementary Note 1.

Modeling tool and key modeling inputs

We use the optimization-based power system model, GridPath, an open-source model whose full code is publicly available on https://github.com/blue-marble/gridpath. We first run GridPath's capacity expansion module, which identifies the cost-optimal installed capacities and power generation of generators, and transmission investments required to meet a projected electricity demand. The model minimizes total system costs while satisfying operational constraints. Given spatially and temporally resolved demand projections, GridPath determines the optimal mix of generators, battery storage, and transmission lines for each modeled year. We then run the production cost module to simulate detailed hourly operations in 2050.

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The total system costs in the objective function include (a) capital costs of all power plants, transmission lines, and storage resources; (b) fixed and variable operation and maintenance (O&M) costs for all power system assets; and (c) variable fuel costs for coal, gas and nuclear generators. Variable costs of wind, solar, pumped hydro storage (PHS), and battery storage are all assumed to be zero. In general, these costs depend on installed capacities within each province, which are model variables to be solved, as well as unit-level capital costs and O&M costs, which are model inputs. Our model includes both short- and long-term energy storage (i.e., batteries and PHS). Capital and O&M cost data for renewable generators, fossil fuel power plants, and battery storage are obtained from BNEF 2021.[42]

We adopt an hourly time step and model each province as a load zone. Long-term investments are represented using four temporal layers: five-year investment periods, months, days, and hours. The analysis divides the time span from 2025 to 2050 into six investment periods of five years each: 2021–2025, 2026–2030, 2031–2035, 2036–2040, 2041–2045, and 2046–2050. We use 12 months to characterize each investment period, two days (a peak and a median load day) to characterize each month, and six hours to characterize each day. For each day, hourly sampling begins at midnight China Standard Time (CST) and includes the 0th, 4th, 8th, 12th, 16th, and 20th hours. This results in (6 investment periods)

× (12 months/investment period) × (2 days/month) × (6 hours/day) = 864 study hours during which the system is dispatched. Results for 2025, 2030, 2035, 2040, 2045, and 2050 are the representative years for the six investment periods and are shown in our figures. To model detailed operations in 2050, we use all 8,760 hours of that year.

We represent China's power using 32 interconnected nodes, connected by 184 interprovincial transmission corridors. Supplementary Figure 7 shows the transmission locations and spatial details included in the model. We assume a balanced system and regional reserve sharing, enabling efficient cross-provincial coordination.

Electricity demand in China over the next 25 years is highly uncertain. Supplementary Figure 4 shows electricity demand projections for 2025 through 2050, and specifically median values from projections by several leading research institutions. Supplementary Table 3 shows the provincial electricity demand projections from 2025 to 2050. Based on publicly available provincial electricity demand data, we converted the national annual electricity demand into 31 provincial hourly load shapes.[31] These projections incorporate assumptions about vehicle, building, and industrial electrification and are subject to change with evolving policies related to China's 2060 carbon-neutrality target.

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The GridPath model requires extensive technological cost inputs, of which the most important refer to wind, solar, battery storage, coal, and natural gas, as well as fuel costs for coal and natural gas. The analysis used projections of capital costs and fixed O&M costs for solar PV, onshore wind, offshore wind, and battery storage in China from BNEF. However, because BNEF projections of cost decreases for offshore wind are lower than those for other renewable technologies, we use actual offshore wind costs from the base year 2020 and then apply the cost decrease rate for offshore wind observed in the ATB 2022 database. Fuel price projections for coal and natural gas are also taken from BNEF. Since long-term coal price trends are uncertain, we assume that provincial thermal coal prices remain constant in real 2019 terms over the study period.

Solar and wind resource potentials and installed solar and wind profiles for each province are derived from Abhyankar et al.[31] Supplementary Table 6 summarizes annual average capacity factors by province for solar PV, onshore wind, and offshore wind. In this study, these capacity factors represent gross technical capacity factors from resource assessments and are used as exogenous model input parameters. They characterize the underlying resource quality and renewable generator performance potential, and do not incorporate curtailment, transmission congestion, or system-integration constraints. The optimization

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model subsequently determines the net electricity generation from each renewable technology after accounting for hourly system balancing requirements, transmission limits, curtailment, and network losses. This distinction between resource-based technical inputs and realized system-level outputs is consistent with the treatment of renewable generation in leading national-scale capacity-expansion frameworks such as *NREL's ReEDS*[49] *and the U.S. EIA's NEMS*[50]*,* where capacity factors are specified exogenously while net generation is computed endogenously under system constraints.

Hydropower and nuclear capacity expansions are shaped by long-term policy commitments, geographic and resource limitations, and regulatory or safety requirements, making their expansion fundamentally different from scalable renewable technologies such as wind and solar. Because these real-world constraints are not fully represented in the model, allowing fully endogenous expansion can produce deployment levels that are unlikely to be feasible in practice, as the model may otherwise favor these technologies for their contributions lowering total system costs and providing reliable firm capacity. We therefore impose exogenous upper bounds on conventional hydropower, pumped hydropower, and nuclear capacity based on national planning targets and documented resource availability, while still optimizing their hourly dispatch and operation within the system. The capital cost trajectories for nuclear, hydropower and pumped-storage hydropower used in GridPath over 2021–2050 are shown in Supplementary Figure 8. This treatment is consistent with the modeling practices used in major national- and regional-scale power system studies, where hydro and nuclear are typically constrained by policy and resource limits rather than optimized endogenously[51-55]. These values are extrapolated from current policy targets contained in national energy plans and existing studies.[56-57] The Medium and Long-term Development Plan for Pumped-hydro Storage (2021–2035), issued by China's National Energy Administration (NEA) in September 2021, also informs these assumptions.[58]

Offshore grid connection costs

Grid connection is an important component of offshore wind investment. We adopt an empirically grounded method to estimate the grid connection costs because the long-term cost trajectory of offshore-wind grid connection infrastructure is highly uncertain and not well captured long-term by learning-curve approaches. Drawing on documented project experience across regions (United States, Europe, and China), we assume that electrical/grid connection systems account for 8–24% of total project capital expenditure (CAPEX)[59-63], a range that reflects site conditions and region variation (Supplementary Table 8). This range captures spatial heterogeneity and avoids reliance on uncertain bottom-up forecasts. We apply these shares to the offshore-wind CAPEX in each scenario to estimate total grid connection

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investment through 2050 under the Base, MOSW, and AOSW scenarios.

Employment estimate

We evaluate changes in employment associated with equipment manufacturing, construction and installation, O&M, and fuel production for coal, natural gas, hydro, nuclear, solar, onshore wind, and offshore wind. Equipment manufacturing jobs refer to those offered by electrical equipment industries, such as the manufacturing of boilers, turbines, and modules. Construction and installation jobs involve the building of new power plants. O&M employees ensure the everyday operations of power plants. As shown in Supplementary Table 4, we apply average employment factors observed in several studies to estimate job changes in our MOSW and AOSW scenarios.[64-65] Our estimation focuses on jobs created in construction, manufacturing, and O&M for generators and energy storage. Other job categories, such as coal mining and fuel transport, which may also involve job changes due to power system decarbonization, are not considered in this estimate.

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Sensitivity analysis

To address uncertainty in offshore wind deployment and broader power system conditions, we develop 16 sensitivity scenarios grouped into five categories: (1) policy, (2) carbon emission caps, (3) technology costs, (4) transmission costs, and (5) total electricity demand. See Supplementary Note 1 and Supplementary Table 2 for detailed assumptions.

Data availability

Key model inputs are described in the Methods section and Supplementary Tables 1–9. GridPath model inputs and source data for the figures are deposited at https://doi.org/10.5281/zenodo.19375841.

Code availability

This study uses the open-source GridPath power system model (https://github.com/blue-marble/gridpath). The script to generate the main figures is provided in a Zenodo repository: https://doi.org/10.5281/zenodo.19375841.

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Author contributions

L.P., J.L. and G.H. conceived the project and designed the research. G.H. provided the data required to run the GridPath model. L.P. performed the optimization experiments and analyzed the results. N.A. contributed to the grid reliability and resilience analysis. H.Y. contributed to the production cost modelling, and U.P. provided the latest renewable capacity factor data used as model inputs. L.P. wrote the manuscript. L.P., J.L. and G.H. revised the manuscript. All authors reviewed and approved the final version of the manuscript.

Competing interests

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.

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Figure Captions

Fig. 1. Energy self-sufficiency of coastal provinces under the Base, MOSW, and AOSW scenarios.
Power generation mix and electricity demand for ten coastal provinces in **(a)** 2030 and **(b)** 2050. (LN: Liaoning, TJ: Tianjin, SD: Shandong, JS: Jiangsu, SH: Shanghai, ZJ: Zhejiang, FJ: Fujian, GD: Guangdong, GX: Guangxi, HN: Hainan.) Columns represent power generation from each technology; red circles represent annual electricity demand for each province. Supplementary Figure 10 and Supplementary Figure 11 shows results for the years 2025, 2035, 2040, and 2045.

Fig. 2. Net electricity exports and coastal regions' energy self-sufficiency under the Base, MOSW, and AOSW scenarios in 2050. (a) Provincial and coastal regions' net electricity transmission flows; **(b)**

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Changes in net electricity flows for Inner Mongolia, a main exporter, and coastal regions; and **(c)** Average energy self-sufficiency index of coastal regions. Less than and larger than 100% represent importing and exporting electricity from (to) other provinces, respectively. The colors of the provinces indicate net electricity exporters (red) and importers (blue).

Fig. 3. Changes in cumulative investment and jobs associated with offshore wind deployment.
Comparison of **(a)** cumulative investments by coastal provinces in the AOSW scenario, and investment differences between that scenario and the Base and MOSW scenarios; **(b)** total investments in the inland and coastal regions; and **(c)** power sector jobs in coastal provinces
under the Base, MOSW, and AOSW scenarios from 2025 to 2050.

Fig. 4. Energy storage discharge in coastal provinces.
Monthly energy storage discharge in 2050 for each coastal province under the **(a)** Base and **(b)** AOSW scenarios. Energy storage includes batteries and pumped hydro storage.

Fig. 5. Impact of offshore wind deployment on net load profiles.
Load and net load in 2050 for Shandong, Jiangsu, Zhejiang, and Guangdong provinces under the Base and AOSW scenarios.

Fig. 6. Uncertainty analysis in offshore wind deployment.
Uncertainties in policy, carbon emission caps, technology costs, transmission costs, and electricity demand affect (a) offshore wind capacity and (b) total system costs by 2050. Gray shaded areas indicate the span from the highest to lowest value. In (b), the demand sensitivity analysis corresponds to the right y-axis, while the other analyses correspond to the left y-axis. System costs include offshore-wind grid connection (electrical) infrastructure, assumed at 16% of project CAPEX (the midpoint of the 8–24% literature range); additional details are provided in Supplementary Table 8–9. Abbreviations: “Cost_min”: cost minimization modeling result; “OSW”: offshore wind; “R OSW cost”: rapid decrease in offshore wind costs; “S OSW cost”: slow decrease in offshore wind costs; “TX”: transmission.

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Editorial summary:
Offshore wind boosts local energy security, reduces storage needs, and creates jobs in coastal regions, shown through national scale modelling and uncertainty analysis of policies, costs, and future electricity demand.

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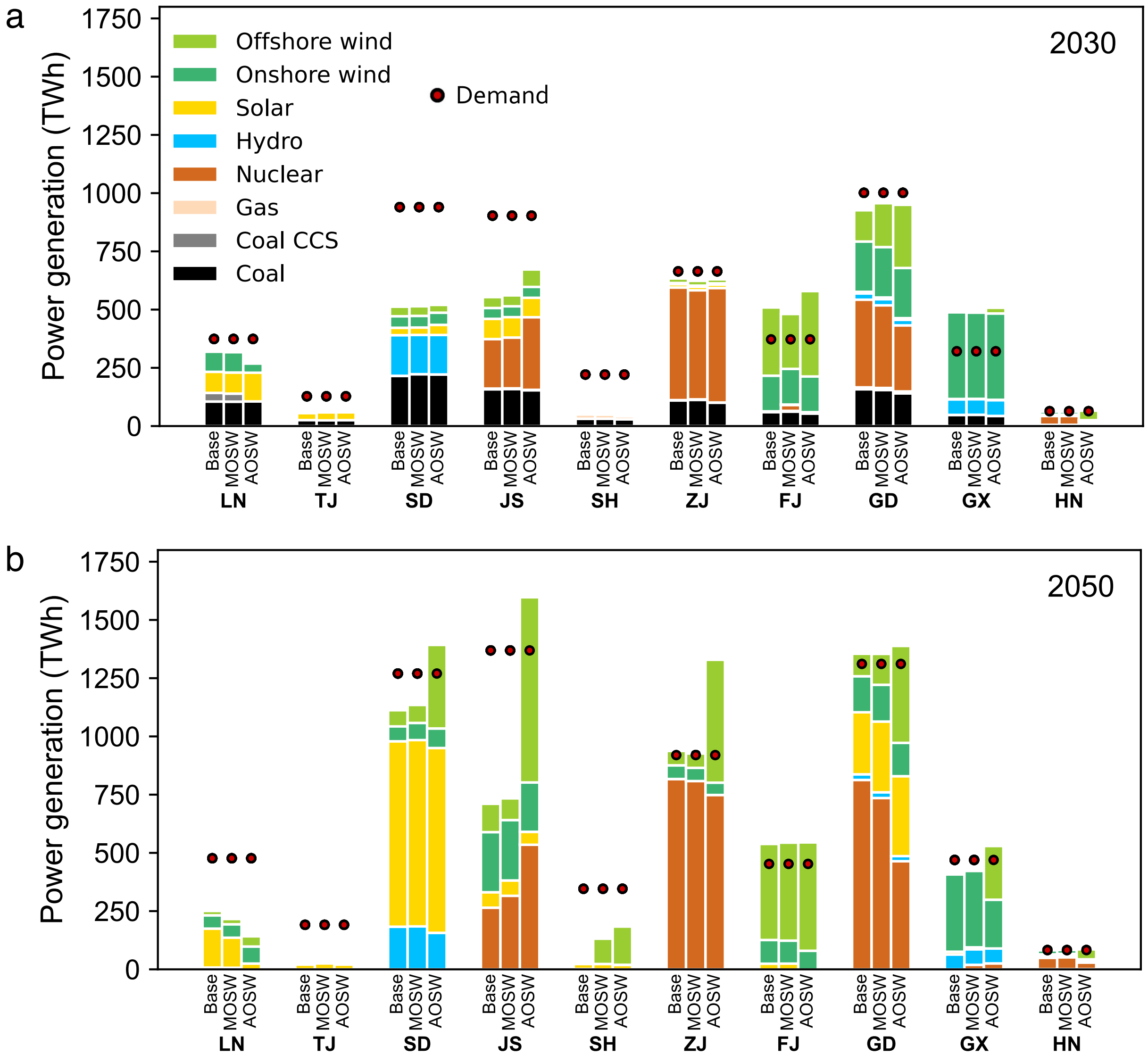
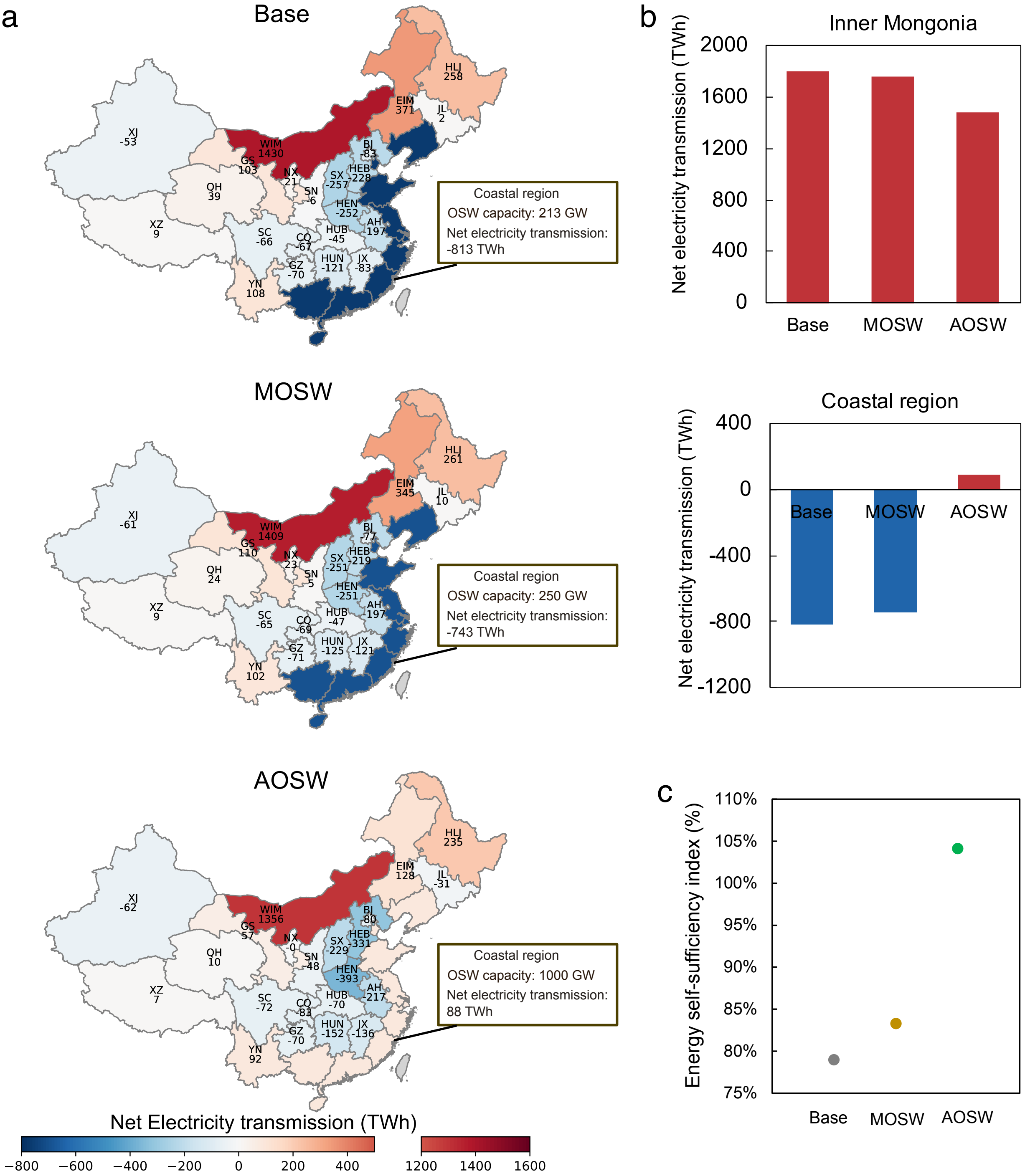
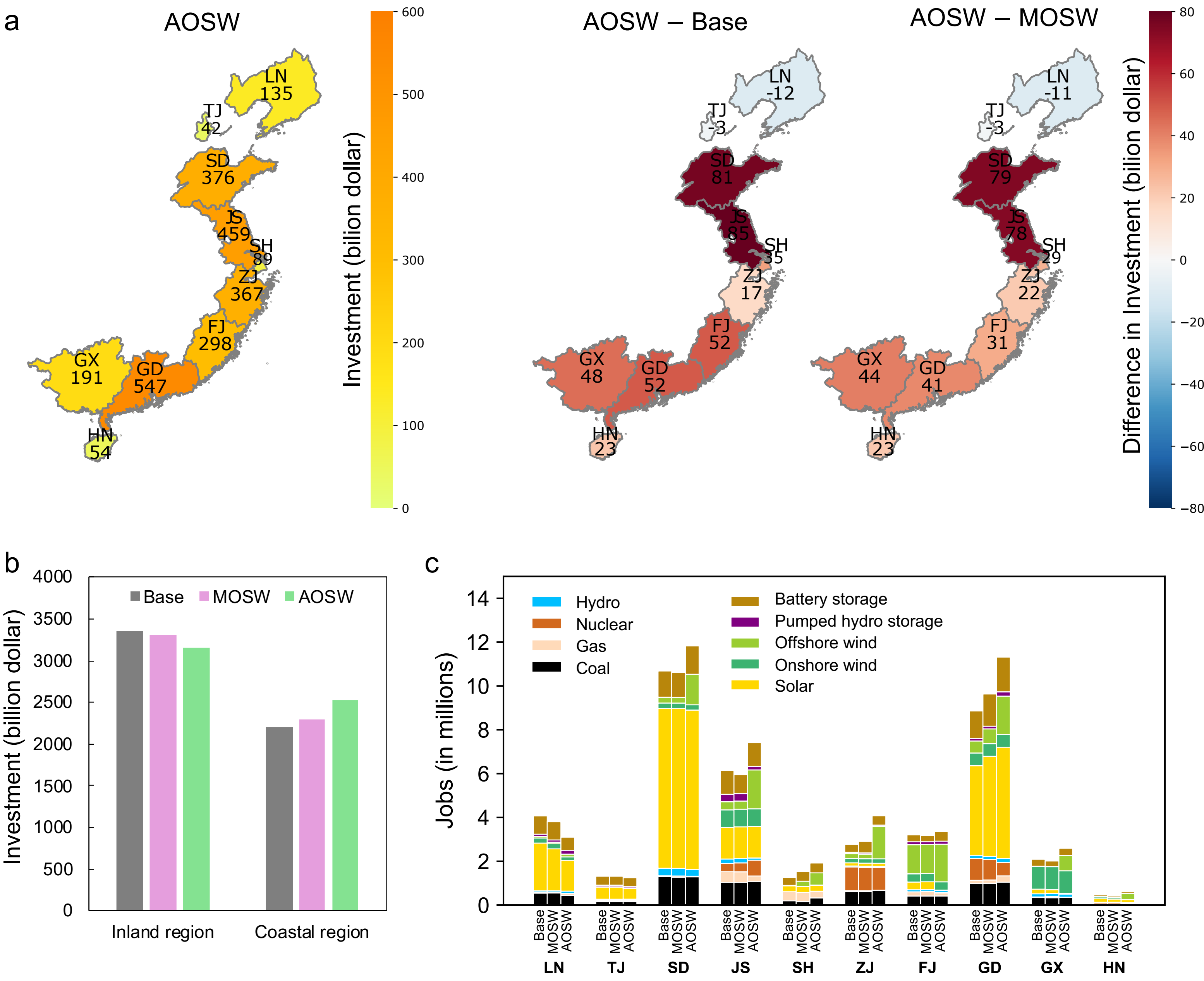
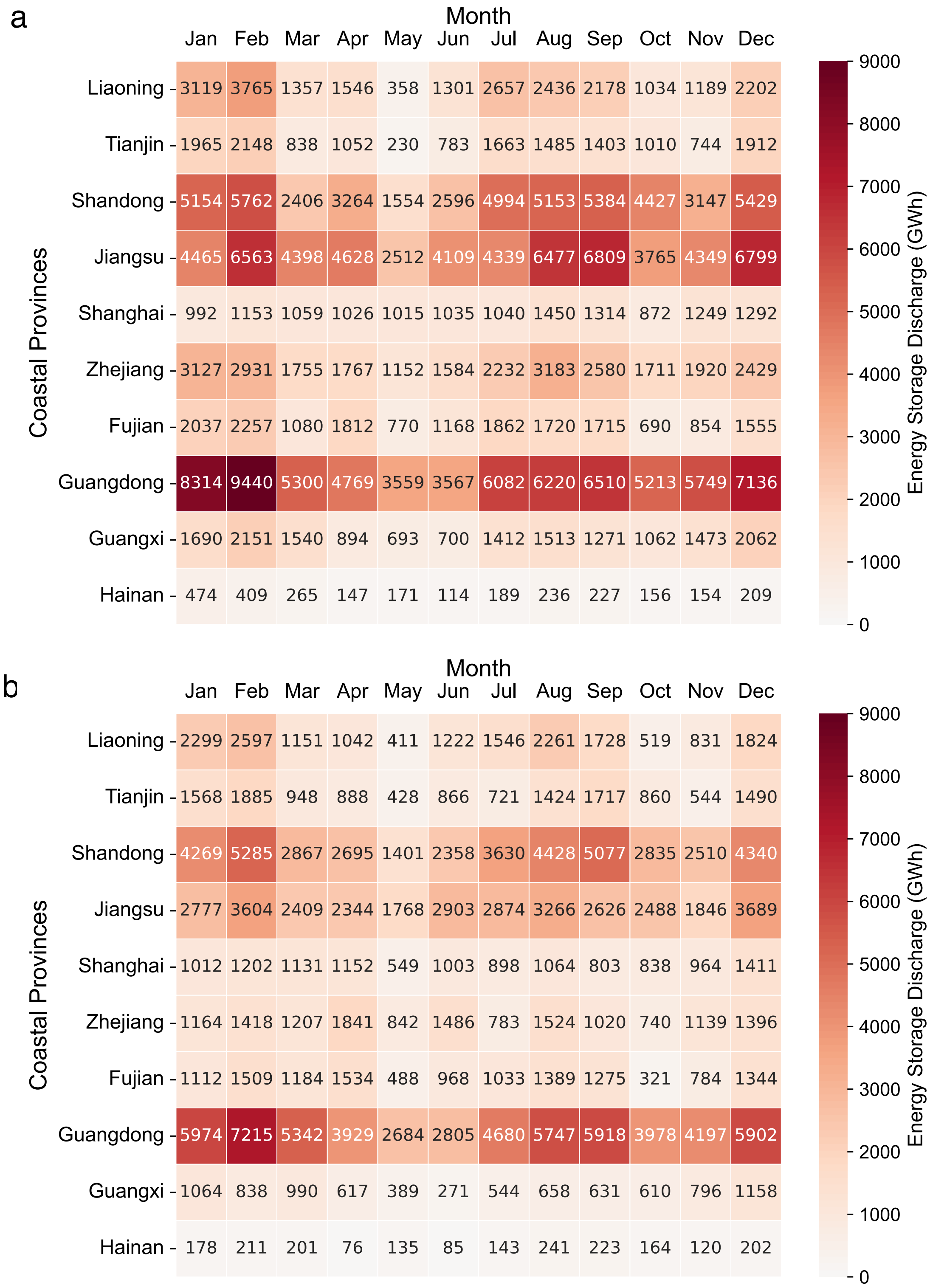

a
2030
Power generation (TWh)
0
250
500
750
1000
1250
1500
1750
Offshore wind
Onshore wind
Solar
Hydro
Nuclear
Gas
Coal CCS
Coal
Demand
Base
MOSW
AOSW
LN
TJ
SD
JS
SH
ZJ
FJ
GD
GX
HN
b
2050
Power generation (TWh)
0
250
500
750
1000
1250
1500
1750
Base
MOSW
AOSW
LN
TJ
SD
JS
SH
ZJ
FJ
GD
GX
HN


a
Base
HLJ 258
EIM 371
JL 2
XJ -53
WIM 1430
BJ -83
GS 103
HEB -228
NX 21
SX -257
QH 39
SN -6
HEN -252
XZ 9
SC -66
AH -197
HUB -45
CQ -67
HUN -121
JX -83
GZ -70
YN 108
Coastal region
OSW capacity: 213 GW
Net electricity transmission: -813 TWh
MOSW
HLJ 261
EIM 345
JL 10
XJ -61
WIM 1409
BJ -77
GS 110
HEB -219
NX 23
SX -251
QH 24
SN 5
HEN -251
XZ 9
SC -65
AH -197
HUB -47
CQ -69
HUN -125
JX -121
GZ -71
YN 102
Coastal region
OSW capacity: 250 GW
Net electricity transmission: -743 TWh
AOSW
HLJ 235
EIM 128
JL -31
XJ -62
WIM 1356
BJ -80
GS 57
HEB -331
NX -0
SX -229
QH 10
SN -48
HEN -393
XZ 7
SC -72
AH -217
HUB -70
CQ -83
HUN -152
JX -136
GZ -70
YN 92
Coastal region
OSW capacity: 1000 GW
Net electricity transmission: 88 TWh
Net Electricity transmission (TWh)
−800
−600
−400
−200
0
200
400
1200
1400
1600
b
Inner Mongonia
Net electricity transmission (TWh)
2000
1600
1200
800
400
0
Base
MOSW
AOSW
Coastal region
Net electricity transmission (TWh)
400
0
-400
-800
-1200
Base
MOSW
AOSW
c
Energy self-sufficiency index (%)
110%
105%
100%
95%
90%
85%
80%
75%
Base
MOSW
AOSW


a
AOSW
LN 135
TJ 42
SD 376
JS 459
SH 89
ZJ 367
FJ 298
GX 191
GD 547
HN 54
Investment (bilion dollar)
0
100
200
300
400
500
600
AOSW – Base
LN -12
TJ -3
SD 81
JS 85
SH 35
ZJ 17
FJ 52
GX 48
GD 52
HN 23
AOSW – MOSW
LN -11
TJ -3
SD 79
JS 78
SH 29
ZJ 22
FJ 31
GX 44
GD 41
HN 23
Difference in Investment (bilion dollar)
80
60
40
20
0
−20
−40
−60
−80
b
Base
MOSW
AOSW
Investment (billion dollar)
0
500
1000
1500
2000
2500
3000
3500
4000
Inland region
Coastal region
c
Hydro
Nuclear
Gas
Coal
Battery storage
Pumped hydro storage
Offshore wind
Onshore wind
Solar
Jobs (in millions)
0
2
4
6
8
10
12
14
Base
MOSW
AOSW
LN
TJ
SD
JS
SH
ZJ
FJ
GD
GX
HN

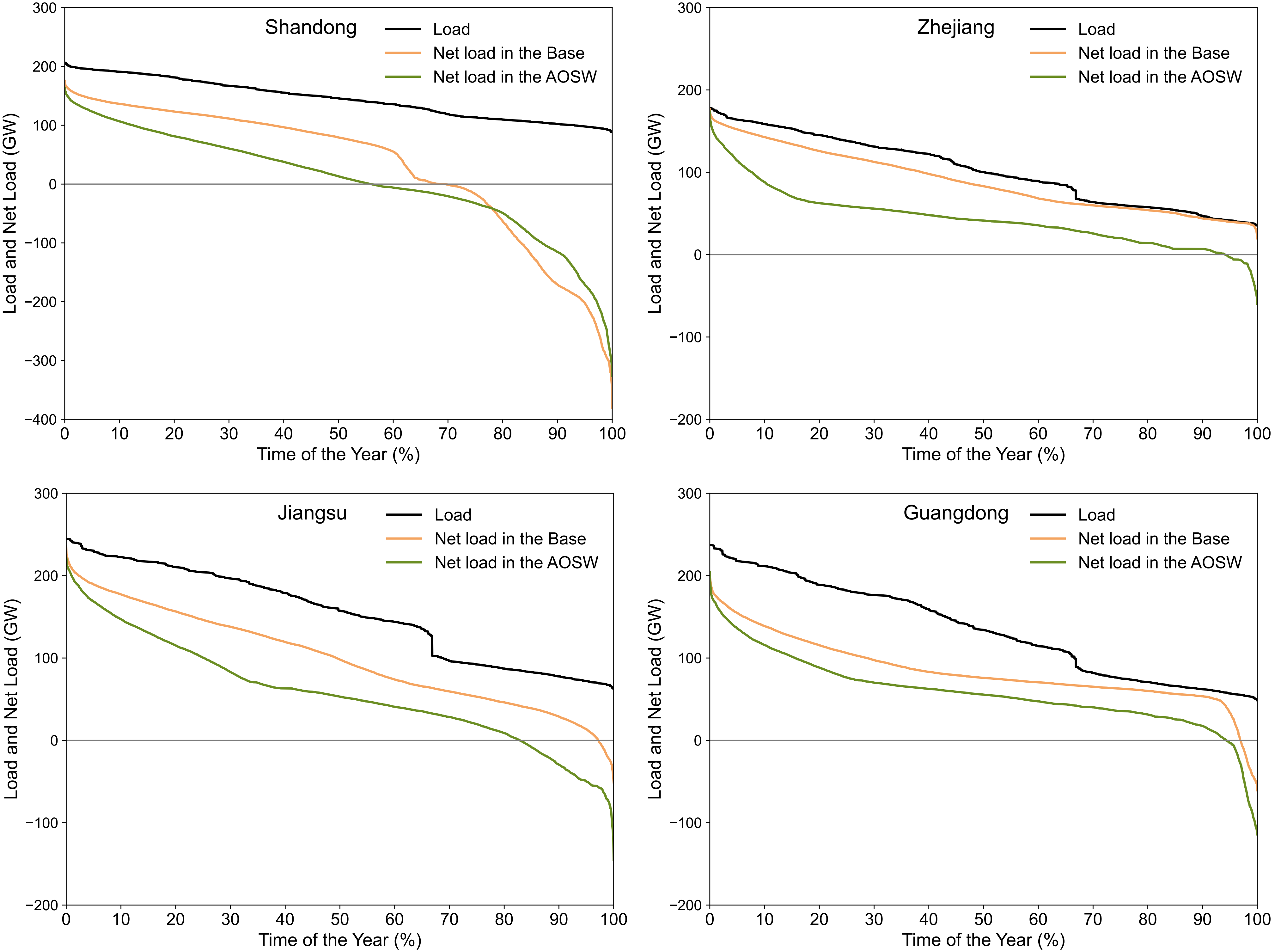


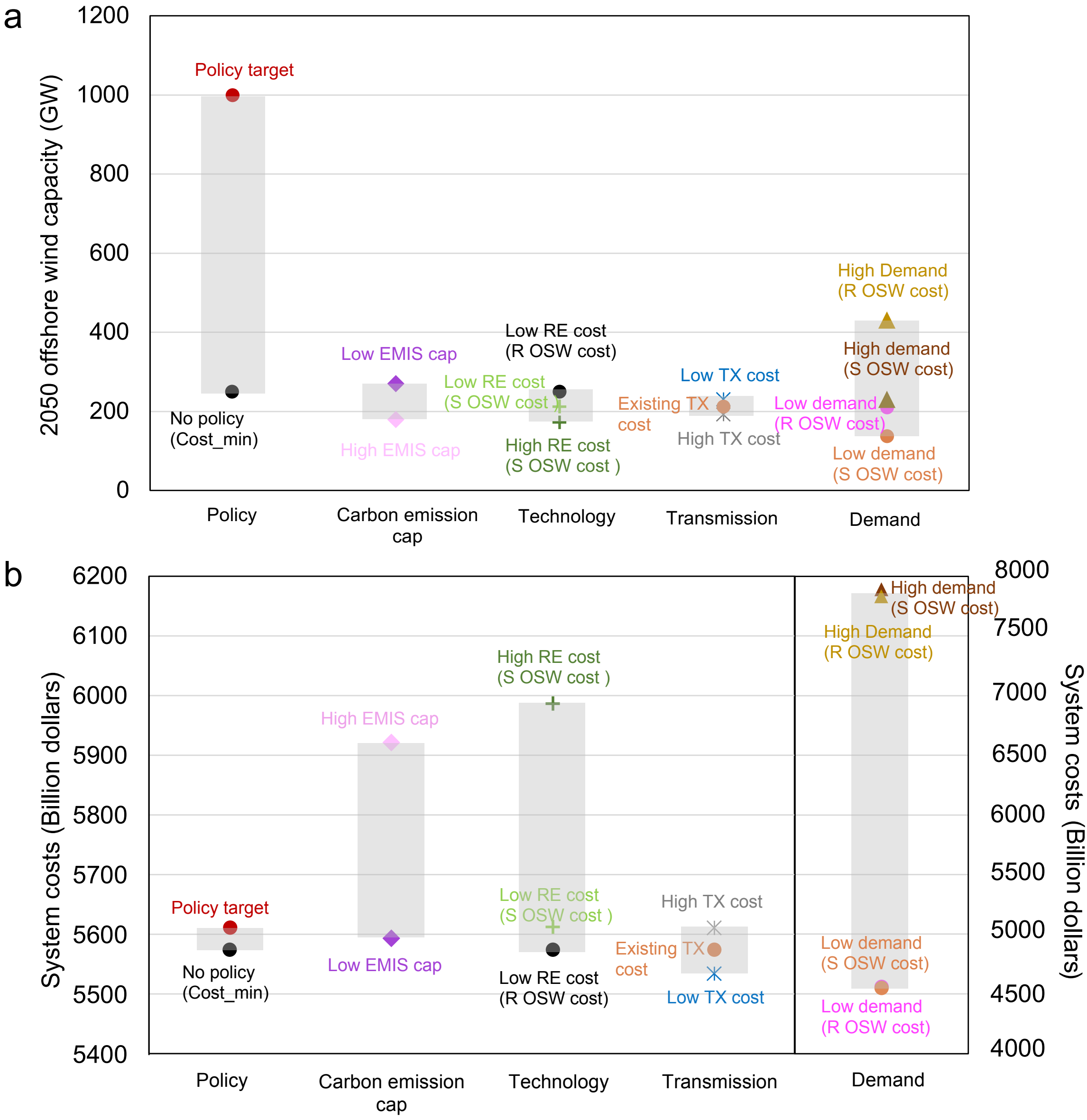
a

Coastal Provinces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Liaoning	3119	3765	1357	1546	358	1301	2657	2436	2178	1034	1189	2202
Tianjin	1965	2148	838	1052	230	783	1663	1485	1403	1010	744	1912
Shandong	5154	5762	2406	3264	1554	2596	4994	5153	5384	4427	3147	5429
Jiangsu	4465	6563	4398	4628	2512	4109	4339	6477	6809	3765	4349	6799
Shanghai	992	1153	1059	1026	1015	1035	1040	1450	1314	872	1249	1292
Zhejiang	3127	2931	1755	1767	1152	1584	2232	3183	2580	1711	1920	2429
Fujian	2037	2257	1080	1812	770	1168	1862	1720	1715	690	854	1555
Guangdong	8314	9440	5300	4769	3559	3567	6082	6220	6510	5213	5749	7136
Guangxi	1690	2151	1540	894	693	700	1412	1513	1271	1062	1473	2062
Hainan	474	409	265	147	171	114	189	236	227	156	154	209

b

Coastal Provinces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Liaoning	2299	2597	1151	1042	411	1222	1546	2261	1728	519	831	1824
Tianjin	1568	1885	948	888	428	866	721	1424	1717	860	544	1490
Shandong	4269	5285	2867	2695	1401	2358	3630	4428	5077	2835	2510	4340
Jiangsu	2777	3604	2409	2344	1768	2903	2874	3266	2626	2488	1846	3689
Shanghai	1012	1202	1131	1152	549	1003	898	1064	803	838	964	1411
Zhejiang	1164	1418	1207	1841	842	1486	783	1524	1020	740	1139	1396
Fujian	1112	1509	1184	1534	488	968	1033	1389	1275	321	784	1344
Guangdong	5974	7215	5342	3929	2684	2805	4680	5747	5918	3978	4197	5902
Guangxi	1064	838	990	617	389	271	544	658	631	610	796	1158
Hainan	178	211	201	76	135	85	143	241	223	164	120	202


Shandong
Zhejiang
Jiangsu
Guangdong
Load
Net load in the Base
Net load in the AOSW
Load and Net Load (GW)
Time of the Year (%)
300
200
100
0
−100
−200
−300
−400
0
10
20
30
40
50
60
70
80
90
100


a
2050 offshore wind capacity (GW)
1200
1000
800
600
400
200
0
Policy target
No policy
(Cost_min)
Low EMIS cap
High EMIS cap
Low RE cost
(R OSW cost)
Low RE cost
(S OSW cost)
High RE cost
(S OSW cost)
Low TX cost
Existing TX
cost
High TX cost
High Demand
(R OSW cost)
High demand
(S OSW cost)
Low demand
(R OSW cost)
Low demand
(S OSW cost)
Policy
Carbon emission
cap
Technology
Transmission
Demand
b
System costs (Billion dollars)
6200
6100
6000
5900
5800
5700
5600
5500
5400
8000
7500
7000
6500
6000
5500
5000
4500
4000
System costs (Billion dollars)
High demand
(S OSW cost)
High Demand
(R OSW cost)
High RE cost
(S OSW cost)
High EMIS cap
Policy target
No policy
(Cost_min)
Low EMIS cap
Low RE cost
(S OSW cost)
Low RE cost
(R OSW cost)
High TX cost
Existing TX
cost
Low TX cost
Low demand
(S OSW cost)
Low demand
(R OSW cost)
Policy
Carbon emission
cap
Technology
Transmission
Demand