Offshore wind replaces coal and reduces transmission, enabling China to meet the 1.5°C climate imperative

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Summary

China is the world's leading installer of wind turbines. Attention is rapidly rising in China to the potential of offshore wind. We utilize the SWITCH-China power sector capacity expansion model to explore the transformative role that offshore wind can play in China meeting the ambitious but critically needed 1.5°C climate objective. We explore alternative energy mixes and analyze the resulting economic and CO_2 emissions benefits of offshore wind as a major energy source for China. We find that offshore wind not only replaces coal-fired power plants, which dominate the energy mix in Chinese coastal regions, but also reduces the need for ultra-high-voltage (UHV) transmission lines to deliver the renewable energy generated in the West China to the coastal regions in the East. Offshore wind enables the coastal provinces to become a new hub of green electricity supply, with offshore wind could provide 2% - 28.6% of coastal generation (between 1% and 13.2% of total generation) by 2030 across cost-effective energy development scenarios.

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Context & Scale

Driven by China's economic growth, the developed coastal East region is a major load center, accounting for a half of national electricity demand in 2016. The electricity generation of the coastal region is dominated by local coal generation, and imported wind, solar, and hydro from the Northwest, the North, and the Southwest through inter-provincial/regional transmission lines. Mitigating ambitious climate change requires decarbonizing the power sector. To meet the increasing electricity demand in the coastal region, coal need to be replaced by other cleaner resources. Some strategies focus on rich solar and wind resources located in the North and the West, supported by future significant expansion of the transmission system of the power system. This paper presents an important alternative that integrate decarbonized electricity sector and massive scale-up of offshore wind to replace coal at a viable, cost-effective pathway for China to embrace an ambitious CO_2 reduction target by 2030. We do a comprehensive techno-economic evaluation of all scenarios with unlimited capacity of offshore wind and limited capacity of offshore wind. China could eliminate 70% of its 2016 carbon emissions from the power sector by 2030 with 13% higher cost compared to business-as-usual scenario. Limiting offshore wind deployment would lead to a 6% higher power cost than the cost under unlimited for offshore wind. Deploying offshore wind leads to a reduction in electricity generation imports for the inland provinces from 3012 TWh under the limited capacity of offshore wind scenario to 2087 TWh under the unlimited capacity of offshore wind scenario. The results can inform policy and investments in technology research, development, and deployment.

Keywords

offshore wind energy, decarbonization of the power system, capacity expansion, China

INTRODUCTION

China's installed capacity for onshore wind has expanded significantly, growing from 0.3 GW of cumulative wind power capacity in 2000 to 204 GW in 2019 (9.3% of total installed generation capacity)[1]. About 405 terawatt-hours (TWh) of electricity was generated from wind in 2019, accounting for 5.5% of total electricity generation in the country[1]. Long-term projections for wind capacity have highly uncertain, ranging from 400 GW to 1200 GW by 2030 and from 1,000 to 2,000 GW by 2050[2]. However, many issues are limiting the development of onshore wind. On the one hand, over the past ten years, China has seen tremendous growth in renewable energy (RE) development accompanied by a high curtailment of RE. Wind curtailment in China hit a record high of 49.7 TWh in 2016, representing an average wind curtailment rate of 20.6%[3]. Recently, the average curtailment rate of wind has a significant decrease, in which decreasing from 20.6% in 2016 to 4% in 2019. On the other hand, although China has rich wind and solar resource located in the North and the Northwest, the electricity load center is in the East region. Due to the geographic imbalance between resource-abundant western regions and demand centers in the east, China's current energy structure is the inverse distribution between energy resources and electricity demand[4]. As source-rich areas cannot consume all of what they generate locally, this enhances the need for a cross-provincial UHV transmission lines[1]. Offshore wind, with its high average capacity factor, lower hourly variability, and declining cost, offers an alternative that deploying offshore wind in the coastal provinces could reduce imported renewable generation from the west and the north through HVDC/HVAC transmission lines[5], because offshore wind would supply coastal provinces directly.

Global offshore wind capacity grew to 29.1 GW in 2019[5]. Currently, the majority of cumulative offshore wind capacity is still in Europe, with the UK (33%), Germany (26%), Denmark (6%), Belgium (5%), and Netherlands (4%), while China (24%) installed 1.98 GW capacity that is more than any other country in 2019[5]. The global offshore wind market is expected to expand significantly over the next two decades, with the cumulative capacity ranging from 154 GW to 193 GW by 2030 and range from 364 GW to 560 GW by 2040[5,6]. Economically, the global weighted average levelized cost of energy (LCOE) for offshore wind was \$0.115 kWh^{-1} in 2019, 29% lower than in 2010[7]. Also, the weighted average LCOE for offshore wind decreased from \$0.214 kWh^{-1} to \$0.117 kWh^{-1} in 2019. Furthermore, new European offshore wind strike prices show declining prices from about \$0.2/kWh (2017 - 2019) to about \$0.075/kWh in 2024 -2025, which is expected to be cost-competitive with present coal-fired and gas-fired power generation technologies[6].

Given the development experience of offshore wind in Europe, improving economics and supportive government policy in China will certainly facilitate China's ambitions for offshore wind deployment. China's cumulative offshore wind capacity grew from 1.5MW in 2007 to 4.4 GW in 2018, totaling only 2.4% of the onshore wind capacity[1], due to higher investment cost of offshore wind than other renewables[7]. For now, with the latest nation-wide incentive policy of feed-in tariffs (FIT) 0.8 RMB/kWh (about \$0.114/kWh in 2019) for coastwide offshore wind, offshore wind is expected to reach cost parity with coal-fired plants, gas, solar PV and onshore wind in terms of LCOE by around 2030 in China[6, 8].

China has rich wind resources, ranging from 6 to 25 PWh/year (onshore) and 1.4 to 11 PWh/year (offshore)[2,9–11], which are 0.5 - 2 times, and 0.1 - 0.9 times for the national projected electricity demand in 2050 of 12 PWh/year[12], respectively. Given the current challenges of China's power system, major load centers will remain in the east, including clusters of mega-cities in the Pearl River Delta, Yangtze River Delta, and Bohai Economic Rim[13], causing a geographical imbalance of major electricity demand regions and major energy resources regions. Meanwhile, China has committed to peaking its CO_2 emissions and requiring at least 20% of non-fossil energy in total energy consumption by 2030[14]. Wind power could be an essential contributor to China's future energy supply. However, developing onshore wind requires significant expansions in high-voltage electricity transmission capacity from renewable resources rich areas to highly populated and polluted regions in the medium-term and long term. We will argue that investment in offshore wind resources can significantly reduce the demand for coal supply for coastal provinces in the eastern and southern China, and reduce the need for inter-regional UHV transmission while providing air quality and climate benefits at the same time[15–18]. Although offshore wind variability has significant impacts on grid flexibility, about 28% of the overall offshore wind potential could be deployed as baseload power replacing the coal-fired system in coastal provinces[19]. Offshore wind resources are expected to cost-effectively provide 42% of the total coastal province's electricity demand in 2030[9]. Previous studies focused on potential resource assessment, economics, and the utilization of offshore wind power[9,11,16,20,21]. Few studies explored integrating future offshore wind power into the power sector to decarbonize China's energy systems. Currently, the assessment methods focus on designing feed-in tariff levels for grid and generation expansion plans. No studies have considered simultaneously power system's operational constraints and long-term planning of with temporal and spatial resolution. Here, we cover this gap by presenting a general framework for considering challenges of grid integration for integration for offshore wind with temporal and spatial resolution.

We focus on the following questions: how sizeable offshore wind capacity would be installed if the capital costs of offshore wind have a rapid reduction trend? What are geographical distributions in offshore wind plants across the coastal province are compatible with high variability of offshore wind, and near-term nation emission goals? Is there an opportunity for China's coastal region to become an offshore wind generation base? How does the system respond to the trade-off between building new ultra-high voltage transmission lines to connect rich-resource regions and rich-electricity demand regions, and developing renewables in the coastal provinces with high electricity demand? By addressing those questions, implications for integrating offshore wind power into the power systems are analyzed that are not fully discussed in the existing literature.

This paper aims to explore the grid integration impacts of offshore wind on the coastal provinces in China by utilizing the SWITCH-China model considering the spatial and temporal distribution of offshore wind power for 2016 - 2030. We updated the SWITCH-China model [22] and developed four scenarios for 2030 to analyze the interplay between offshore wind, electricity supply mixes, and CO_2 emission constraints. The results provide a guide for future capacity expansion in offshore wind to decarbonize the power system cost-effectively.

Results

Mix of electricity generation and generation capacity

Across the cost assumptions of generation technologies and power system characteristics considered, we find that low capital costs of offshore wind result in a larger installed capacity of offshore wind. By 2030, offshore wind increase from 87 GW in the BAU scenario to 198 GW in the LC scenario (Figure 1). Further, offshore wind capacity is 432 GW by 2030 under the C70 scenario. There is no obvious change in the need for new coal capacity across scenarios. Coal capacity would remain current capacity from 1,024 GW in the C70-LO scenario to 1,100 GW in the BAU scenario.

Under the LC scenario, offshore wind generation significantly increases from 310 TWh in the BAU scenario to 642 TWh by 2030, an over two times increase (Figure 2). The non-fossil generation would be 3,764 TWh by 2030, accounting for 42.2% of national generation. The C70 scenario would lead to a decrease in coal generation from 5,346 TWh in the BAU scenario to 1,268 TWh by 2030, a 76.3% reduction, while the share of non-fossil generation would further increase 70.1% by 2030. Besides, offshore wind generation would increase to 1,178 TWh, accounting for about 13.2% national generation and 28.6% of coastal provinces' generation (Guangdong, Jiangsu, Hebei, Shandong, Zhejiang, Liaoning, Fujian, Shanghai, Tianjin) by 2030 (Figure 4). While under the C70-LO scenario, the offshore wind generation would decrease to 67 TWh by 2030 due to maximum capacity limitation of offshore wind. Onshore wind and solar generation from the non-coastal province would fill the generation gap under the C70-LO scenario. We observed that maximum economically achievable renewables (onshore wind and solar) would be 1,722 GW by 2030 under the C70 scenario, while the C70-LO leads to an increase to 2,073 GW.

The C70 scenario leads to an increase in gas capacity from 60 GW to 225 GW to incorporate renewables resources, coming from a lower CO_2 emission intensity and higher flexibility in gas. Notably, offshore wind could help to reduce requirements for gas-fired generation capacity. For instance, the C70-LO scenario installed 412 GW offshore wind less by 2030 than under the C70 scenario. Its gap will be filled by onshore wind and solar power in the west and the north, resulting in a higher variation of generation in these provinces. Thus, the C70-LO scenario would need more gas-fired capacity to incorporate this variation of renewable generation that is transported to the coastal provinces. Besides, the offshore wind is built in the East region with load center, and its generation almost be fully consumed by load center, avoiding possible scalable curtailment of renewables under importing electricity generation from the North, Northwest through long distance transmission lines.

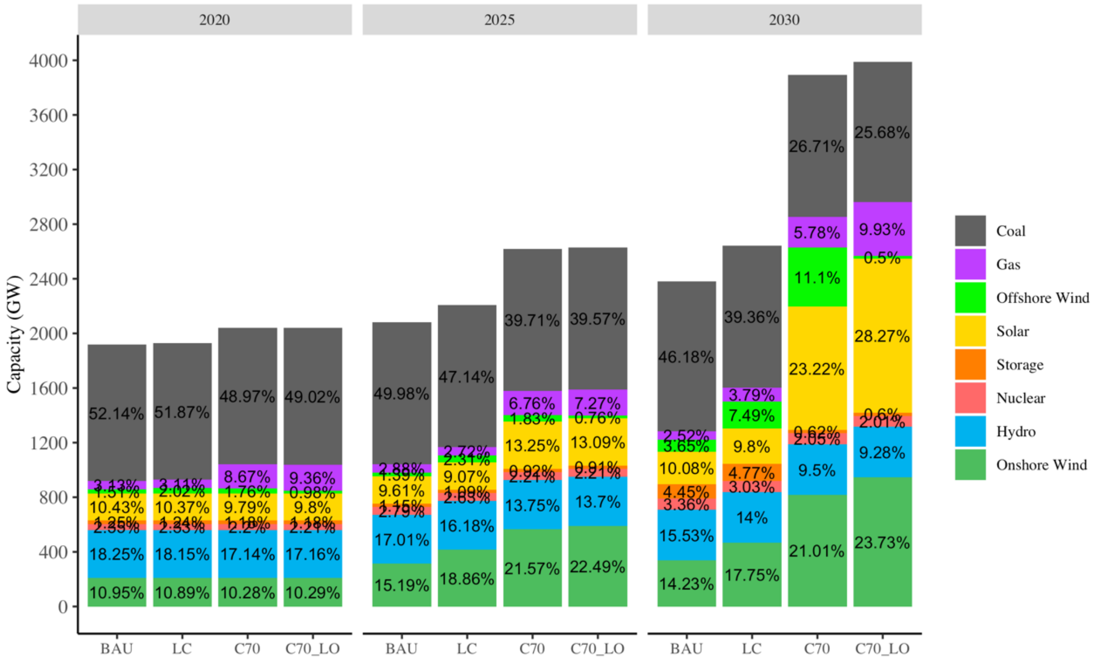


Figure 1. National Generation Capacity across Scenarios in 2020, 2025, and 2030. The scale of the bar chart is the installed capacity by technologies, and the data labels show that the share of each technology in total capacity.

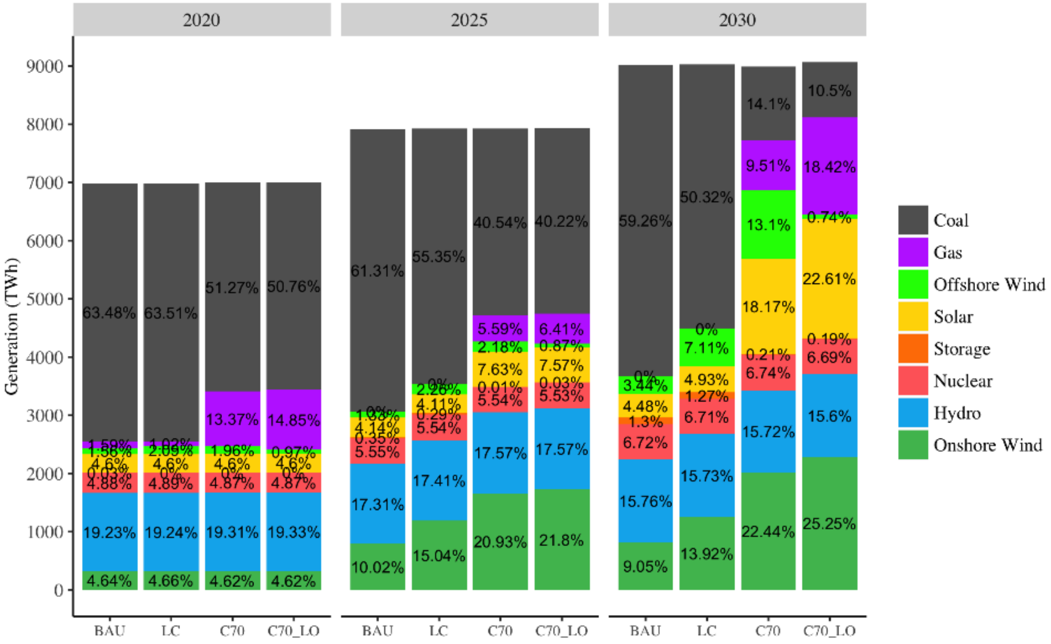


Figure 2. National electricity generation across scenarios in 2020, 2025, and 2030. The scale of the bar chart is the installed capacity by technologies, and the data labels show that the share of each technology in total capacity.

Energy costs and carbon emissions

The low cost (LC) scenario could reduce CO_2 emissions from 5.13 $BtCO_2$ in the BAU scenario (17.1% above the 2016 level) to 4.35 $BtCO_2$ (0.7% below the 2016 level) by 2030 (Table 1). Given the rapid cost reduction assumption in renewables and storage, this 16.4% reduction in CO_2 emissions can be achieved at a similar cost under the BAU scenario (Table 2). The CO_2 emission reduction results from a new installed capacity of cost-competitive renewables compared with coal units. Under the C70 scenario, CO_2 emissions in 2030 would be 30% of CO_2 emissions in the 2016 level, consistent with the 1.5 degree climate target pathway[12]. However, its CO_2 emission target requires $53.64/MWh by 2030, which is about 13% higher than costs under the BAU scenario. Notably, the C70-LO scenario leads to an increase in energy costs, about 6% higher than costs under the C70 scenario.

Table 1. National Emissions (billion ton CO_2)

PERIOD	BAU	LC	C70	C70-LO

2016	4.38	4.38	4.38	4.38
2020	4.40	4.29	3.59	3.59
2025	4.76	4.26	3.09	3.09
2030	5.13	4.35	1.31	1.31

Table 2. Average energy costs ($/MWh)

PERIOD	BAU	LC	C70	C70-LO
2020	49.64	49.53	50.28	50.51
2025	46.89	46.35	51.33	51.45
2030	47.47	47.56	53.64	56.85

Figure 3 and Table 3 explain what contributes to the changes in the annual costs of the power sector. A carbon emission constraints scenario would change the investment structure that switches from coal fuel costs to more capital costs of carbon-free power plants than the BAU scenario. The fuel costs of coal decrease from $139.3 billion by 2030 under the BAU scenario to $27.6 billion under the C70 scenario. Similar results occur under the LC scenario. The capital costs from solar, wind, and storage would be $170.1 billion by 2030, accounting for 38.5% of annual costs in the C70 scenario, compared with the 14.8% in the BAU scenario. Specifically, there is the vast market potential for offshore wind, representing a $16.8 billion annual and $41.5 billion capital investment under the LC scenario and the C70 scenario, respectively. As a result, this will require a significant number of suppliers, such as wind turbines, foundations, cables, and transformers.

From the perspective of cost-saving of offshore wind, compared with the C70-LO scenario, deploying offshore wind costs $26.6 billion less annually under the C70 scenario. The cost reduction is mainly driven by a decrease in capital costs of solar, onshore wind, transmission lines, and fuel costs of gas. Specifically, offshore wind makes deploying local renewables resources in coastal provinces be cost-competitive compared to importing electricity from the resource-rich western and northern regions through existing or new inter-provincial/regional transmission corridors. For instance, although deploying offshore wind increase capital costs from $3.2 billion by 2030 in the C70-LO scenario to $41.5 billion in the C70 scenario, it would reduce capital costs for onshore wind and solar $23.8 billion in the same year. Additionally, deploying offshore wind could increase local renewable generation, helping to reduce capital costs of inter-provincial/regional transmission corridors from $49.3 billion under the C70-LO scenario to $41 billion under the C70 scenario by 2030. As a consequence, the coastal provinces could import less green generation from the west and the north (such as Xinjiang and Inner Mongolia), resulting in building fewer transmission corridors. We observed that fuel cost for gas under the C70-LO scenario is \$73.1 billion, which is about two times the costs under the C70 scenario. The reason is that the additional 351 GW installed capacity for onshore wind and solar needs more gas-fired capacity to incorporate these variation generations. Although, the maximum economically achievable level of offshore wind is below 198 GW under the LC scenario, the carbon emission constraints would deploy 432 GW offshore wind by 2030 under the C70 scenario. The annualized total cost of the power system is \$444.8 billion for the C70 scenario and \$471.4 billion for the C70-LO scenario in 2030. It can be concluded that carbon emission constraints would enable offshore wind to be more cost-competitive than the costs from the combination of building renewables in the inland province plus building new inter-provincial/regional transmission corridors connecting inland and the coastal provinces.

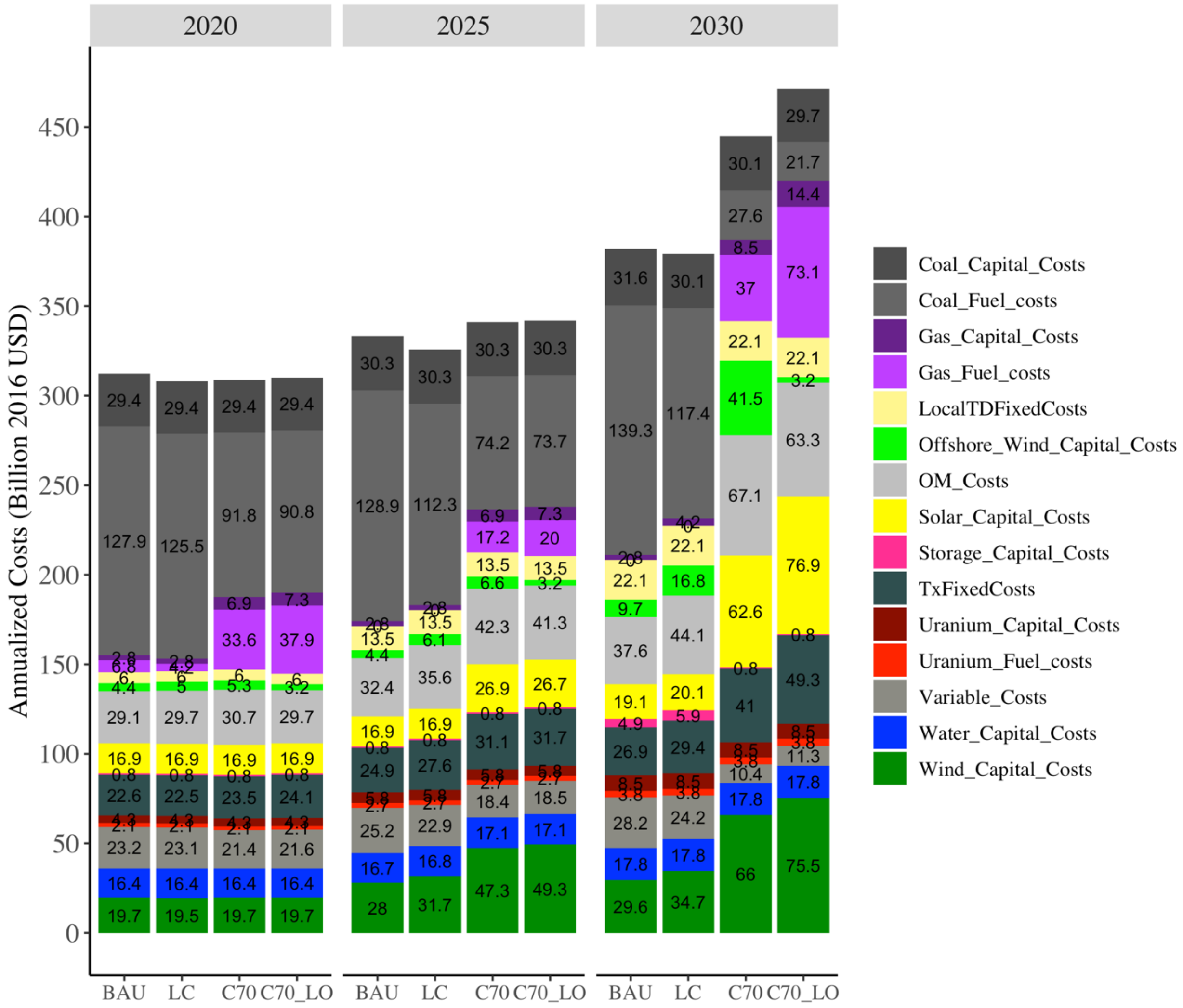


Figure 3. Total Annualized Costs in 2030. The total annualized cost is the discounted sum of the investment costs for new generators and transmission lines, the O&M costs, the fixed O&M costs for transmission lines and distribution systems, the variable costs, the start-up costs and the fuel costs.

Table 3. The annual costs in 2030 (USD billion)

Component	BAU	LC	C70	C70-LO
Coal-Capital Costs	31.6	30.1	30.1	29.7
Coal-Fuel Costs	139.3	117.4	27.6	21.7
Gas-Capital Costs	2.8	4.2	8.5	14.4
Gas-Fuel Costs	0	0	37	73.1
Local TD Fixed Costs	22.1	22.1	22.1	22.1

Offshore Wind-Capital Costs	9.7	16.8	41.5	3.2
O&M costs	37.6	44.1	67.1	63.3
Solar-Capital Costs	19.1	20.1	62.6	76.9
Storage-Capital Costs	4.9	5.9	0.8	0.8
Tx Fixed Costs	26.9	29.4	41	49.3
Uranium-Capital Costs	8.5	8.5	8.5	8.5
Uranium-Fuel costs	3.8	3.8	3.8	3.8
Variable Costs	28.2	24.2	10.4	11.3
Water-Capital Costs	17.8	17.8	17.8	17.8
Wind-Capital Costs	29.6	34.7	66	75.5
Total	381.9	379.1	444.8	471.4

Contributions of offshore wind

Source-based variations in gross electricity generation of the coastal provinces from 2020 through 2030 are shown in Figure 4. Under the LC and C70 scenario, offshore wind plays a crucial role to replace coal generation that dominated the electricity generation under the BAU scenario. The share of coal generation in the coastal provinces decreases from about 50% by 2030 under the BAU scenario to 10.3% under the C70-LO scenario. The LC scenario is significant for the growth in electricity generation from offshore wind by 2030. Its share, which is 14.8% of the coastal province's electricity demand, increased by 100% compared with the share under the BAU scenario. Notably, compared with the C70-LO scenario, deploying offshore wind leads to a reduction in electricity imports for the inland provinces of 3,012 TWh under the C70-LO scenario to 2,087 TWh under the C70 scenario (Figure 4).

Furthermore, the C70 scenario saw a significant increase in offshore wind installed capacity by 2030 and reached a share of 27.2% in total demand from the coastal provinces in the same year (Figure 5). Specifically, the map of mix of resource capacity and cumulative transmission capacity under the C70 scenario shows regional difference for deployment of renewables (Figure 6). First, offshore wind capacities are concentrated in the coastal provinces (Guangdong, Zhejiang, Jiangsu, Shandong, Fujian, Liaoning). Each of those provinces has more than 30 GW of offshore wind capacity. Wind capacities are concentrated in the North and Northwest. Xinjiang, Inner Mongolia, Heilongjiang, and Hebei have the greatest installation capacity. Each of those provinces has more than 30 GW of wind capacity. Solar capacities are located along the North, Northwest, and Southwest. Inner Mongolia, Yunnan, Shanxi, Sichuan, Shanxi, Ningxia, Henan, Xinjiang, and Qinghai have more than 30 GW of solar capacity.

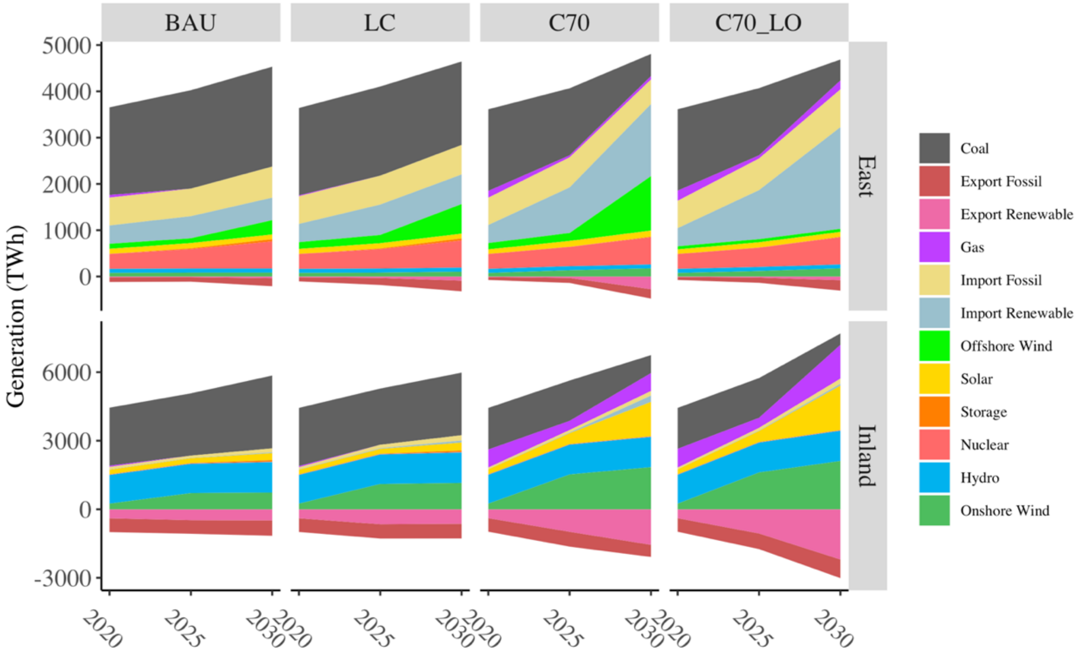


Figure 4. Source-based variations in gross electricity generation by region from 2020 to 2030. (The East region includes: Guangdong, Fujian, Zhejiang, Shanghai, Jiangsu, Shandong, Hebei, Tianjin, Liaoning. The inland provinces are other provinces that do not include east provinces)

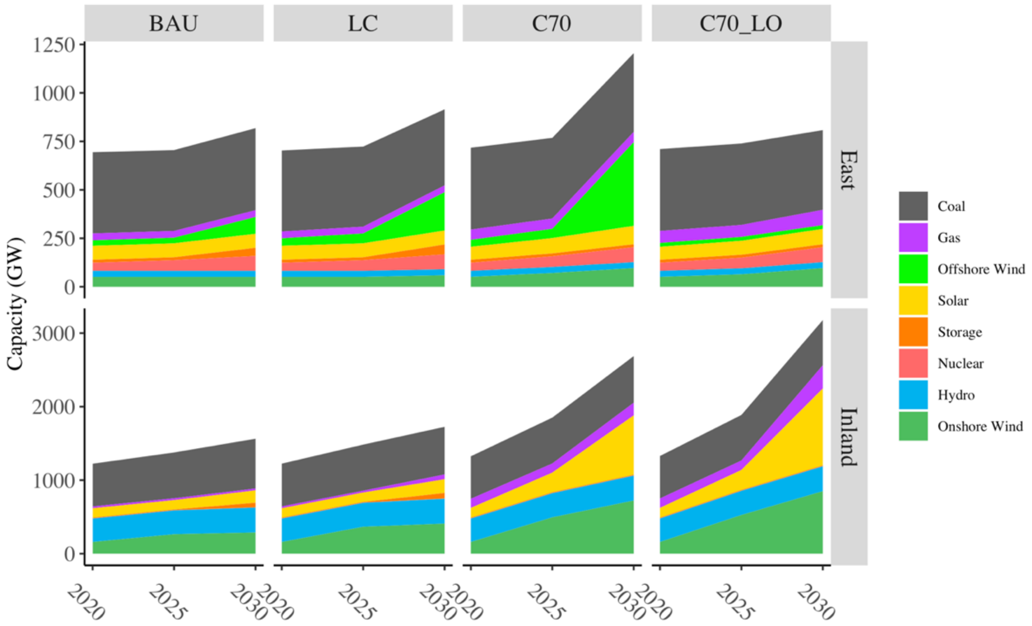


Figure 5. Installed Capacity by region. (The East region includes: Guangdong, Fujian, Zhejiang, Shanghai, Jiangsu, Shandong, Hebei, Tianjin, Liaoning. The inland provinces are other provinces that do not include east provinces)

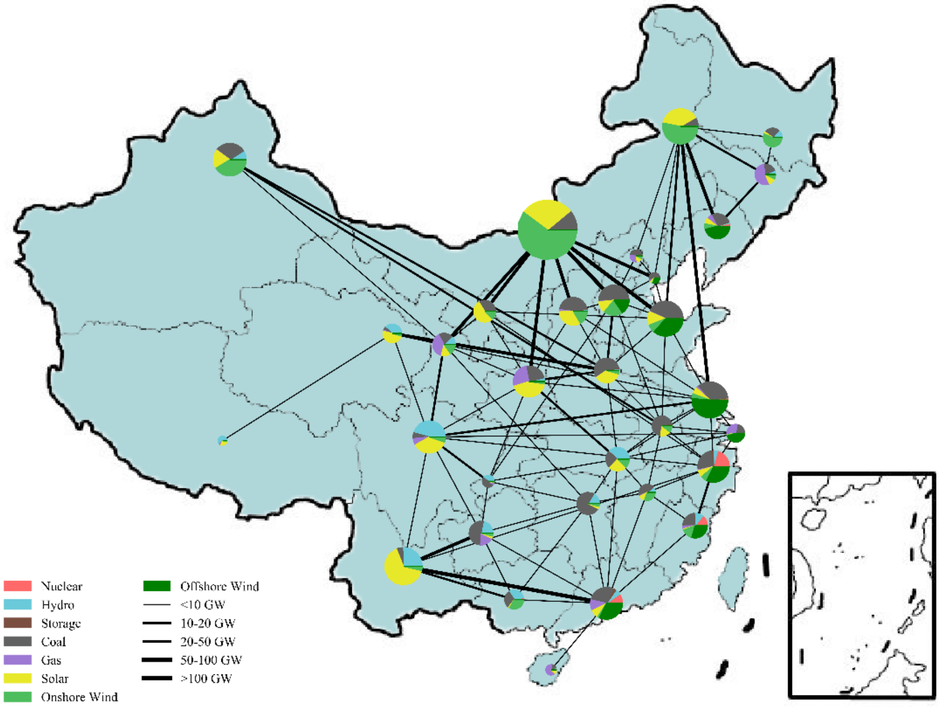


Figure 6. Provincial total capacity mix and cumulative transmission lines by 2030 under the C70 scenario

Although the energy self-sufficiency rates (ESSR) of the coastal provinces decrease from 80.2% by 2030 under the BAU scenario to 64.8% under the C70 scenario, the portion of renewable energy (wind, solar, and hydropower) in the coastal provinces significantly increases from 23.9% to 65.8% in the same year (Figure 7). deploying offshore wind could play a crucial role in increasing the ESSR of coastal provinces. For instance, the ESSR of the coastal provinces increases from 39.9% by 2030 under the C70-LO scenario to 64.8% under the C70 scenario, a 62.4% increase. The results show that offshore wind enables the coastal provinces to be a new "hub" of energy generation.

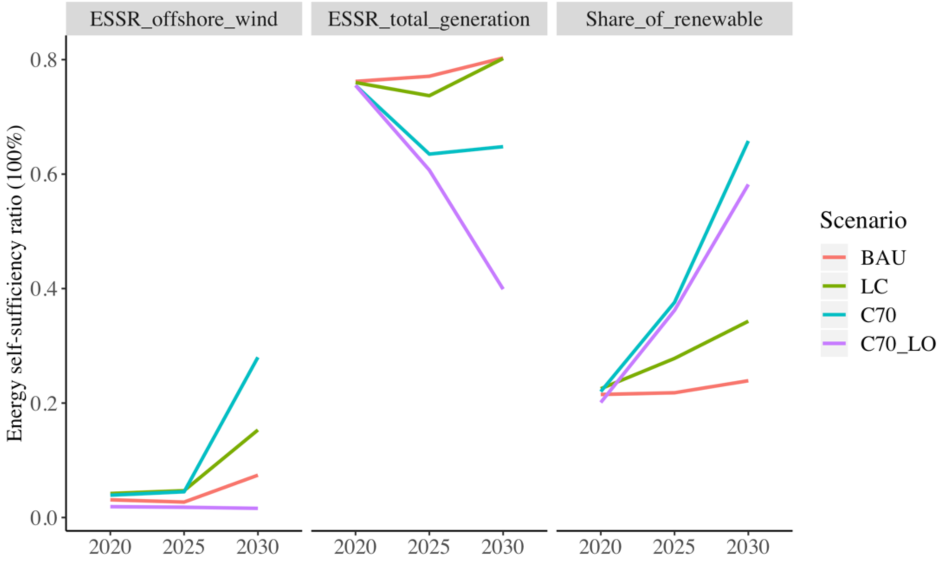


Figure 7. Energy self-sufficiency rates (ESSR) in coastal provinces between 2020 and 2030; The first left figure shows that the ratio between generation from offshore wind and electricity demand in the coastal province. The middle figure shows that the ratio between generation and electricity demand in the coastal province. The first right figure shows that the ratio between generation from renewables between total generation in the coastal province.

As large-scale integration of solar and onshore wind into the North, Northwest, and Southwest, importing generation from those areas to coastal center in the East with load center needs extensive transmission infrastructure (Figure 6). Deploying offshore wind could reduce the needs for cross-regional/provincial UHV transmission lines between the west and the coastal provinces. For instance, beginning in 2020, the transmission line capacity steadily increases because of increasing cross-provincial energy transmission in the future (Figure 8). Compared with the BAU scenario, the C70 scenario lead to an increasing requirement for transmission line capacity from 623 GW in the BAU scenario to 1,039 GW by 2030, a 66.7% increase, while under the C70-LO scenario, it further increases to 1,230 GW by 2030. Limiting offshore wind deployment would lead to an increase in other carbon-free renewables, like solar and wind in the west (Xinjiang, Inner Mongolia, and Yunnan), resulting in more cross-regional/provincial transmission lines between the west and the coastal provinces.

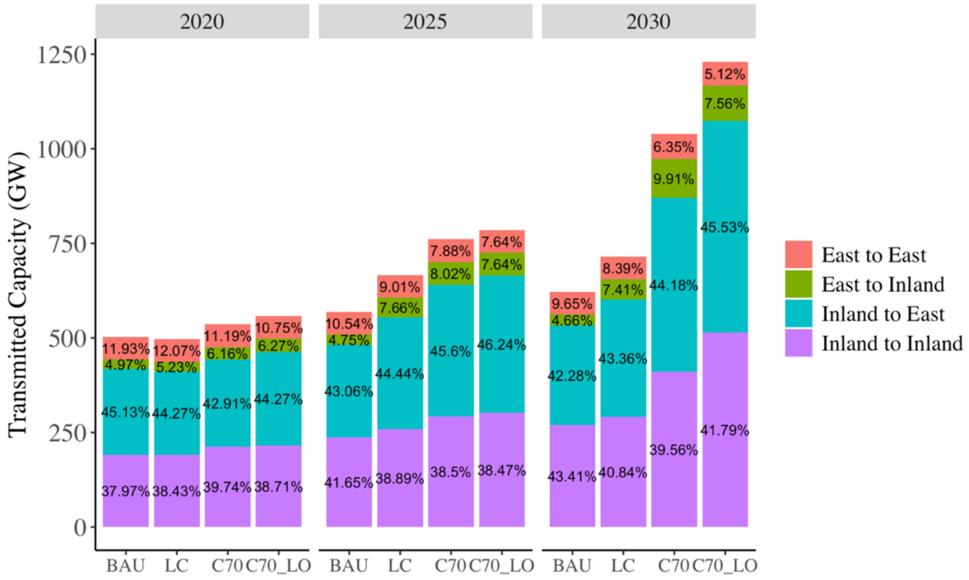


Figure 8. Transmission capacity across scenarios in 2020, 2025, and 2030. The transmission lines include 500 kV high voltage AC/DC transmission lines, ±800 kV Ultra-high-voltage (UHV) DC transmission lines, and 1000 kV Ultra-high-voltage (UHV) AC transmission lines. The figure legends represents direction of transmission line. For example, the "East to East" means that the transmission line locates in the East region, connecting both the East province and the East province.

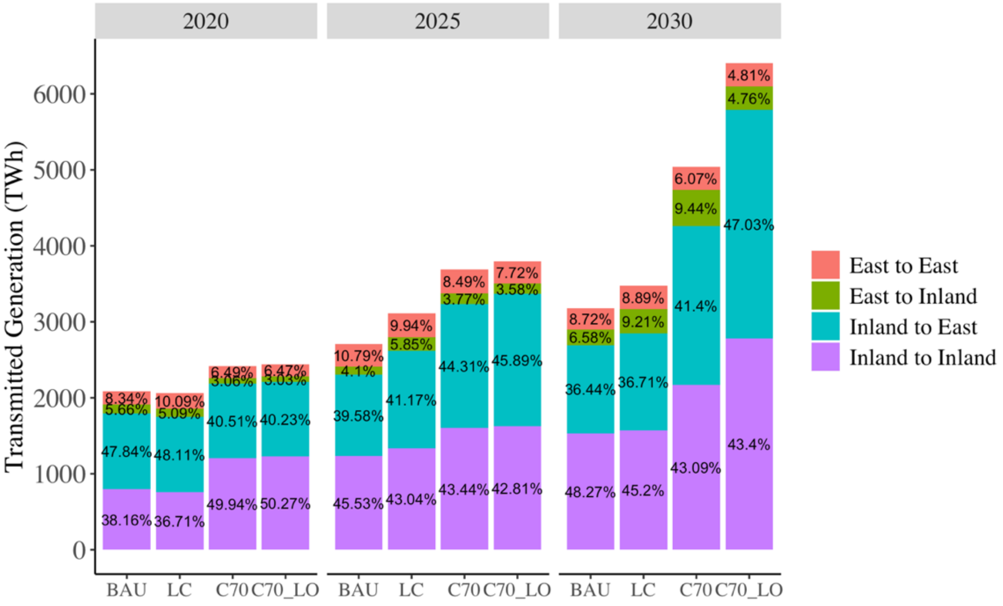
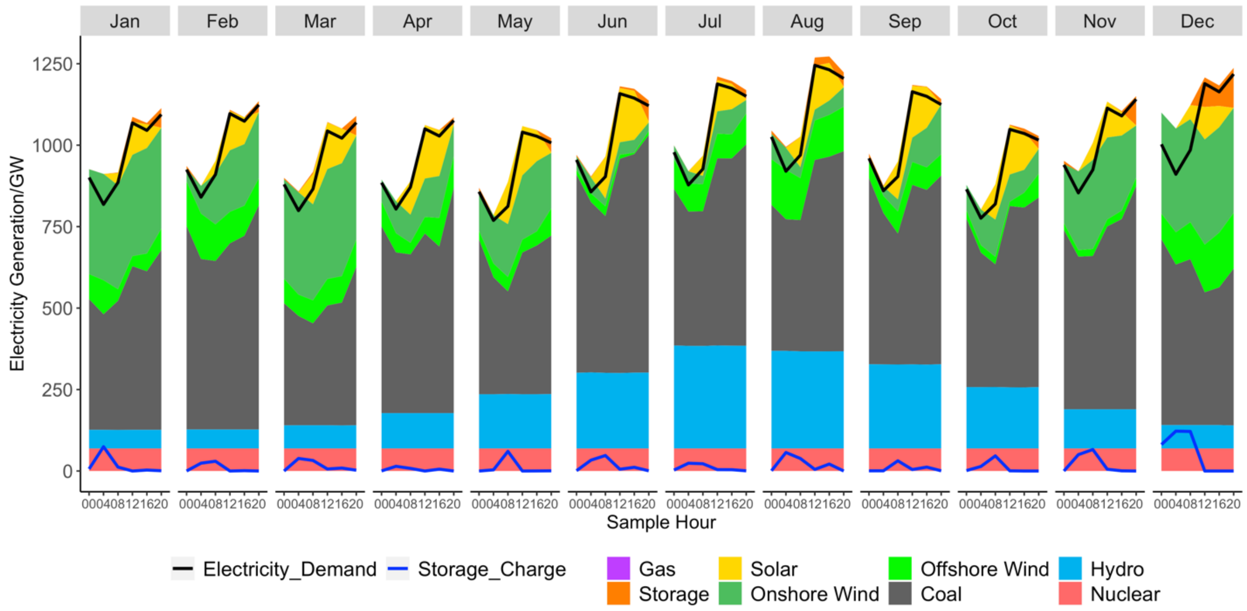


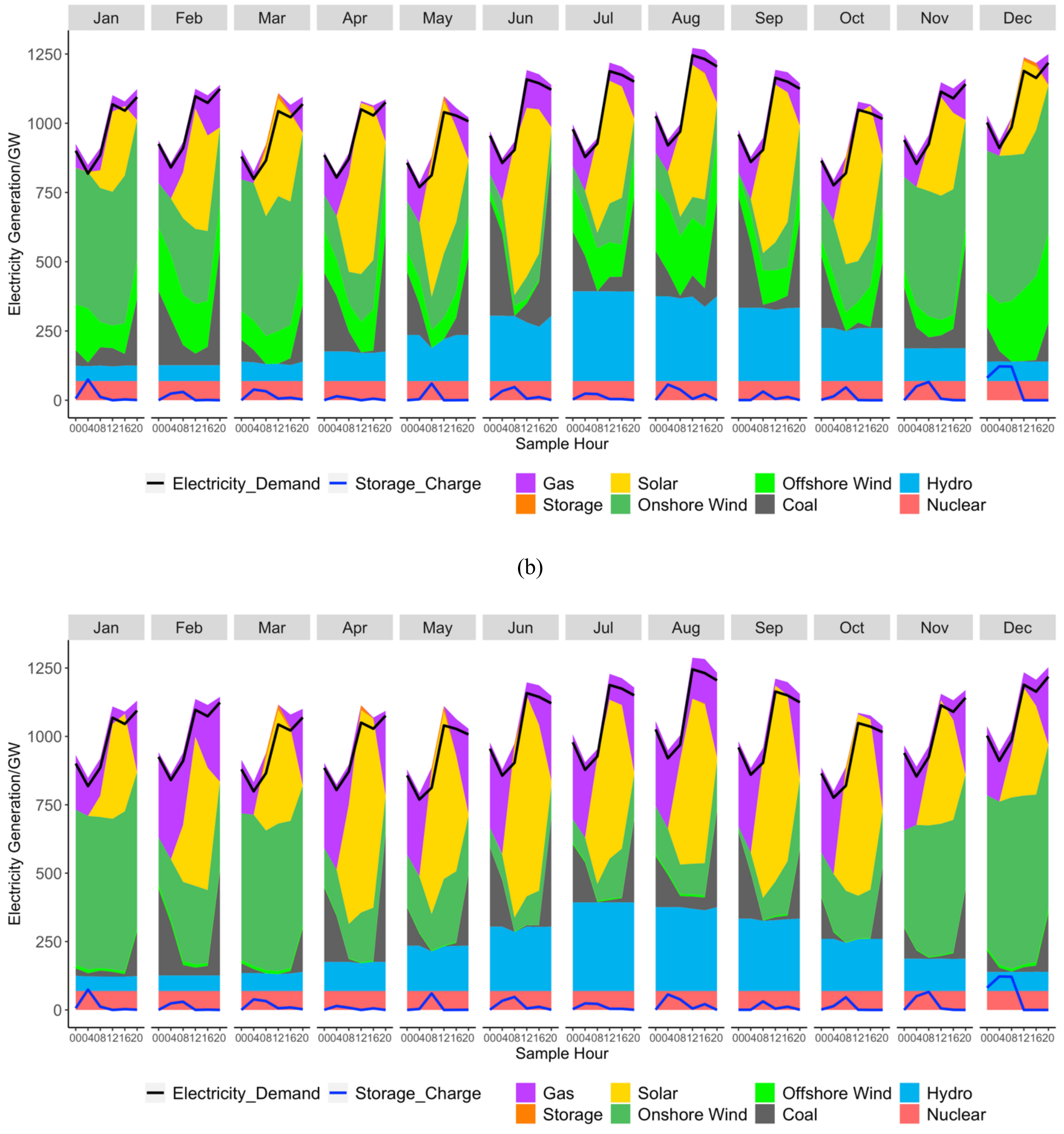
Figure 9. Inter-provincial/regional transmission generation across scenarios in 2020, 2025, and 2030. The figure legends represents transmission direction of generation. For example, the "East to Inland" means that the generation are transmitted from the East region to the Inland region.

Hourly dispatch

Figure 10 illustrates hourly dispatch in 2030 across the LC, C70, and C70-LO scenarios. The generation capacity expansion can meet electricity demand growth and peak demand. On one hand, renewable energy generation profiles vary throughout the year due to seasonal patterns. With a restrictive carbon cap, renewable energy resources dominate generation mixes and generation capacity mixes. As a result, this dramatically changes the power system operating characteristics, such as load balancing and ramping flexibility. Under the C70 scenario, gas-fired plants are attractive for providing flexibility in the absence of solar because of their relatively low capital cost, a high degree of efficiency, operational flexibility, and lower CO_2 emissions factors, despite having a higher fuel price than coal.



(a)



(b)

(c)

Figure 10. Hourly dispatch in 2030 under the LC, the C70 and the C70-LO scenario. (a) Hourly dispatch under the LC scenario; (b) Hourly dispatch under the C70 scenario;(c) Hourly dispatch under the C70-LO scenario. The figure depicts six hours per day, one day per month, and twelve months. Each vertical line separates the months, each of which contains one day. Total generation exceeds load because of local distribution transmission, transmission line losses, storage charge and discharge losses. For abscissa scale, each time instant represent a time slot. For instance, the ‘00’ represents “00:00”, the “20” represents ”20:00”.

DISCUSSION

The offshore wind development in China is at a critical moment. It has a huge potential yet the full realization of such potential depends on investment decisions at today. Although many studies focus on offshore wind's technical and economic potential, there is few forward-looking researches to assess how much offshore wind could be installed economically considering operational constraints in power systems. How offshore wind might affect China's power system generation mix and CO_2 emissions targets, and energy flow between resource-abundant western regions and demand centers in the east. This paper shows how the mix of generation and capacity will change as a rapid reduction in the capital cost of offshore wind and carbon cap. Our results show that both the capital cost of offshore wind and the carbon cap has positive effects on offshore wind capacity buildout, with carbon cap the has the most significant effect. If offshore wind capital costs follow global trends of decline, offshore wind could provide about 7.1% national generation by 2030. Even under the moderate cost scenario, the carbon cap makes offshore wind more attractive than the low-cost scenario for offshore wind. As the carbon cap tightens, it is better able to compete with other renewable technologies and existing coal, leading to a more replacement of coal generation and a reduction in generation imports from the inland provinces. Despite slower solar and wind growth in the coastal provinces, offshore wind capacity additions lead to a significant increase in renewable contributions to the coastal provinces. As a result, offshore wind enables the coastal provinces to be a new "hub" of electricity generation.

Under the carbon cap (C70) scenario, China could eliminate 70% of its 2016 carbon emissions from the power sector by 2030 with 13% higher cost, while delivering 13.2% of electricity from offshore wind. In the carbon cap with limitation for offshore wind (C70-LO) scenario, the same emissions reduction target can be achieved by 2030 but involves about a 6% higher power cost than under the C70 scenario. The cost reduction is mainly driven by a decrease in capital costs of solar, onshore wind, inter-provincial/regional transmission lines, and fuel costs of gas. Offshore wind development in China enables the 1.5° climate goal to be more cost-competitive than the scenario with limited offshore wind capacity. The system cost saving should deliver subsidies to stakeholder who invest offshore wind, and should upgrade local transmission systems to improve the ability to incorporate offshore wind, ultimately increasing their market share.

Our results show the possible decarbonization pathway of the China's power system by 2030, especially the ambitious development potential for offshore wind under the low costs scenario and the carbon cap scenario. There is the vast market potential for offshore wind, representing a $16.8 billion annual and $41.5 billion capital investment under the LC scenario and the C70 scenario, respectively. However, the scale and speed of expanding the capacity of offshore wind highly depends on government policies, supply train of offshore wind, and stakeholder interests, et al. In reality, China is accelerating its offshore wind development. There is a cumulative 9 GW of under construction, and even 36 GW of authorized offshore wind power to be online by 2020[23], even 30 GW of authorized offshore wind only for Guangdong province by 2030[24].

The transition of the global energy system from burning fossil fuels to safer, cleaner and cheaper renewable sources has accelerated in recent years. As the world's largest coal producer and consumer, China will play a critical role in this energy transition. Our analysis indicates that fast decarbonization of the power system is technically feasible and cost-competitive coupled with large-scale deployment of offshore wind, and it provides an alternative prospect for energy transition.

EXPERIMENTAL PROCEDURES

The SWITCH-China model

This paper utilizes and adapts the SWITCH-China model - a long-term capacity expansion planning model for the power system - to evaluate the multifaceted implications for future integration of offshore wind into coastal provinces' power system from 2016 to 2030 [22,25]. The SWITCH-China model is a mixed-integer linear program whose objective function is to minimize overall costs of generation, storage, and transmission during the simulation period. The corresponding constraints include power balance, unit commitment constraint (range of thermal unit power outputs, ramping limits, minimum on/off time, power balance and marginal power reserve), potential physical limits of renewable resources, transmission line constraints, and existing and future policies constraints.

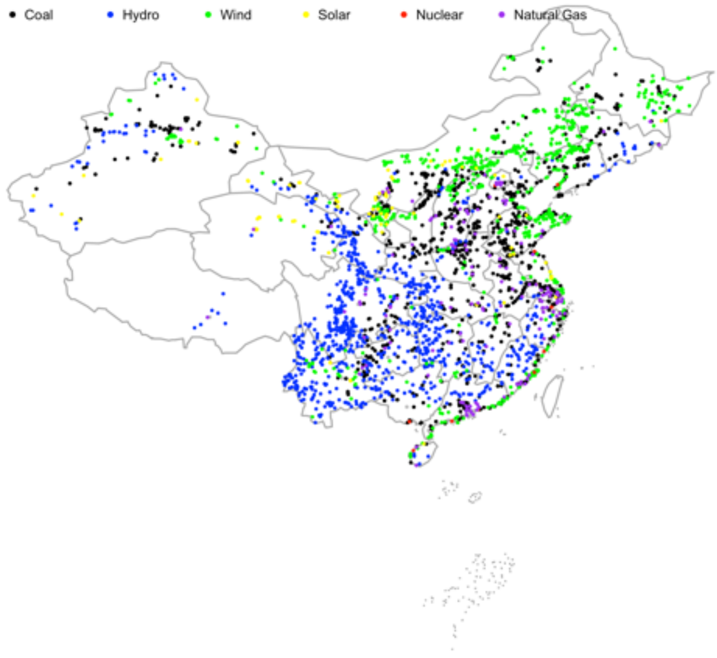
The objective function of the SWITCH-China model is to minimize the sum of (1) capital costs of existing and new power plants and storage projects; (2) fixed O&M costs incurred by all active power plants and storage projects; (3) variable costs incurred by each plant, including variable O&M costs, fuel costs to produce electricity and provide spinning reserves, and any carbon costs of greenhouse gas emissions; (4) capital costs of new and existing transmission lines and distribution infrastructure; and (5) annual O&M costs for new and existing transmission lines and distribution infrastructure. The table below presents the SWITCH-China calculations of the factors presented above.

The electricity demand and generation of the coastal provinces were 2923 TWh (half of the national demand) and 2458 TWh in 2016, respectively. The "West mainly filled its energy demand gap to East" project, which transports electricity from the West to the East. Using energy self-sufficiency rate (ESSR) reflects the impacts of offshore wind on the energy structure of the coastal provinces. The energy self-sufficiency rate is defined as the ratio between electricity generation and load demand in the same year. The utilization of local RESs in the power sector is one of the best ways to increase energy self-sufficiency rate of the coastal provinces and achieve rapid emission reductions. Here, we use coastal provinces' energy self-sufficiency rate to quantify the possibility of the coastal provinces becoming a new "hub" of energy generation, decreasing the importing electricity from the west.

Data Resources

We summarized all power plants built from 1970 to 2018[23,26,27] (Figure 11). Specifically, for offshore wind, the hourly capacity factor of offshore wind is obtained from the *Renewables.ninja*[28]. The average capacity factor of offshore wind by province are shown in Table S2.7. The hourly capacity factor of onshore wind and solar by province are shown in the supplementary[11,29]. We built an offshore wind power plant dataset including existing, consent authorized offshore wind power plants with name, location, capacity, build year, depth, distance to onshore, average wind speed, et al[23,29]. The physical offshore wind potential, and wind power plants are created at a spatial resolution of four to five locations with average wind speed larger than 6 m/s in each of China's ten provinces that have offshore resources[11].

We considered two cost scenarios for renewables technologies from 2016 to 2030: moderate and low, based on the trajectories of NREL's annual technology baseline (ATB) projections[2,30,31] (Figure 12). All other costs and fuel prices are updated according to the latest reports and literature (Supplementary). The Electricity demand projection, CO_2 emission calculation method, and transmission line updates are detailed in the Supplementary.



(a) The existing power plants

(b) The proposed renewable power plants

Figure 11. The spatial distribution of existing and proposed power plants

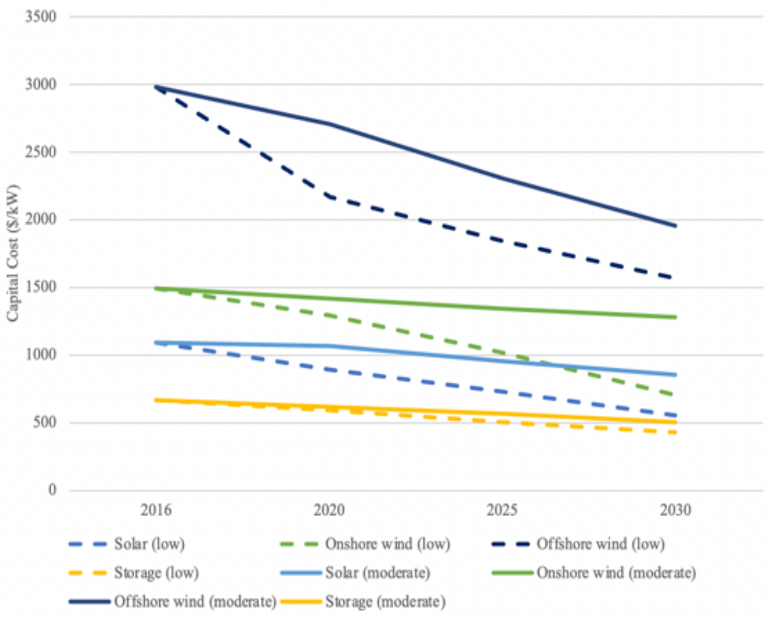


Figure 12. Capital costs of renewables and storage. Other capital cost of generation technologies are showed in the supplementary.

Scenario Descriptions

We built four scenarios (Table 4): First, business as usual scenario (BAU), which assumes the current policies and moderate cost reduction in renewables and storages. The second is the low-cost offshore wind scenario (LC), which assumes the rapid cost decrease in offshore wind and storage. Third, deep carbon emission constraints (C70), which assumes a further 70% reduction in carbon intensity from 2016 to 2030. Fourth, an assumption of a capacity limit for offshore wind scenario along with deep carbon emission constraints are considered(C70-LO), as offshore wind construction will occupy marine resources, which are controlled and approved by the government. If the government does not fully support the development of offshore wind considering the scarce marine resources and the impact of offshore wind on the marine ecosystem, there will be a capacity limit for offshore wind. The C70 and C70-LO scenarios adopt the same low costs trend for offshore wind. The C70-LO scenario represents that offshore wind deployment needs a variety of government policy-based incentives, because marine energy resources are public resources, resulting in requirements of cooperation for multi-government departments. The results provide a guide for future capacity expansion in offshore wind to decarbonize the power system cost-effectively.

Table 4. Scenario Descriptions

	BAU	LC	C70	C70-LO
Research periods	Three investment periods: 2016 to 2020, 2021 to 2025, 2026 to 2030			
Existing policies	The Chinese "Five-year plan" from 2016 – 2020; No new coal-fired power plants after 2020			
Future renewable cost trends	Moderate cost reduction in renewables	Rapid cost reduction in all renewables	Moderate cost reduction in renewables	Moderate cost reduction in renewables
Carbon cap emissions	-	-	A 70% reduction in carbon intensity from 2016 to 2030	A 70% reduction in carbon intensity from 2016 to 2030
Offshore wind policy	-	-	-	Capacity limit (20GW) for offshore wind by 2030

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Declaration of Interests

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

References

1. CEC (2019). Annual Development Report of the Chinese Power Sector.
2. IEA (2014). China Wind Energy Development Roadmap 2050.
3. NEA (2016). 2016 Wind Industry Development. Natl. Energy Adm.
4. Hurlbut, D., Zhou, E., Bird, L., and Wang, Q. (2015). Transmission Challenges and Best Practices for Cost-Effective Renewable Energy Delivery across State and Provincial Boundaries.
5. IEA (2019). Offshore Wind Outlook 2019 – Analysis - IEA.
6. Musial, W., Beiter, P., Spitsen, P., Nunemake, J., and Gevorgian, V. (2018). 2018 Offshore Wind Technologies Market Report. US DOE Off. Energy Effic. Renew. Energy.
7. IRENA (2019). Renewable Power Generation Costs in 2018.
8. China Energy Policy Newsletter: May and June 2019 NDRC and NEA issue official renewable energy obligation policy (2018).
9. Hong, L., and Möller, B. (2011). Offshore wind energy potential in China: Under technical, spatial and economic constraints. Energy *36*, 4482–4491.
10. Davidson, M.R., Zhang, D., Xiong, W., Zhang, X., and Karplus, V.J. (2016). Modelling the potential for wind energy integration on China's coal-heavy electricity grid. Nat. Energy.
11. He, G., and Kammen, D.M. (2014). Where, when and how much wind is available? A provincial-scale wind resource assessment for China. Energy Policy *74*, 116–122.
12. IEA (2017). Energy Technology Perspectives 2017.
13. NBS (2018). China Statistical Yearbook 2017.
14. NDRC (2015). Ehanced actions on climate change: China's intended nationally determined contribution.
15. Lu, X., McElroy, M.B., Nielsen, C.P., Chen, X., and Huang, J. (2013). Optimal integration of offshore wind power for a steadier, environmentally friendlier, supply of electricity in China. Energy Policy *62*, 131–138.
16. Davidson, M.R., Zhang, D., Xiong, W., Zhang, X., and Karplus, V.J. (2016). Modelling the potential for wind energy integration on China's coal-heavy electricity grid. Nat. Energy *1*, 16086.
17. Peng, W., Yuan, J., Zhao, Y., Lin, M., Zhang, Q., Victor, D.G., and Mauzerall, D.L. (2017). Air

quality and climate benefits of long-distance electricity transmission in China. Environ. Res. Lett. *12*.

18. Sherman, P., Chen, X., and McElroy, M.B. (2017). Wind-generated Electricity in China: Decreasing Potential, Inter-annual Variability and Association with Changing Climate. Sci. Rep. *7*, 16294.
19. Lu, X., McElroy, M.B., Chen, X., and Kang, C. (2014). Opportunity for offshore wind to reduce future demand for coal-fired power plants in china with consequent savings in emissions of CO2. Environ. Sci. Technol.
20. Lu, X., McElroy, M.B., Nielsen, C.P., Chen, X., and Huang, J. (2013). Optimal integration of offshore wind power for a steadier, environmentally friendlier, supply of electricity in China. Energy Policy *62*, 131–138.
21. Sherman, P., Chen, X., and McElroy, M.B. Offshore wind: an opportunity for cost-competitive decarbonization of China's energy economy. Sci. Adv.
22. He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., and Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nat. Commun.
23. 4COffshore (2019). Global Offshore Wind Farms.
24. GPDRC (2018). Guangdong Offshore Wind Planning (Chinese). Guangdong Prov. Dev. Reform Comm.
25. He, G., Avrin, A.-P., Nelson, J.H., Johnston, J., Mileva, A., Tian, J., and Kammen, D.M. (2016). SWITCH-China: A Systems Approach to Decarbonizing China's Power System. Environ. Sci. Technol. *50*, 5467–5473.
26. CSHE (2016). China hydropower Generation Statistical.
27. Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, and World Resources Institute (2018). Global Power Plant Database.
28. Pfenninger, S., and Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy.
29. ERI (2010). 2030 China Wind Development Outlook: the Feasibility Study of Meeting 10% of Electricity Demand.
30. NREL (2019). Annual Technology Baseline. Natl. Renew. Energy Lab.
31. International Renewable Energy Agency (IRENA) (2019). Renewable Power Generation Costs in 2018.