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MACRO AND GREEN FINANCE LAB
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CAPITAL

Economic and Environmental Benefits of and Financial Support for Wind Repowering Projects

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MACRO AND GREEN FINANCE LAB
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The Macro and Green Finance Lab is a think tank based at the National School of Development (NSD), Peking University (PKU). The Lab is dedicated to conducting policy and market research in the areas of macroeconomics, financial stability, green finance, and climate policy. The Lab also actively engages in international cooperation in the areas of sustainable finance and climate policy.

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Abstract

During the period of "14th Five-Year Plan" and the "15th Five-Year Plan", wind turbines with a total capacity of over 60 GW are expected to be decommissioned in China. Against this backdrop, wind farm repowering has great potential and becomes one of the key to the development of China's wind power industry. According to the analysis of this paper, wind repowering projects will deliver more economic benefits than greenfield projects; likewise, they also have more positive impacts on the environment and the climate. Under our assumptions, the IRR of repowering in many regions can top 14%. At the same time, repowering projects can considerably trim the land use of newly added wind turbines, and therefore mitigate the potential adverse impacts on the ecology while facilitating reductions in carbon emissions. At the current stage, however, large-scale wind repowering projects are mainly constrained by the capacity of regional power grids to absorb wind power and the difficulty in obtaining regulatory approval from the government. Our analysis suggests the following. Local governments should issue detailed implementation guidelines and streamline the administrative procedures for repowering projects. Financial institutions, especially banks, should analyze the economic benefits of repowering projects and develop innovative financial products targeting these projects under the framework of green finance taxonomies and PBoC's carbon-reduction supporting tools.

I Repowering: key to China's wind power development

1. Current state and future prospect of China's wind power industry

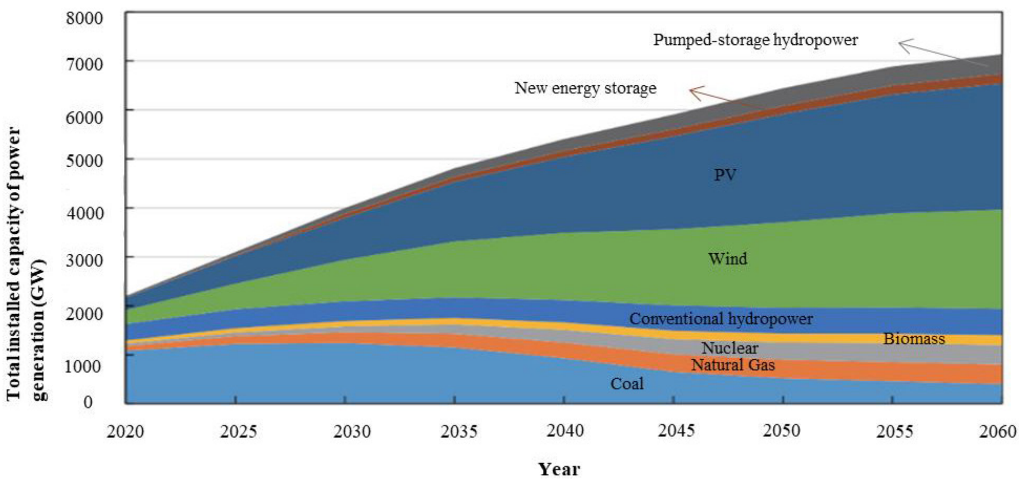
Starting from scratch in the 1990s, China's wind power industry now boasts the highest installed capacity in the world after over two decades of development. In the 1990s, China kick-started the construction of small pilot wind farms with foreign grants and loans. After 2003, China introduced the bidding of wind power concession programs and the *Renewable Energy Law*, which quickly scaled up the development of wind power and improved its ability to make wind power devices locally. Later in 2008, its proposal to build eight "10-GW wind power bases" in Inner Mongolia, Xinjiang, Gansu, Hebei, Shandong, and the coastal areas in Jiangsu, etc. ushered in the first boom of large-scale wind power development, pushing its total installed wind power capacity to the world's top one in 2010.

As of 2021, China had an installed wind power capacity of around 330 GW, accounting for approximately 13% of the total installed capacity of power generation in the country; the total wind power generation stood at 652.6 TWh, making up 7.9% of the total electricity consumption in China[1]. In the following four decades, installed wind power capacity and power generation in China will continue to have a higher share under the "dual carbon" strategy[2]. According to Shu Yinbiao et al. (2021), the installed capacity of wind power will hit 800 GW, constituting 21% of the total installed power generation capacity and 16% of the total power generation (with all non-fossil fuels accounting for 51% of the total power generation) by 2030 under the influence of the dual carbon strategy, economic growth, demand of energy consumption, technological advances, and constraints in resources, industries, and policies; by 2060, the installed capacity

1. Source: The National Energy Administration.
2. China's goal to peak its emissions by 2030 and become carbon neutral by 2060.

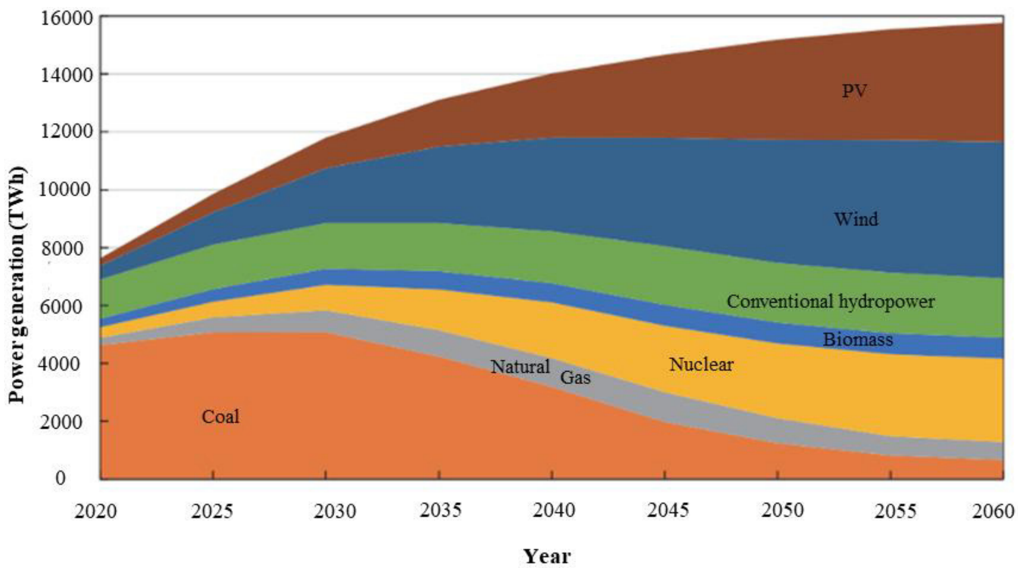
will reach 2000 GW, representing 28% of the total installed capacity, and 30% of the total power generation (with the proportion of non-fossil fuels climbing to 92%)[3].

Figure 1 Composition of installed capacity of power supply between 2020 and 2060 in the zero-carbon scenario



Source: Shu et al.(2021)

Figure 2 Composition of power generation between 2020 and 2060 in the zero-carbon scenario



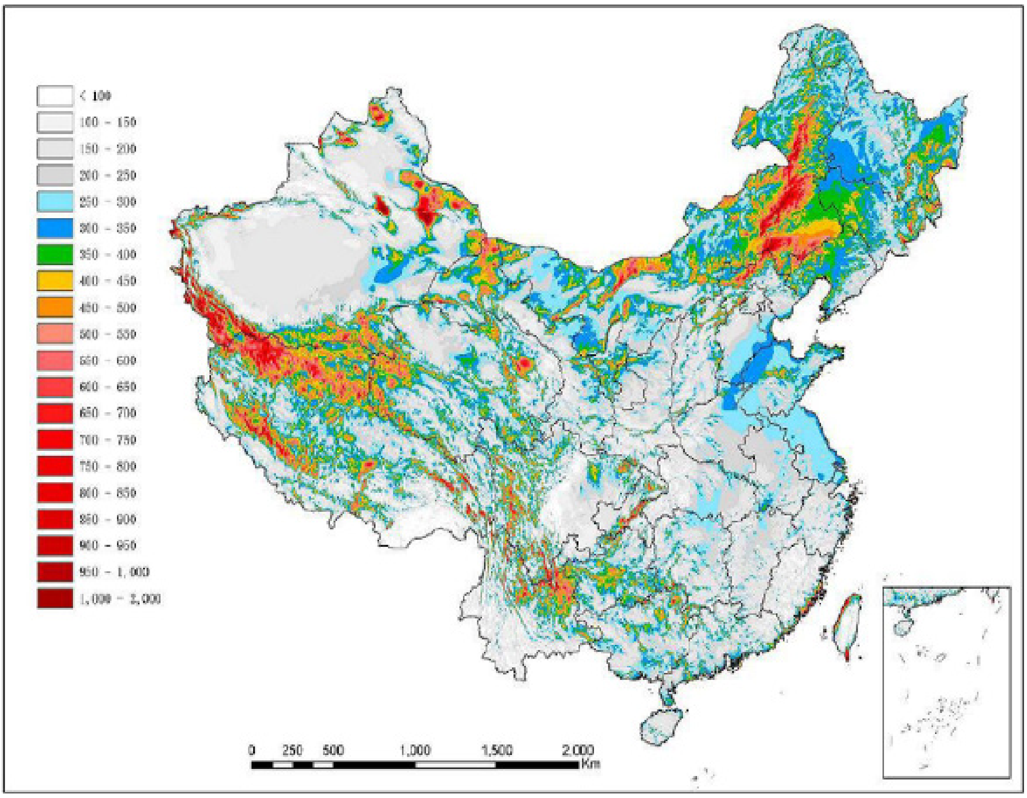
Source: Shu et al.(2021)

3. Shu Yinbiao, Zhang Liying, Zhang Yunzhou, Wang Yaohua, Lu Gang, Yuan Bo, and Xia Peng. Carbon Peak and Carbon Neutrality Path for China's Power Industry [J].Strategic Study of CAE, 2021, 23(06): 1-14.

Considering the requirements of wind power development for geographical locations, the increase in onshore wind power will come primarily from locations with rich wind energy resources now. As these locations are gradually developed and utilized, renovation and technology upgrades of existing projects will be necessary for the long term. In recent years, despite the rising popularity of offshore wind power and distributed wind power in China’ s eastern and middle regions, centralized development of onshore wind power remains the mainstream in China’ s wind power development. According to Figure 3 below, areas with the highest wind power density at the height of 70 meters in China include "the Three Norths" (i.e. the Northwest, the North, and the Northeast China) and the Southwest China. "The Three North Areas" have an abundance of land for developing wind power, which has put them in the foreground of China's onshore wind power development. The cumulative installed capacity in China is mostly concentrated in Inner Mongolia Province, Xinjiang Province, Hebei Province, Gansu Province, Shandong Province, etc. (as shown in Figure 4)[4]. Given the distribution of China's wind resources, future development of wind farms will still feature "large-scale development, centralized construction, and long-distance transmission".[5] Moreover, a large number of existing projects will need renovation and technology upgrades as areas with quality wind resources are largely developed and wind turbine fleets in current wind farms are approaching the end of their lifespan.

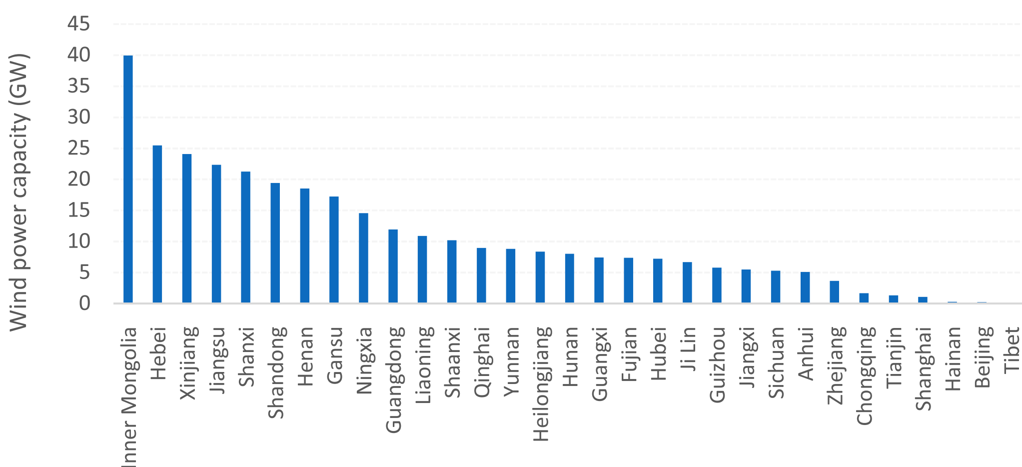
4. Source: The National Energy Administration.
5. China's goal to peak its emissions by 2030 and become carbon neutral by 2060.

Figure 3 Distribution of wind power density at the height of 70m in China



Source: China Meteorological Administration, Energy Research Institute of NDRC

Figure 4 Distribution of cumulative installed wind power capacity in China (2021)



Source: China Electricity Council

2. Drivers of wind repowering

a) The rising number of decommissioned wind turbines

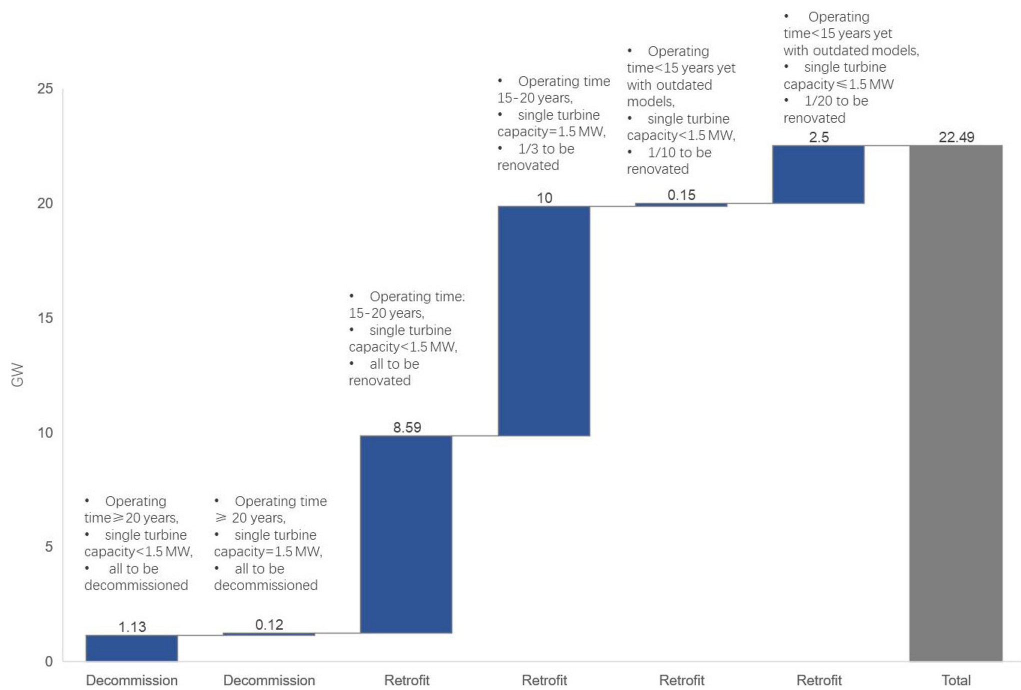
At present, despite the fact that the newly-added installed capacity of wind power comes mostly from new projects, repowering projects[6] are showing greater potential as more and more end-of-use wind turbines are being decommissioned. The lifespan of wind turbines is usually between 20 and 25 years. After two decades of development of China's wind power market, the first wind turbines installed at the turn of the century will reach their retirement during the period of "14th Five-Year Plan", while those installed on a large scale between 2005 and 2011 will need to be decommissioned during the period of "15th Five-Year Plan", pushing the demand for wind repowering to shoot up.

During the period of "14th Five-Year Plan" and the "15th Five-Year Plan", the cumulative decommissioned and retrofitted wind power capacity nationwide (namely the upgraded capacity of old wind turbines) will exceed 60 GW. According to the research and calculation of the Energy Research Institute of the National Development and Reform Commission[7], it is assumed that the design and operation of wind farms last somewhere between 20 and 25 years; some of the wind turbines that have operated for 15 years or longer need to be repowered; 20-year-old unrepowered wind turbines will start to be decommissioned, and be fully retired by the 25th year of their lifecycle. Based on this assumption, the cumulative wind power capacity to be retired or repowered between 2021 and 2030 will surge past 60 GW nationwide, with 20 GW during the period of "14th Five-Year Plan" and 40 GW during the period of "15th Five-Year Plan" as is shown in the chart below.

6. repowering project in this report means that small-capacity turbines were replaced with larger-capacity ones.

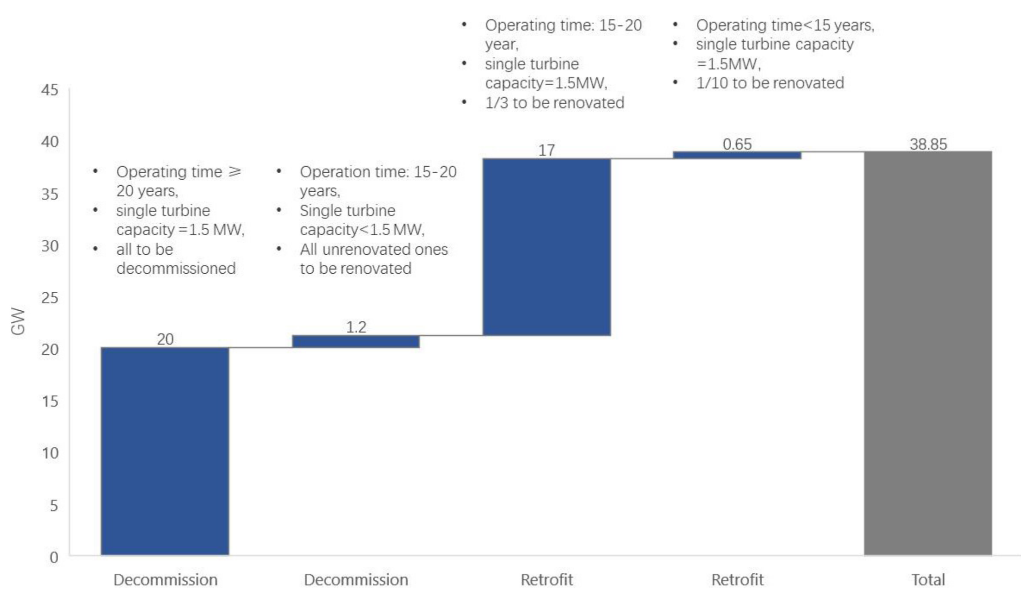
7. Demand Analysis and Policy Suggestions for Decommissioning, Retrofitting, and Replacing Wind Turbine Fleets in China, Energy Research Institute of the National Development and Reform Commission

Figure 5 Decommissioning and retrofitting requirements for wind turbines with a capacity of 1.5 MW and below in China between 2021-2025 (GW)



Source: Energy Research Institute of NDRC

Figure 6 Decommissioning and retrofitting requirements for wind turbines with a capacity of 1.5 MW and below in China between 2026-2030 (GW)



Source: Energy Research Institute of NDRC

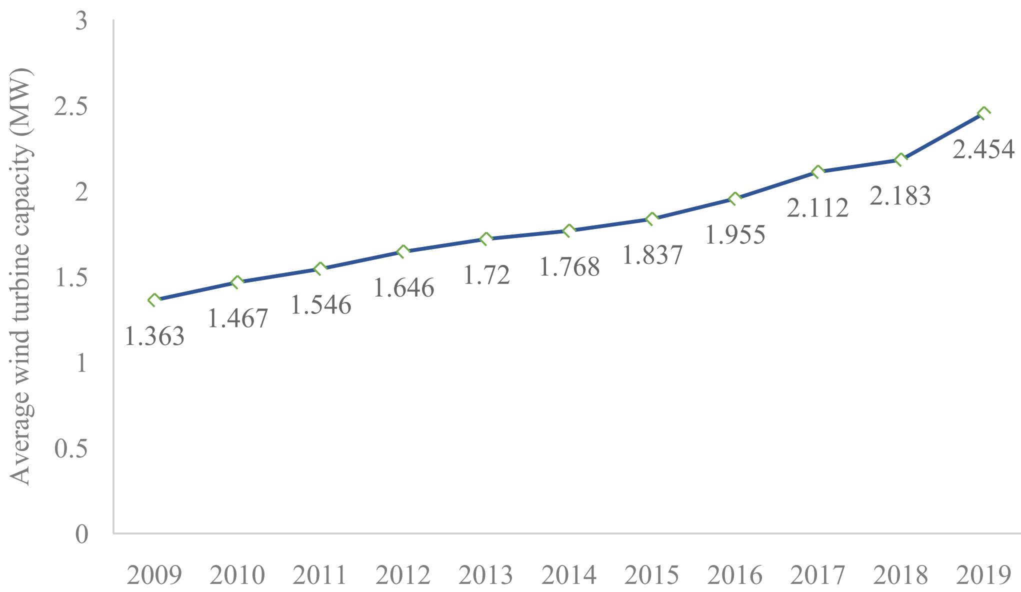
b) Low wind power utilization rate and high operation and maintenance costs of old wind turbine units

Many wind turbines that have been operating for over a decade are troubled by a wider range of problems, including aging devices, insufficient wind power capacity, suspended production of spare parts, and operational failures, which results in higher costs of operation and maintenance, along with lower electricity output, drastically eroding the economic benefits of wind farm operators.

Repowering projects can double the installed capacity and extend the lifespan of wind farms by another 20 to 25 years. According to the statistics of CWEA, the average capacity of a wind turbine rose from 1.363 MW in 2009 to 2.454 MW in 2019. As of now, wind turbines with a capacity of 3 to 5 MW are becoming mainstream. Repowering can remarkably increase the utilization hours of wind energy; for example, analysis of existing literature suggests that, if we leave power rationing out of the equation, replacing 600kW wind turbines with 1.5 MW, 2.0 MW, 2.5 MW, and 3.0 MW models will raise the annual utilization time by 1983h, 2169h, 2147h, and 2245h respectively[8]. Take 1.5 MW wind turbines as an example: there are now roughly 6,600 wind turbines with lower than 1,500 utilization hours, making up over 12% of the total, and over 14,000 wind turbines with lower than 1,800 utilization hours[9]. If all of the latter ones are upgraded into 3 MW wind turbines[10], power generation will increase by around 49.2 TWh, which translates into a huge hike in the electricity income of old wind farms.

8. Ma Xiaoping, Analysis of Replacing Old Wind Turbine Units in China
9. Source: Goldwind
10. Calculated with 2,000 utilization hours.

Figure 7 Changes in the mean capacity of wind turbines between 2009 and 2019 in China



Source: CWEA

c) Benefits of repowering wind farm in reducing carbon emission

Wind repowering contributes to carbon emission reductions by allowing the wind power sector to play a larger role in China's net zero transition.

From the lifecycle perspective, the carbon emissions of wind farms come mainly from the upstream manufacturing side. The CO_2 emissions from the manufacturing of metals such as iron & steel, aluminum, and copper, as well as the manufacturing of wind turbines, account for around 86% of the total carbon emissions from wind power; the remaining 14% of the emissions are generated during transportation, hoisting, operation, and maintenance, as well as the disposal of retired wind turbines, etc.; the carbon emissions during the operation of wind farms are neglectable, which means it can be construed as a zero-emission process[11]. Therefore, when the carbon emissions of other processes remain unchanged, the higher the power generating capacity and output during the operation of wind farms, the greater the benefits in carbon emission reduction compared with fossil fuel power generation. At the same time, the

11. China Energy News. Transformation of Wind Power Towards "Net-Zero Emission" During the Life Cycle [O/L],2021.

amount of carbon emissions from the upstream and downstream of the wind power sector is way smaller than the extra reduction in carbon emissions brought by wind power during the operation of wind farms in comparison with fossil fuels. In other words, the carbon emission per unit of power during the lifecycle of wind power is way lower than that of fossil fuels. Hence, repowering projects can magnify the benefits of wind farms in reducing carbon emission by increasing the power generating capacity and output during the operation of wind farms to offset the additional carbon emissions from the raw materials, manufacturing, transportation, and installation, etc. of new wind turbines. One study[12] conducted a lifecycle assessment (LCA) of a signature wind farm repowering project in Spain, where it adopted GWP (global warming potential)[13] to assess the impacts of wind farm repowering on greenhouse gas emissions. The study found out that the wind turbines in this project showed GWP values of 2.43E+07kgCO_2eq, and the substation and the electrical line showed values of 5.14E+05kgCO_2eq, which were clearly offset by the increased electrical power generation after repowering (GWP values of -9.03E + 08 kg CO_2 eq). This indicates that the newly added wind power can reduce more carbon emissions than it produces. With the greenhouse gas emissions of all relevant activities taken into account, the net GWP value of this wind farm repowering project was -8.78E+08kgCO_2eq.

Wang Yanzhe et al. (2021) evaluated the carbon emission per unit of power in the lifecycle under the actual power generation hours of different methods of power generation: 839g CO_2/kWh for coal, 452g CO_2/kWh for natural gas, 40.6g CO_2/kWh for hydropower, 29.2g CO_2/kWh for PV, 10.9g CO_2/kWh for nuclear power, and 8.6g CO_2/kWh for wind power; even with the adoption of the CCS technologies (with 90% of carbon capture rate), the carbon emission per unit of power during the lifecycle of coal and natural gas is still up to 144g CO_2/kWh and 118g CO_2/kWh respectively, much higher than that of wind power[14]. With reference to the estimates above, electricity output will grow by around 49.2 TWh per year if all

12. E. Martínez, J.I. Latorre-Biel, E. Jiménez, F. Sanz, J. Blanco,Life cycle assessment of a wind farm repowering process,Renewable and Sustainable Energy Reviews,Volume 93,2018,260-271.

13. Global Warming Potential (GWP) is an index to assess the impact of a certain greenhouse gas or product/activity on global warming, which has two connotations: In terms of global warming, what the CO_2 equivalent of one unit of a greenhouse gas is (unitless); Carbon emission equivalent of a certain product/activity (unit: kg CO_2 eq.). GWP in this paper refers to the latter, and the GWP value of wind power is the amount of emission reduction in comparison with coal-fired power.

14. Wang Yanzhe, Zhou Sheng, Wang Yu, Qin Xuying, Chen Fubing, Ou Xunmin. Comprehensive assessment of the environmental impact of China's nuclear and other power generation technologies[J]. Journal of

1.5 MW wind turbines with fewer than 1,800 utilization hours across China are replaced by 3 MW models. Assuming that newly added wind power will replace all coal and natural gas in power generation, this repowering project can reduce CO_2 emissions by 40.86 million tons and 21.82 million tons when compared with coal and natural gas (without CCS technologies) respectively without additional demand for land.

The reconstruction and expansion project of Chongqing Siyanping Wind Farm of China Aneng Group Second Engineering Bureau Co. Ltd. is the first large-scale repowering project where small-capacity turbines were replaced with larger-capacity ones. Table 1 exhibits the carbon reductions resulting from the increased installed capacity and power generation capacity in this project.

Table 1 Benefits of the repowering project in Chongqing Siyanping Wind Farm in reducing carbon emissions

Repowered facilities: 35 old wind turbines with a capacity of 850 kW were dismantled, with six 3.6 MW, eleven 4 MW, and four 5 MW wind turbines installed.		
	Before repowering	After repowering
Total installed capacity (MW)	46.75	102.6
Annual power generation (kWh)	87.47 million	250 million
Annual equivalent full-load hours	1813	2328
Annual saving of standard coal ('000 tons)	34.1	78
Annual reduction of CO_2 emission ('000 tons)	123.3	236

Note: The annual saving of standard coal and the annual reduction in CO_2 emission are calculated against the benchmark of coal-fired power.
Source: Collected from public information by the research group.

In addition to maximizing the carbon reduction benefits by increasing the power generation capacity and output during the operation of wind farms, repowering projects can also bring down the life-cycle carbon emissions of wind power

Tsinghua University (Science and Technology), 2021, 61(4): 377-384.

by replacing old wind turbines suffering from high carbon footprints with new ones that have lower carbon footprints. First of all, choosing low-carbon raw materials for wind turbines, such as green steel and concrete made with low-carbon techniques or wooden towers, is one major approach to reducing carbon emissions of wind power since its life-cycle carbon emissions come mainly from the raw materials and wind turbine manufacturing. For example, the leading wind turbine manufacturer Vestas lowers the life-cycle carbon emissions of its wind turbines by investing in wooden towers[15], with an aim to reduce the carbon emissions per kWh by 45% across the supply chain before 2030.[16] Moreover, advances in wind turbine technologies also help to increase their reuse rate, and therefore cut the life-cycle carbon footprints of new wind turbines. In July 2021, Siemens Gamesa Renewable Energy S.A., announced that it would recover and reuse all its wind turbine blades before 2030 and all its wind turbines before 2040 while achieving net-zero emissions across its value chain before 2040.[17] Last but not least, new wind turbines are more durable than their predecessors, and therefore have lower demand for on-site operation and maintenance, as well as lower carbon emissions from such practices. Goldwind, Ming Yang Smart Energy Group, Envision Energy, and other Chinese manufacturers have their attention focused on the life-cycle carbon footprints of wind power. In this context, repowering projects that upgrade old wind turbines with higher carbon footprints into new ones with lower carbon footprints present an opportunity for homegrown wind power players to achieve net-zero emissions for Scope 3 (across the value chain).

d) Reduce environmental damages and accidents

In contrast to greenfield projects, repowering projects do not involve the construction of new wind farms or the acquisition of land, which can alleviate the disturbance of the local environment, including fauna and flora, caused by human activities. Besides, more attention should also be drawn to the safety of old wind farms as accidents will pose a threat to the economic benefits of wind farm owners and the safety of the operators. Due to the absence of an early

15. It is estimated that the wooden towers can reduce carbon emissions by 80% compared with traditional steel towers: https://reneweconomy.com.au/stronger-than-steel-vestas-invests-in-wood-wind-turbine-tower-maker/

16. Vestas.Vestas to become carbon-neutral by 2030[O/L],2020.

17. Siemens Gamesa.Siemens Gamesa puts decarbonization, recyclability and technological education at heart of ambitious new sustainability strategy[O/L],2021.

warning system caused by insufficient safety considerations, early wind turbine fleets are prone to accidents, including overspeed, blades hitting the tower due to excessive vibration of the wind turbines, and fire arising from the excessively high local temperature of wind turbines.

3.Measures rolled out to support wind farm repowering

China's National Energy Administration understands the importance of wind farm repowering and has introduced policies to support the industry. In addition, the upgrade, replacement, and retirement of wind turbines in wind farms involve a range of issues including project approval (for extended operation and land use for increased capacity), grid connection, and the recycling of retired materials, which necessitates the alteration of relevant policies to provide the support and the timely rollout of repowering policies.

In May 2020, Liaoning Province took the lead in offering explicit support for repowering projects of existing wind turbines, which accumulated practical experience for the later introduction of national policies. Subsequently, Shanxi Provincial Energy Bureau also put forward a plan for the wind repowering and capacity expansion project. In May 2021, the National Energy Administration launched the repowering project of old wind turbines, and later in September of the same year, Ningxia Province started the pilot project of repowering wind farms by replacing small-capacity wind turbines with bigger-capacity models.

In December 2021, the National Energy Administration released *the Administrative Measures for Wind Farm Renovation, Upgrade, and Decommissioning (Draft for Comment)*, which contained the implementation rules for wind farm refurbishment and upgrade projects, breaking down into the organizational management, grid connection, safeguards, recycling, and disposal, etc. This draft also addressed the key concerns of wind power developers, including whether the subsidies could be extended, whether land acquisition needed to be renewed, and who the regulative authorities were before, during, and after the projects. Furthermore, it also laid out the approval requirements for refurbishment with equal capacity and with increased capacity, whilst streamlining the procedures.

This *Draft for Comment* sets out the guidelines to formulate regional administrative rules, yet there are still some problems waiting to be resolved. At the current stage, most provinces have not introduced detailed repowering policies, leaving a large number of such projects floundering without policy support. While early wind turbines and box-type substations in wind farms were built without the consideration of ecological conservation redlines (ECRs), during the replacement of small-capacity wind fleets with larger-capacity substitutes, expansion of acquired lands for large units or relocation due to wake effects, the additional land required would touch the ECRs. In addition, these projects cannot increase the capacity before submitting a new application for grid connection and obtaining approval from the corresponding power grids. The procedures they follow are the same as those for new projects, yet they face greater difficulty in getting approval at present.

Table 2 Overview of national and regional wind repowering policies

Time of issuance	Issuer	Policy name	Main content
April 2020	Liaoning Provincial Energy Bureau	*Construction Plan of Wind Power Projects in Liaoning Province*	To support the repowering projects of existing wind turbine fleets in Liaoning Province.
March 2021	Shanxi Provincial Energy Bureau	*Construction Plan for Wind Power Upgrade and Expansion Projects in 2021*	To lay out the implementation plan for the technology upgrade and capacity expansion of wind power in Shanxi Province.
May 2021	National Energy Administration	*Notice on the Development and Construction of Wind and PV Power in 2021*	To initiate the repowering projects of old wind turbines.
September 2021	Development and Reform Commission of Ningxia Province	*Notice on the Pilot Repowering Project to Replace Small-Capacity Wind Turbines with Larger-Capacity Turbines in Old Wind Farms in Ningxia*	The first regional pilot policy after the National Energy Administration initiated the repowering of old wind turbines, and also the first implementation rules of wind repowering (Replacing small-capacity wind turbines with larger-capacity turbines) in China.
December 2021	National Energy Administration	*Administrative Measures for Wind Farm Renovation, Upgrade, and Decommissioning (Draft for Comment)*	To specify the implementation rules of wind farm repowering projects.

Source: Based on publicly available information

Table 3 Requirements of the *Administrative Measures of Wind Farm Renovation, Upgrade, and Decommissioning* (Draft for Comment) on compliance approval procedures

Approval document	Upgrade with the same capacity	Upgrade with larger capacity
Quota approval	Obtain quota and approval from the provincial energy authority.	
Grid connection	No occupation of newly-added absorption; review of the grid system connection.	The increased capacity will be prioritized in the guaranteed grid connection of the province (district or city); it is encouraged to achieve grid connection via the market; the system connection plan needs to be renewed.
Approval of land use	In principle, wind farms located inside natural reserves shall not be repowered. Repowering projects meeting the following three conditions are exempted from the preliminary review of land use and the proposal for project site: 1. Keep the original site of the wind turbine fleets; 2. Occupy a smaller area of land after the repowering; 3. Abide by the national spatial planning.	
Environmental Impact Assessment (EIA) approval	Yes	
Water and soil conservancy approval	Repowering projects that keep the original site of the wind turbine units are exempted from this.	
Grid Connection Dispatch Agreement/Electricity Purchase Contract	Need to be renewed.	
Electric Power Business License	No	Alter the electric power business license

Source: *China Wind Farm Repowering and Upgrade White Paper,* Huaneng Tiancheng Financial Leasing Co., Ltd. & China General Certification Center

II Economic analysis of wind farm repowering

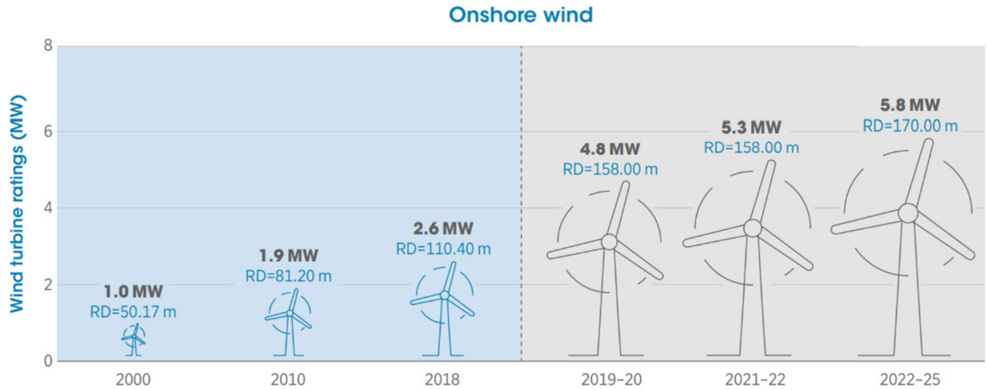
1. Options of wind farm repowering

There are several options of wind repowering, including upgrades by replacing small-capacity wind turbines with large-capacity ones, partial replacement (e.g., replace blades, hub and nacelle), and specific technology upgrades. The first option has the greatest potential as it can be widely adopted across different regions in China. Larger-scale wind turbines are dominating the global development of wind power (as shown in Figure 8) since they can significantly reduce the costs of investment, operation, and maintenance per unit of electricity generated[18]. In the first type of repowering, small-capacity wind turbines are dismantled and higher-capacity ones are commissioned to boost the efficiency and capacity of degraded wind farms. The upside of these projects lies in the higher applicability as loads of the existing units and the control strategy of the existing models can be left out of the equation. In the meantime, there are stronger signals that this type of project will receive more support from the national and regional governments, making them more likely to be scaled up in the future.

With respect to the other two types of repowering, partial replacement mostly refers to the replacement of the blades, hub, and nacelle for the same or higher capacity, while specific technologies upgrades are usually customized. Optimization of the start of blades, extension or replacement of blades, intelligent optimization of the master control system, and in-depth renovation of certain components are among the commonly seen plans for technology upgrades. This report focuses on the more scalable type, namely the replacement of wind turbines with larger-capacity ones.

18. Roland Berger

Figure 8 Trending towards larger-capacity turbines in the world

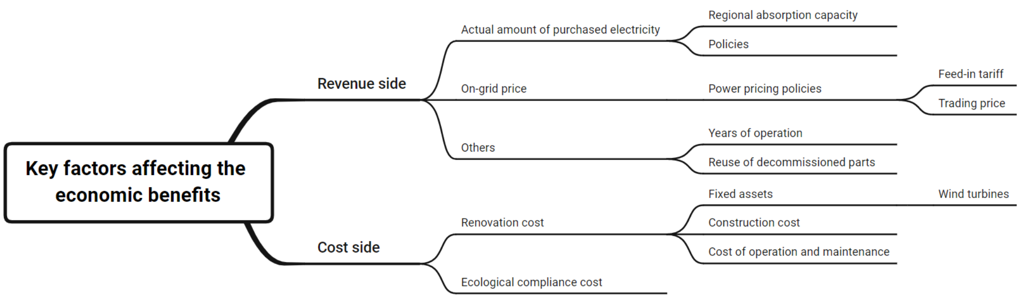


Source: IRENA

2. Driving factors of the financial performance of repowering projects

As a most straightforward impact of replacing wind turbines with larger-capacity ones, the repowered wind farms will generate more electricity, which will bring extra profits. As is shown in Figure 9, the revenue of these projects is directly influenced by the actual amount of electricity that grid firms purchase from wind farms and the on-grid price realized. The quantity of electricity sold is subject to local energy policies and how much renewable electricity local power grids can absorb, while the on-grid price also falls under the sway of electricity pricing policies; moreover, the revenue is also affected by the extended operating life after renovation and the resource recycling at the end of its lifespan, etc. For the costs perspective, wind turbines have a greater impact on the costs, whilst costs incurred in compliance with ecological and environmental protection regulations show greater uncertainty.

Figure 9 Key factors affecting the financial performance of repowering of old wind farms



a) Absorption capacity of power grids

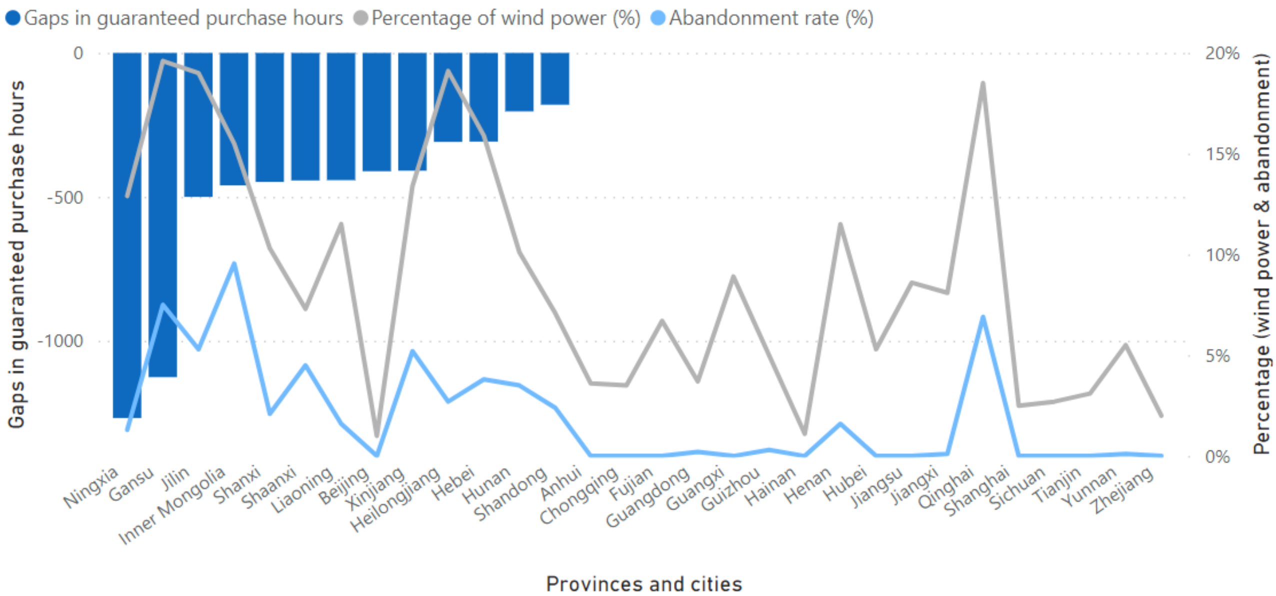
The ability of power grids to consume electricity generated from new energies faces a number of constraints and varies from region to region. In this context, the newly added electricity may not be sold 100% to grids. There are two major constraints: currently, the share of new energy that can be consumed by the grid is relatively low; and the costs of expanding the capacity of old power grids are very high.

Specifically, the ability of power grids to consume new energy-powered electricity relies on the real-time dispatch by grid firms, and the costs of the idle capacity of replaced coal-fired power are relatively high. As a result, any radical changes in the shares of the energy market in a non-market-oriented environment in the short run will face tremendous hindrances without a electricity demand spike. In reality, the geographical locations with abundant wind resources and a high proportion of wind-powered electricity are more likely to have a higher rate of wind power abandonment (as shown in Figure 10 to Figure 13). Judging from the abandonment rate, Jilin, Inner Mongolia, and Shaanxi are among the top-ranking provinces, while the rate in Southeast China is close to zero; wind power constitutes a higher proportion of power consumption in northern provinces, including Inner Mongolia, Hebei, Heilongjiang, and Qinghai, and at the same time.

On the other hand, some power grids with older facilities will be impeded by the enormous costs of capacity expansion and grid connection even when the demand for electricity grows at the same pace as the newly-added wind power capacity. For example, power grids built 15 to 20 years ago have limited capacity to consume extra electricity owing to the conservative design in the past, and therefore fall behind the growth of the local economy. What’s worse, due to the limited capacity of power lines within a regional power grid and between grids, more power transmission lines must be added to raise their capacity, which involves additional procedures such as land use approval and environmental impact assessment (EIA), driving the costs higher than the profits and ultimately demotivating grid firms.

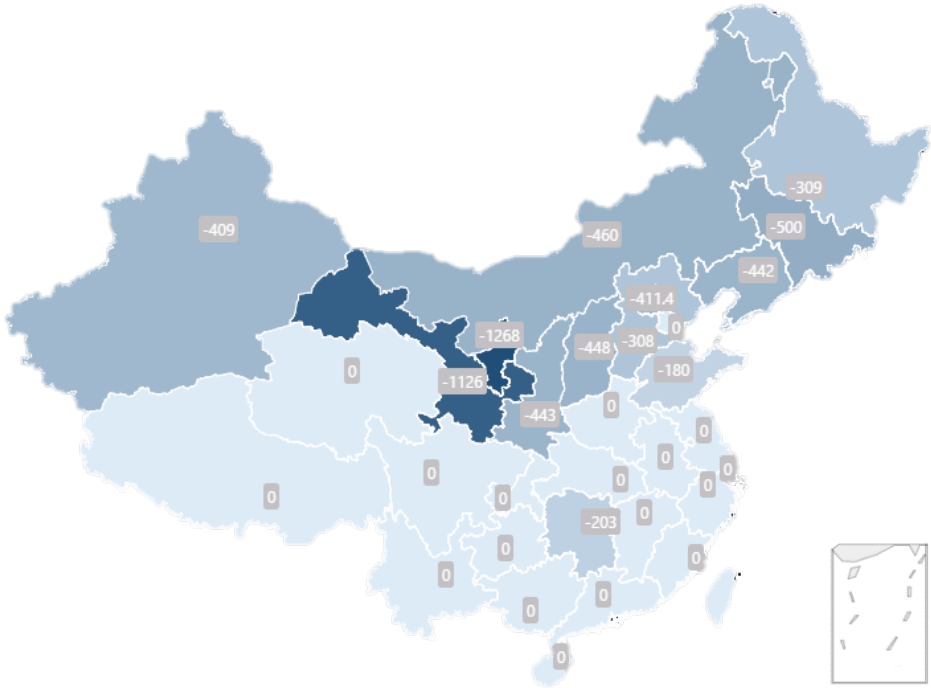
Given the constraints above, the Chinese government has introduced policies to strengthen the consumption of electricity generated from renewable energies to bolster the growth of new energies. In 2016, the National Energy Administration and the National Development and Reform Commission (NDRC) stipulated the guaranteed purchase hours of new energies in some key regions inside the four types of wind resource areas, requiring local power grids to purchase at least 1,800 to 2,000 annual full-load hours of wind-powered electricity for benchmark on-grid power tariffs; between 2016 and 2021, some provinces and cities lowered the floor of the guaranteed purchase hours and demanded that the purchase price should not be higher than the guiding wind power on-grid tariff. In 2020, Gansu, Ningxia, and Qinghai were the three provinces that fell short of the purchase requirement with the greatest gaps. For other areas without guaranteed purchase requirements, local power grids should purchase wind power at a price no higher than the guiding wind power on-grid tariff without discount based on the local resource conditions.

Figure 10 Comparison of wind power absorption requirements in different provinces and cities



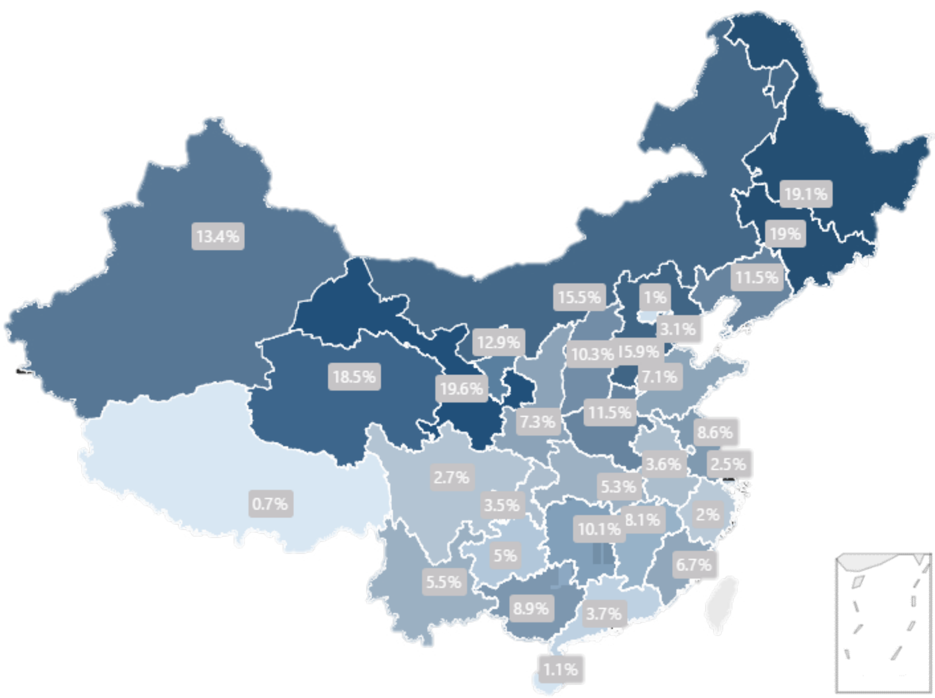
Note: Gaps in guaranteed purchase hours is calculated from the available newest data of annual utilization full-load hours and guaranteed purchase hours. Percentage of wind power and abandonment rate are accumulated as of 2022 Q3.

Figure 11 Gaps in annual guaranteed purchase hours in 2021 (Guaranteed purchase hours – Average equivalent utilization hours of wind power; hours in unit)



Source: China Renewable Energy Monitoring Platform, compiled by the research group

Figure 12 Proportion of wind-powered electricity in the total electricity generation across China in the first 3 quarters of 2022



Source: China Renewable Energy Monitoring Platform, compiled by the research group

Figure 13 Abandonment rate of wind power across China in the first 3 quarters of 2022

Source: China Renewable Energy Monitoring Platform, compiled by the research group

b) Electricity pricing

Electricity prices are the major factor affecting the internal rates of return (IRR) of repowering projects. The revenue of these projects is largely affected by the temporal and spatial differences in electricity pricing policies. The wind power pricing policy underwent three stages: benchmark feed-in tariff, bidding pricing, and grid parity (as shown in Table 1). With the gradual decrease of the national subsidies for wind power to zero, wind power entered the grid parity era from January 1, 2021. To increase the absorption of new energies, the government encourages some regional grids to launch pilot projects that allow for wind power with lowered prices. Geographically speaking, benchmark prices for coal-fired power (namely the implementation price in the grid-parity era) vary greatly across China, with higher power prices in Tibet, South China, and Southeast China, and lower prices in the northwestern and northern part of China, including Xinjiang, Ningxia, Inner Mongolia, and Gansu. Hunan topped the list of power prices within the State Grid in addition to Tibet, and Guangdong has the highest power price within the China Southern Power Grid (as shown in Figure 14).

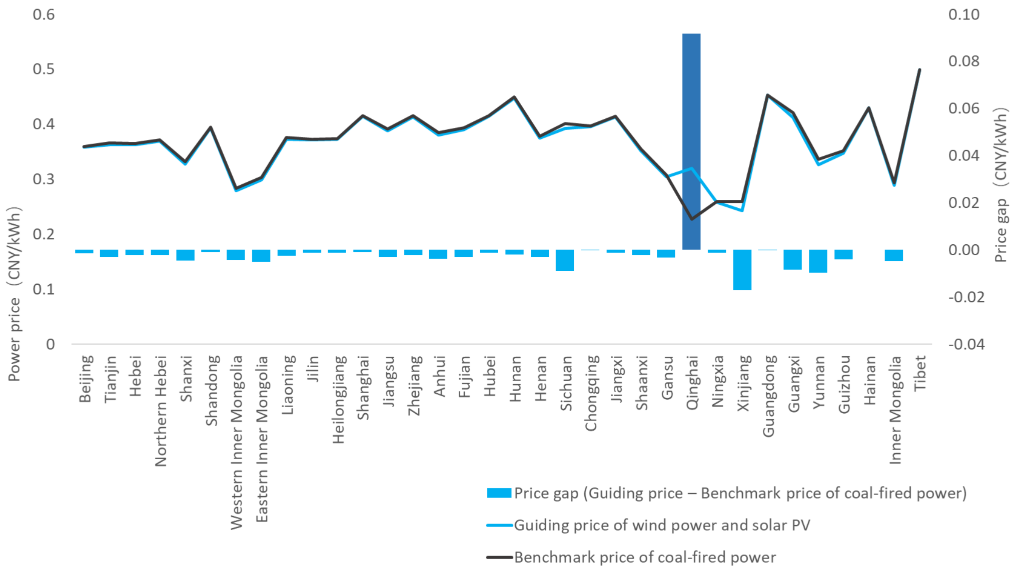
Table 4 Comparison of the three types of power pricing policies

Power pricing policy	Time period	Definition/Description
Benchmark feed-in tariff	2009-2018	The country was divided into four types of resource areas based on their wind resources and construction conditions, with a corresponding benchmark feed-in tariff assigned to each area and subsidies offered on the basis of benchmark tariff for on-grid power generated using desulphurization[19]. The benchmark feed-in tariff in each resource area was then lowered every year in a dynamic manner to encourage the bidding pricing.
Bidding pricing	2019-2020	Newly added centralized onshore wind power projects were all configured with their on-grid tariff determined via bidding[20]. In 2019, the benchmark feed-in tariffs were replaced by the guiding prices, and it was further required that the power prices set via bidding shall not surpass the regional guiding price[Notice of the National Development and Reform Commission on Improving the Policies for On-Grid Wind Power Prices[21].
Grid parity	Since 2021	The feed-in tariff of wind power (the benchmark power price) should not be higher than that of local coal-fired power, and additional subsidies from the government were removed.
Low-price grid	Pilot projects	Low-price pilot grid projects shall be launched in areas with abundant resources and high power consumption, and the feed-in tariff should be set lower than the benchmark feed-in tariff of coal-fired power.

Source: the National Energy Administration and research done by experts

19. July 20, 2009, Notice of the National Development and Reform Commission on Improving the Policies for On-Grid Wind Power Prices (No. 1906 [2009] of the National Development and Reform Commission)
20. Notice of the National Energy Administration of the Requirements on Wind Power Construction and Administration in 2018 (No. 47 [2018] of the National Energy Administration)
21. Notice of the National Development and Reform Commission on Improving the Policies for On-Grid Wind Power Prices (No. 882 [2019] of the National Development and Reform Commission)

Figure 14 Benchmark prices of coal-fired power, guiding prices of wind power and the price gap across China

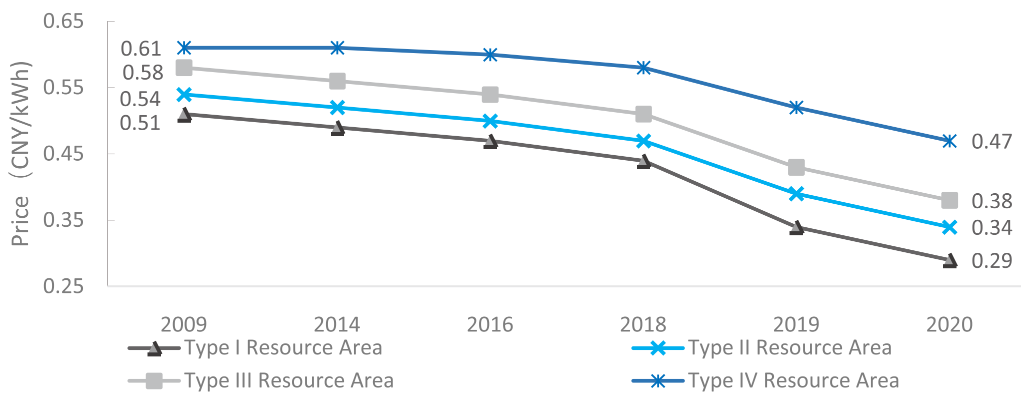


Source: Provincial and municipal development and reform commissions, energy bureaus, and the research group.

Wind power pricing has two components: the purchase price of the guaranteed purchase hours and the trading price of the remainder. Known as the benchmark feed-in tariff in the past, the purchase price corresponds to the benchmark price of the guiding prices set by the government and is subject to adjustments at any time. Over the past years, it has experienced phased declines (as shown in Figure 15) and there have been fluctuations when implemented in different projects. The specific settlement price is decided by the provincial power grid according to the benchmark tariff and shall not exceed the local guiding feed-in tariff of wind power. Power generation exceeding the guaranteed purchase hours needs to be traded in the market. Such electricity (namely spot market) is traded in local power trading centers, with the trading price fluctuating around the benchmark tariff by 20%. Lower guaranteed purchase hours are likely to affect the trading price to a great extent.

Grid parity policy brings down the feed-in tariff of incremental electricity generation. Repowering projects have no impact on the feed-in tariff of the originally guaranteed purchase hours; however, power generation exceeding the guaranteed purchased hours should be traded according to the benchmark on-grid price of local coal-fired power in order to pace the use of subsidy budget and advance the marketization of new energies. This heralds a lower on-grid price of incremental electricity from repowering projects than that enjoyed by existing power. Considering the high grid-parity on-grid price in the eastern and southern parts of Jilin and Heilongjiang, it makes more economic sense to launch repowering projects in these areas.

Figure 15 Government guiding prices in different wind resource areas in the past (subsidized portion included)

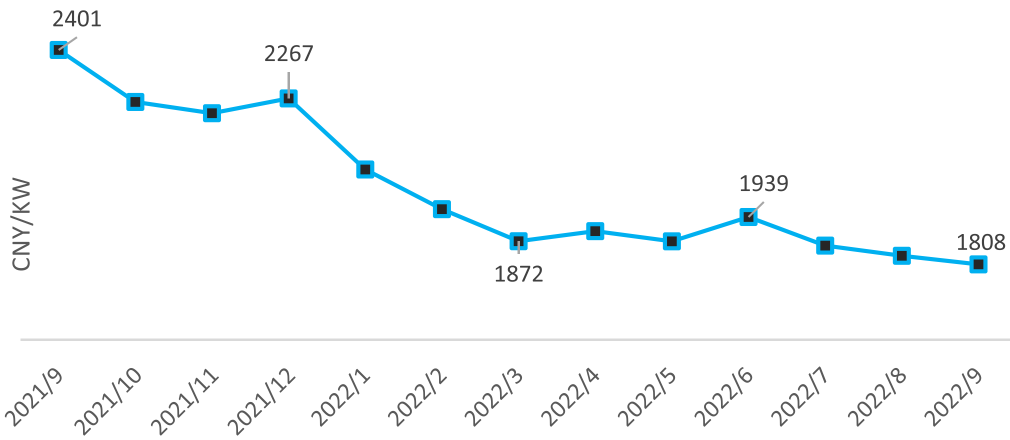


Source: National Energy Administration of China

c) Costs of repowering projects

The costs of wind turbines are now on a downward trend, with the potential to bounce back in the future. The overall investment in repowering projects where small-capacity units are replaced with larger-capacity ones fluctuates between 4,000 and 5,000 yuan/kW, in which the cost of wind turbines takes up 50% to 60%. Since 2021, wind turbine price has been sliding from 3,081 yuan/kW all the way to 1,808 yuan/kW in Q3, 2022 (as shown in Figure 16), with a continued decrease at the current stage; going forward, however, the price is expected to rebound due to the rising prices of raw materials, which constitute 95% of the cost of a wind turbine, with glass fiber representing the highest proportion.

Figure 16 Average price in public monthly bidding of wind turbine generators since 2021



Source: Goldwind

The construction costs remain relatively stable, while the operation and maintenance costs are lower in repowering projects. Other construction expenditure includes the cost of dismantling wind turbines (such as dismantling fee, transportation fee, and hoisting fee), which is relatively stable. According to Roland Berger's estimate, the static investment cost per unit of capacity will drop by 14% if the capacity of the wind turbine fleet is upgraded from 3 MW to 6 MW. Most of the wind turbines to be repowered in China have a capacity of 1.5 MW and an O&M cost of 40 yuan/kW per year[22]. Therefore, their O&M cost will be slashed by 37% if their capacity is upgraded to 3 MW.[23] The cost of land acquisition accounts for 3% to 5% of the total investment in a new wind farm, which varies greatly from region to region; repowering projects, in contrast, can decrease the number of wind turbine sites needed and reduce the area of land required accordingly when they utilize the existing land and sites for renovation with the same capacity.

More stringent ecological and environment conservation requirements drive up compliance risks and costs. When rolling out repowering projects, extra attention should be given to avoiding Ecological Conservation Redlines (ECRs) or bird migration routes and meeting the distance requirements regarding noise,

22. Chinese Wind Energy Equipment Association: http://www.cweea.com.cn/xwdt/html/5908.html
23. Estimated based on the findings of Wiser, R., Bolinger, M., Lantz, E., Assessing wind power operating costs in the United States: Results from a survey of wind industry experts[J]. Renewable Energy Focus, 2019. 30: 46-57

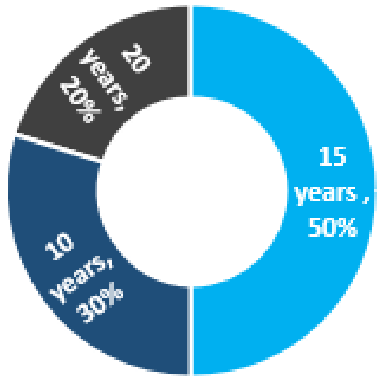
light, and shadow, etc. According to the *Administrative Measures for Ecological Conservation Redlines* released by the Ministry of Natural Resources of the People's Republic of China, existing wind power facilities inside the ECRs shall not be expanded to any extent; in regions including Inner Mongolia[24] where ECRs cover a high percentage of the area, some wind power projects need to be vacated with compensation[25], which will incur more costs than expected.

Recycling facilities and parts is a potential supportive plan for repowering projects. When wind farm facilities reach their end of life, there are two environmentally friendly ways to address the old parts: one is to reuse the parts or facilities, and the other is to reutilize various solid wastes. Typical examples of reusing the components include the reuse of towers. The redundancy of early towers was designed at around 20%, but after 2017, this percentage was curtailed as wind farm operators and developers became more cost-sensitive. The actual capacity of wind turbines was 15%-25% lower than the design capacity due to the widespread power rationing in the early stage of wind farms' development, which extends their load cycle and the service life of the reused components (as shown in Figure 17). The re-utilization of solid wastes can also come in different forms. For instance, Goldwind produced a set of concrete flower beds from the solid waste of the decommissioned parts using 3D printing technology. Reaching the standards of conventional building concrete, these printing materials present a scalable solution to reuse retired wind turbine blades with a higher value.

24. 50.46% of the land area in Inner Mongolia is within the ECRs.

25. News report: Wind Turbines on Huiteng Xile Grassland Started to Be Dismantled. December 25, 2020, https://news.bjx.com.cn/html/20201225/1125218.shtml

Figure 17 Proportion of the projects by potential service life of reused components



Source: Research by experts

3. Sensitivity analysis: a case study

The impacts of different factors on the IRR of repowering projects will be analyzed with the Discounted Cashflows (DCF) method based on a simulation case in this section. The benchmark assumptions in the simulation case are shown in Table 5 below with reference to Western Inner Mongolia. It should be noted that the power price, guaranteed purchase hours, and the previous annual utilization hours vary region by region; explicit regional requirements on the guaranteed purchase hours will be followed, in the absence of which 80% of the power will be purchased[26]. The lower one between the local guiding feed-in tariff of wind power and the benchmark on-grid price of coal-fired power will be adopted as the purchase price in this case, whilst the trading power price will be set at 80% of the purchase price.

26. With reference to Huaneng Tiancheng Financial Leasing Co., Ltd. and China General Certification Center for the percentage of traded power (2022).

Table 5 Key assumptions in the simulation case (take Western Inner Mongolia as an example)

Installed capacity and power generation			
Original installed capacity (MW)	1.5	Installed capacity after renovation (MW)	3
Incremental capacity (%)	100%	Original annual electricity generation (kWh)	3,450,000
Original annual utilization hours (hour)	2,300[27]	Electricity generation after renovation (kWh)	7,500,000
Annual utilization hours after renovation (hours)	2,300-3700	Hours of traded power	660
Guaranteed hours (hours)	1,840	Guaranteed minimum purchase (kWh)	5,520,000
Remaining subsidized period (years)	5	Traded electricity (kWh)	1,980,000
Extended service life (years)	20		
Purchase price (CNY/kWh)			
Price of guaranteed purchase hours after renovation	0.289	With reference to	Western Inner Mongolia
Purchase price of traded power	0.231		
Cost (CNY/kW)			
Investment[28]	7,000	O&M cost before renovation	30
Removal of wind turbines:	250	O&M cost after renovation	25.14
- Hoisting fee	100	Effective income tax rate	15%
- Transportation fee	130		
- Dismantling fee	20	Total cost	
Wind turbines	3,000	Initial CAPEX (CNY)	10,500,000
Other capitalized costs	3,750	Disposal cost	1,872,000
Disposal cost	624	O&M cost after renovation	75,429

27. Average utilization hours of wind power facilities in 2021. Source: Wind Database and China Wind Farm Repowering and Upgrade White Paper.
28. Investment cost per unit is around 70% of the new wind farms. Huaneng Tiancheng Financial Leasing Co., Ltd., China General Certification Center, China Wind Farm Repowering and Upgrade White Paper [R]. 2022.

a) Power prices and guaranteed purchase hours

Power prices across China bear significantly on the IRR of repowering projects via sources of revenue (as shown in Figure 18), and to be more specific, the IRR is more sensitive to the fluctuations in the traded power price in regions with lower guaranteed purchase hours. Take West Inner Mongolia as an example (as assumed in Table 3): the IRR declines by 0.38% for every 0.01 CNY drop in the subsidized power price and by 0.24% for every 0.01 CNY decrease in the traded power price. In Gansu, among other areas typified by lower guaranteed purchase hours, where the guaranteed purchase is 774 hours, the IRR will edge down by 0.39% for every 0.01 CNY dip in the subsidized power price and by 0.47% for every 0.01 CNY decline in the traded power price if the annual utilization hours can hit 3,000 hours after repowering. As is shown in the chart below, if we assume that the annual utilization hours after repowering remain unchanged and take into account only the differences in the power price and the guaranteed purchase hours, South China, the Central Plains, and East China are among the areas that are likely to enjoy higher returns from repowering.

Figure 18 Relationship between IRR and local benchmark on-grid price for coal-fired power

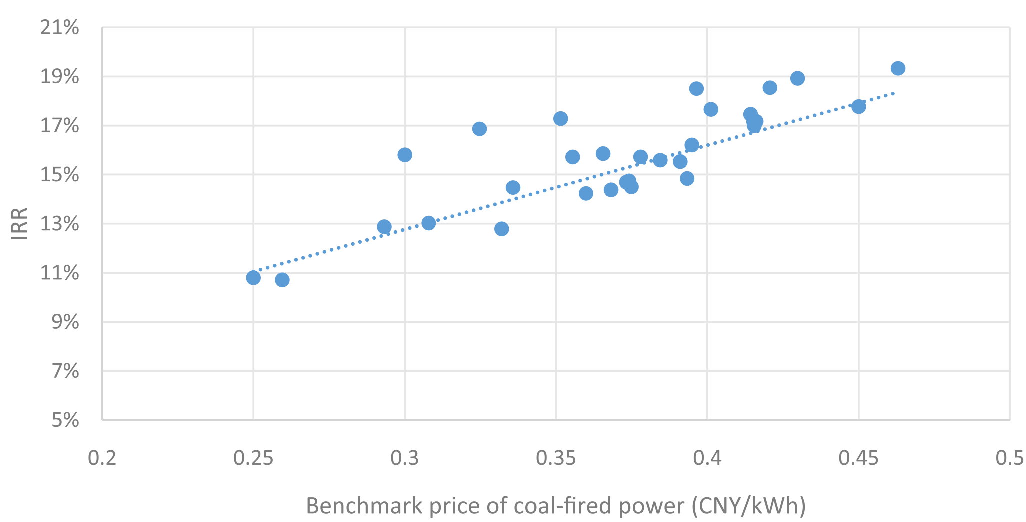


Figure 19 Impacts of the regional guaranteed purchase prices on IRR

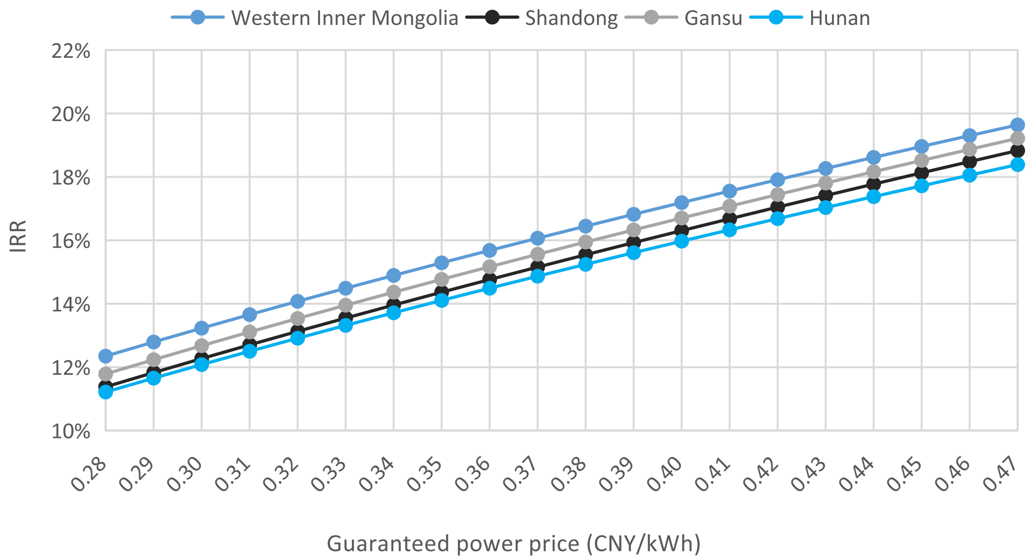
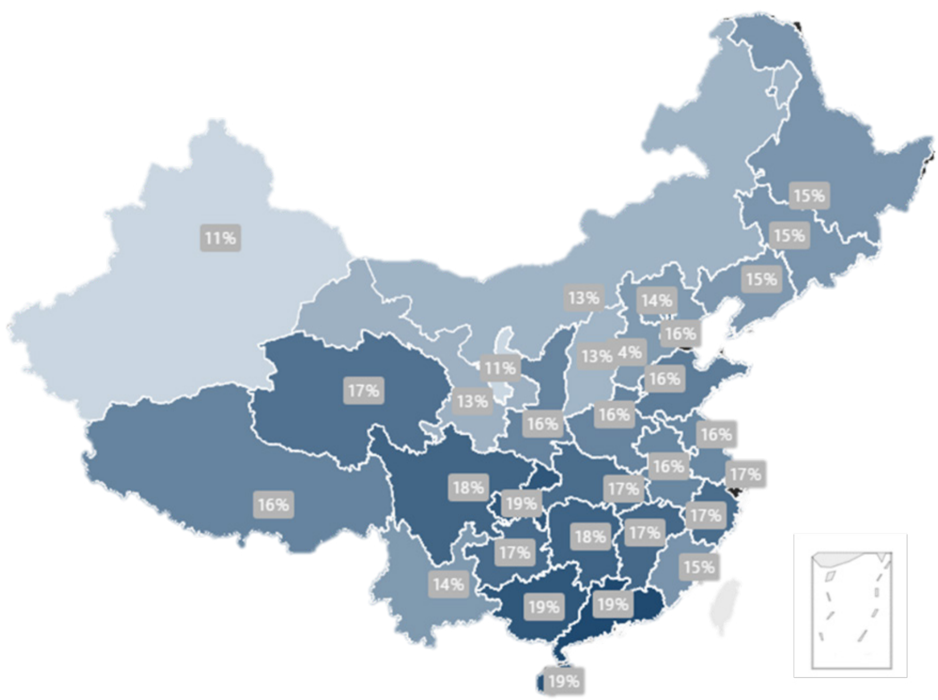


Figure 20 Repowering IRR across China

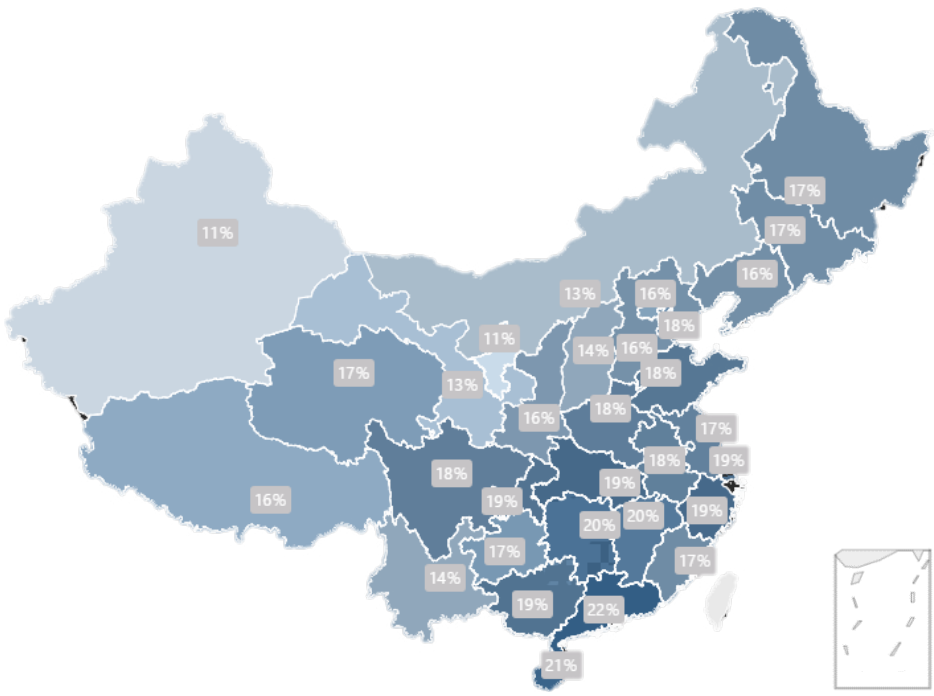


Note: It is assumed that the annual equivalent utilization hours stand at 3,000 after repowering.

b) Equivalent utilization hours

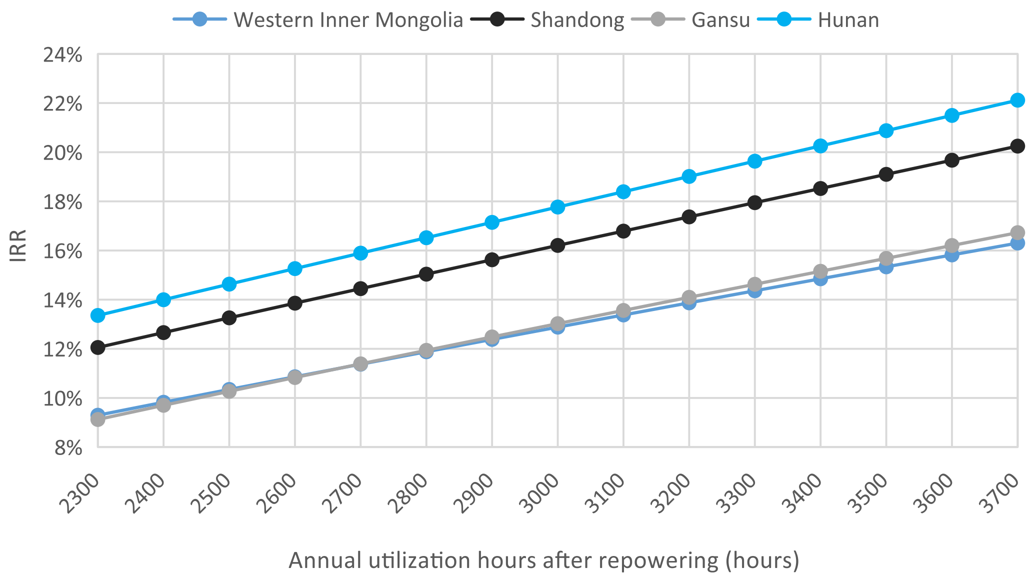
Repowering projects will dramatically increase the annual equivalent utilization hours of wind power projects. As is shown inFigure 21, Yunnan and Fujian have the highest annual utilization hours of wind power, while Tibet and Qinghai bring up the rear. Sensitivities of IRR to equivalent utilization hours vary across regions. For instance, in Western Inner Mongolia, the IRR will increase by 0.5% for every 100 hours of increase in equivalent utilization hours;forJiangxi, Zhejiang, Hubei, and Sichuan, IRR on projects are more sensitive to the changes in equivalent utilization hoursand every 100-hour increase will result in a 0.65%~0.73% rise in the IRR; ForGuangdong, Chongqing and Guangxi, every 100-hour increase can bring the IRR up by more than 0.75% (see Figure 22).

Figure 21 Annual average utilization hours of wind power generators across China (2021)



Source: Wind, Huaneng Tiancheng Financial Leasing Co., Ltd. and China General Certification Center (2022)

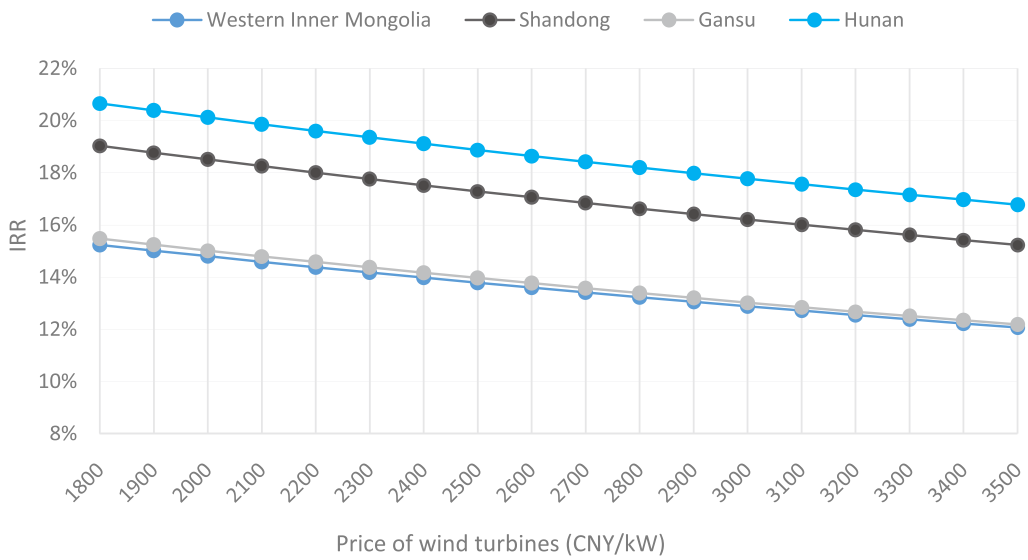
Figure 22 Impact of annual utilization hours on IRR of repowering projects by region



c) Cost of wind turbines

Wind turbine-related costs account for the highest proportion of the overall cost of repowering projects. By affecting the initial investment and depreciation, they also have a huge bearing on the IRR of such projects. Take West Inner Mongolia as an example again: when the price of wind turbines goes up by 100 CNY/kW, the IRR slides by 0.2%. Factoring in the guaranteed purchase hours and the purchase prices in different provinces and cities, it is not difficult to tell that projects in Guangdong, Hainan, Qinghai and Chongqing are among the most sensitive to the wind turbine price: for every 100 CNY/kW-rise in the wind turbine price, the IRRdecreases by 0.24%-0.25%. In contrast, Xinjiang and Ningxia are the least sensitive to the wind turbine price, and every 100 CNY/kW rise in the price rachet the IRR down by 0.17% (see Figure 23).

Figure 23 Impact of wind turbine prices on IRR of repowering projects by region



III Ecological and environmental impacts of repowering wind farm

Despite the fact that wind power is clean energy with significantly fewer pollutants and carbon emissions than thermal power and other fossil fuels, the construction and operation of wind power projects still impact the ecology and the environment in multiple dimensions. Therefore, measures should be taken to minimize the adverse impacts.Research[29] shows that wind power projects may have the following ecological impacts: first, changes in the ecological function of the land, such as the permanent occupation of land by roads, collector lines and wind turbine units inside the wind farm; second, impacts on biodiversity, such as disruptions on birds (including the occupation of their habitats, collision with turbine blades, and low-frequency noise); third, noise pollution; fourth, shadow flicker effect, which refers to the periodical changes in ambient brightness when sunrays are blocked by wind turbine blades, disturbingthe residents and animals nearby; fifth, changes in the regional climate.

Wind repowering projects are usually carried out on the existing sites, with few new sites orland occupation involved, and therefore can steer clear of the above-mentioned adverse ecological or environmental impacts. However, their construction may still damage the ecology and environment to some extent. For example, cut and fill in earthwork, including the foundation construction of wind turbines and box-type substations, as well as road reconstruction and expansion along the device transportation lines, may cause surficial vegetation destruction, water and soil erosion, noise pollution, etc.Generally speaking though, the efficient utilization of existing land resources by wind repowering projects can mitigate the damages to the ecology and the environment per unit of power generated.

For some time past, issues including policy orientation of uncompensated land

29. Hui Jingxuan, Cui Cheng, Han Xue, Liu Yiming. Suggestions on Eco-Friendly Wind Power and PV Development [J]. Energy of China, 2021, 43(07): 46-53.

occupation, lack of forceful supervision and mandatory restriction measures from the authorities, biased understanding and inappropriate practices of some project designers, and the desire of project owners to occupy more land for higher profits have contributed to the disordered and unreasonable land use of wind farms. Consequently, the capacity rate of wind power per unit area fell short of expectation, which is a horrendous waste of land and wind resources.[30] Against this backdrop, repowering projects can increase the annual power output and annual equivalent full-load hours of wind farms by virtue of higher quality and efficiency without occupying additional land. Thus, they have the potential to push up the capacity rate per unit area of wind farms, which is beneficial to intensive land use. With the current technologies, the installed capacity density of wind power in China is around 5 MW/km2 (with geographical variation).[31] According to the estimate in the first chapter that the cumulative decommissioned and renovated capacity of wind turbine fleets in China from 2021 to 2030 adds up to around 60 GW, it is possible to add another 60 GW of installed capacity without additional land use if these wind turbine fleets are replaced with larger-capacity ones at the ratio of 1:2.[32] Based on this figure, such a repowering project can save 12,000 km2 of land compared with building new wind turbine units without taking into consideration the restrictions of wind resources. If we add such restrictions into the equation, the land area saved by the repowering project will be smaller than the estimated figure, but can still alleviate the potential adverse impacts of wind power development in China on the ecological functions of land and biodiversity by considerably scaling down the potential land occupation.

30. Yu Wuming. A Strategic Question in Wind and PV Power Development: Capacity Rate of Per Unit Area [O/L]. Wind Energy,2016.

31. Wang Yang. How Many Lands Will Be Occupied for the Development of Wind and PV Power in China to Achieve Carbon Neutrality? [O/L]. National Climate Center, 2021.

32. Beijing Wind Power Website. "Replacing Old, Small-Capacity Wind Turbines with Bigger-Capacity Models" —A New Round of Wind Power Trend Is Here! [O/L], 2022.

IV Conclusions and recommendations

During the period of "14th Five-Year Plan" and the "15th Five-Year Plan", the cumulative decommissioned and renovated capacity of wind turbine fleets across China (namely the upgraded capacity of old wind turbines) is estimated to surpass 60 GW. Although newly-built projects remain the main approach to increasingwind power capacity, the potential of repowering projects has become more prominent as the number of old wind turbines soars. Repowering projects can double the installed capacity and extend the lifespan of wind farms by another 20 to 25 years. This report has drawn the following conclusions based on the analysis of wind repowering projects' economic, environmental and emission-reduction benefitsas well as influencing factors.

Repowering projectsin China are generally expected to offer double-digit returns. Considering that old wind farms are located in areas with adequate wind resources, repowering projects are generally more profitable thannewly-built wind farmsbecause oflower investment costs, remarkably less land use, and higher annual equivalent utilization hours. The IRRs of wind repowering projects in most regions can reach 13% and higher when the realized on-grid electricity prices hit 0.33 yuan.

Repowering projects are more environmental and climate friendly than newly-built wind power projects. Carried out on the original sites, repowering projects seldom involve new sites or land expansion, and can therefore significantly reduce the potential land occupation of newly added wind power. In this way, they can mitigate the adverse impacts on the ecology and environment, including damages to the ecological functions of land, loss of biodiversity, noise pollution, shadow flicker effect, and change in the regional climate, etc. Likewise, by lifting generation capacity and output, repowering projectscan also significantly improve wind power's carbon emission reduction benefit compared with fossil fuel power. For example, if all 1.5 MW wind turbines with lower than 1,800 utilization hours per year in China are replaced with 3 MW ones, the increased power generation can reduce 40.86 million tons and 21.82 million tons more of CO_2 emissions compared with coal power and natural gas-fired power, respectively. Moreover, repowering also has the potential to lower the lifecycle carbon emissions by applying low-carbon materials, raising the recycling rate of wind turbines, and reducing maintenance activities during their operation.

Currently the major challenges faced by large-scale repowering projects are the limited absorption capacity of regional grids and the complex bureaucratic procedures. Due to the limited local power consumption demand, prohibiting costs in expanding the capacity of old power grids and cross-region power transmission, and the features of wind power output, local power grids are hamstrung by their limited absorption capacity when it comes to the purchase of power generated by windrepowering projects. This is also a major challenge in the net-zero transition of China's power system. Furthermore, successful repowering projects also depend heavily on policy factorssuch as regulatory approval. Over an extended period of time, wind power operators, despite their demand for repowering, have been hesitant to sail into uncharted waters due to ambiguous policies regarding the land, subsidies, and grid connection. Currently, although the National Energy Administration has released *the Administrative Measures for Wind Farm Renovation, Upgrade, and Decommissioning (Draft for Comment)*, implementation rules are still absent in many regions, leaving local wind power developers struggling with compliance procedures.

Based on the analysis above, we propose the following suggestions:

Firstly, local governments should improve administrative processes and streamline approval procedures for wind repowering projects. Despite the issuance of *the Administrative Measures for Wind Farm Renovation, Upgrade, and Decommissioning (Draft for Comment)* by the energy authority, regulations for implementing the measures at the provincial level are yet to be introduced. The increasingly higher number of wind farms waiting to be decommissioned will further boost the demand for repowering, making it all the more important to establish and clarify the administrative policies for wind repowering. Therefore, it is imperative for local competent authoritiesto perfect relevant administrative measures. In response to the headache facing repowering projects in regulatory approval, local governments should fully recognize their environmental benefits and simplify approval procedures regarding grid connection and land approval, etc.

Secondly, wind power operators should followthe developments of policies and technologies in order to design the roadmap to decommission and repower existing wind farms. To achieve the "dual carbon" goal, the power system in China is making headway in its net-zero transition, along with accelerated construction of power transmission infrastructure, grid supply-side reform, and wind-solar-storage integration, in a bid to solve the grid absorption problem of new energiesgradually. Therefore, it is necessary for wind power operators to predict the changes in local grid policies, technologies, and market development in areas where their old wind farms are situated before setting out their repowering projects.

Lastly, financial institutions shouldexamine the economic viability of wind repowering projects and provide financial support under the framework of green finance taxonomies and carbon-reduction supporting tools. The relatively high return of wind repowering projects remains untapped as financial institutions are yet to develop the understanding and ability to evaluate these projects. Given the market potential of wind repowering projects, it is advisable for financial institutions to develop relevant financing businesses from a forward-looking perspective and design well-targeted financial service plans, formulating crediting guidelines for the economic value and investment risks of such projects. Furthermore, as wind power development and operation feature in China's green finance standards, banks can give full play to existing green finance incentive policies including carbon-reduction supporting tools to lower the cost of capital for wind repowering projects and make financing more convenient for related companies.

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