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Using green finance to counteract the adverse effects of COVID-19 pandemic on renewable energy investment-The case of offshore wind power in China

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ABSTRACT

The outbreak of COVID-19 pandemic has increased the production costs of renewable energy facilities and undermines the profitability of renewable energy investment. Green finance polices, e.g. carbon pricing, tradable green certificate (TGC) and green credit, can provide low-cost finances and counteract the adverse effects of COVID-19 pandemic. In this work, the generation costs of offshore wind power before and after the COVID-19 pandemic in China are analyzed using the data of 97 offshore wind power projects implemented in the period of 2014–2020, and the effect of green finance policy on the generation cost and the project profitability are evaluated. The results show that the average levelized cost of electricity (LCOE) of offshore wind power decreased from 0.86 CNY/kWh in 2014 to 0.72 CNY/kWh in 2019, while it increased to 0.79 CNY/kWh in 2020, i.e. 10.85% increase relative to that in 2019. With the average carbon price of 50 CNY/t CO_2, the average TGC price of 170 CNY and the green-credit policy being introduced, the average LCOE decreases to 0.76 CNY/kWh, 0.67 CNY/kWh and 0.74 CNY/kWh respectively. The green finance policy mix is still necessary to support the offshore wind power investment during the Covid-19 pandemic.

1. Introduction

Renewable energy development plays a key role in promoting China's energy transformation and mitigating climate change, in which wind power has gradually become a major component of China's renewable energy due to its high level of technology and commercialization (Chen et al., 2020; Tu et al., 2019a). Despite hopeful prospects for China's onshore wind power, there are a number of issues associated with onshore wind power in China that hinder its development, such as curtailment of onshore wind, limited construction land and grid flexibility (Cui et al., 2020; Tu et al., 2019a). Offshore wind power has gradually become more and more important in the future, because of the characteristics of no occupation of land, high wind speed, and close to electricity load center (Sherman et al., 2020). In recent years, driven by economies of scale and technological progress, the investment cost of China's offshore wind power has been significantly reduced. According to NEA (2020) and IRENA (2020), cumulative installed capacity of China's offshore wind power has increased from 0.15 GW in 2010 to 6.40 GW in 2019 (NEA, 2020), and the unit investment cost has decreased from 23829.20 CNY/kW to 17260.30CNY/kW in 2019 (IRENA, 2020), with a 28% decrease as shown in Fig. 1.

Despite that the downward trend of China's offshore wind power costs has emerged, with the outbreak of COVID-19 pandemic at the end of 2019, the bid price of China's offshore wind turbine has increased significantly, rising from about 6000 yuan/kW in Mar. 2019 to 7000 yuan/kW in Feb. 2020.[1] Moreover, due to the impact of COVID-19 pandemic on the wind turbine industrial chain, the shortage of wind turbine production capacity has further emerged (Kuzemko et al., 2020). In addition, as the Feed-in Tariffs (FIT) for China's offshore wind power reducing in 2020 (NDRC, 2019), the "rush to install" will become increasingly severe, and the demand for wind turbines in the offshore wind power industry will further increase (Liu and Xu, 2020). Finally, as a result of the negative effect of COVID-19 on China's economy (Duan et al., 2020), the original financing costs of offshore wind power may

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[1] Data source: https://fd.bjx.com.cn/hsfd/.

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greatly increase due to the growth of systemic risks in the finance market. Under the background above, the profitability of China's offshore wind power may further become worse in short term.

In order to counteract the negative effect of COVID-19 on the profitability of wind power and promote the investment of offshore wind power, green finance can play an important role in offering lower cost finance for renewable energy investment and operation (He et al., 2019). Among them, green credit, carbon pricing and tradable green certificate (TGC) are the three representative green finance policy instruments in China. Firstly, China started its carbon trading pilot in 2013, and now there are 8 local carbon markets in Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei, Chongqing and Fujian. Based on the experiences from the carbon trading pilots above, the nationwide carbon market was announced in December 2017, and with the implementation of "Measures for the Administration of Carbon Emission Trading" published by NDRC (NDRC, 2020), the national carbon market will start trial operation in 2021. Secondly, the TGC market in China is currently in its initial stage. Due to the lack of a mature pricing system, the fluctuation of TGC prices is significant, ranging from 128.6 to 382.3 CNY in 2021. By the end of 2020, the number of issued TGCs for wind power in China is more than 20 million, and the trading volume is about 73000. Thirdly, green credit has been expanding in recent years. According to "Green Finance Development Report" published by People's Bank of China (2021), the scale of green credit in China has grown from 2.9 trillion CNY in 2013 to 12 trillion CNY in 2020, and the proportion of green credit invested in the field of clean energy has also been increased from 7.2% in 2013 to 10.9% in 2020.

Some research show that the offshore wind cost reductions in the past decade not only stem from technological innovation but also, to a substantial extent, from improved financing conditions for offshore wind power projects (Sherman et al., 2020). Green finance can offer lower cost finance and revenue for investment and operation of offshore wind power projects. For example, under the carbon pricing policy, offshore wind power plant investors can sell the issued certified emission reduction (CERs) and obtain emissions reduction revenues with a specific carbon price to offset the increased investment costs of offshore wind power projects duet to COVID-19 pandemic. However, the green finance system in China is currently in its initial stage, the effectiveness of green finance policy on promoting the offshore wind power investment has been little explored, especially in the context of COVID-19 pandemic.

To fill this gap, the impact of COVID-19 pandemic on the cost of the offshore wind power projects is firstly explored. Then the green finance policies, i.e. carbon pricing, tradable green certificate and green credit, were incorporated into the appraisal of the wind power investment, and the effectiveness of green finance policies on counteracting negative effect of COVID-19 are evaluated. Third, the critical values of the policies and the policy mix of green finance policies to support offshore wind power investment are obtained, and policy suggestions on how to improve the current green finance system in China derived.

The reminder of this paper is organized as follows. Section 2 makes a literature review. The methodology in this paper is introduced in Section 3. Section 4 describes the data. Section 5 presents the results. The conclusions are summarized in Section 6.

2. Literature review

In this section, the relevant studies focusing on the cost of offshore wind power, the effect of Covid-19 pandemic on renewable energy investment and the green finance in China is reviewed, based on which the research gap of existing studies are identified, and the main contributions of this paper are clarified.

2.1. Cost evaluation of wind power

Renewable energy Cost evaluation is of great significance for analyzing cost evolution of renewable energy and grid parity in future (Wiser et al., 2016; Zhou et al., 2020; Zhang et al., 2020). With the development of global wind power technology, wind power cost evaluation has gradually become a research hotspot. As a method to evaluate the costs of power generation technologies overall lifetime (Grunewald, 2017), Levelized Cost of Electricity (LCOE) is widely used to evaluate the cost-effectiveness of renewable energy power (Ouyang and Lin, 2014; IRENA, 2020; Mattar and Guzmán-Ibarra, 2017). Ouyang and Lin (2014) firstly systemically analyzed the LCOE of Chinese onshore wind power and found that it ranged from 0.50 to 0.62 CNY/kWh with a discount rate of 5%. Li et al. (2018) calculated the average LCOE of wind power at six locations in China, i.e. Tongliao, Zhangjiakou, Chaoyang, Qingdao, Jiujiang and Quanzhou, and found that the LCOEs ranged from 0.37 to 0.57 CNY/kWh. Tu et al. (2019b) analyzed the future cost evolution of onshore wind power in China using the LCOE model, and the results showed that the cost of onshore wind power in China would decrease from 0.40 yuan/kWh in 2016 to 0.35 yuan/kWh in 2020.

With the gradual maturity of offshore wind power technology,

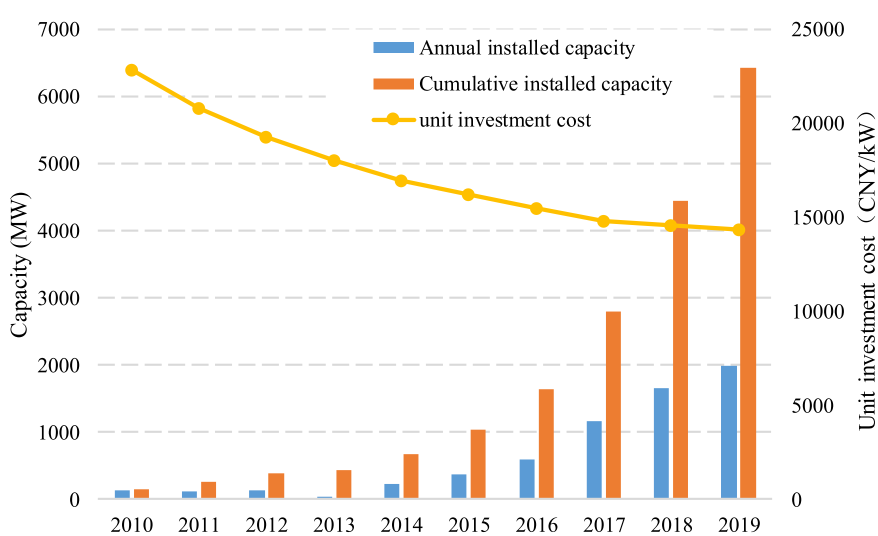

Fig. 1. Capacity and unit investment cost of offshore wind power in China.

researchers have paid much attention to the cost evolution of offshore wind power. As shown in Table 1, the existing studies focus on cost evaluation of offshore wind power in different countries, and analyze the impact of operation and maintenance cost, grid connection cost, discount rate and other factors on the overall cost of offshore wind power (Irawan et al., 2017; Lutzeyer et al., 2018). The results show that the costs of offshore wind power in UK, Denmark and other European countries have dropped rapidly, and offshore wind power can compete with the traditional fossil energy power; in the US, Japan and other countries, the costs of offshore wind power are still higher than that of traditional fossil energy power. With the gradual expansion of offshore wind power capacity in recent years, the offshore wind power development in China is attracting more and more attention. The relevant studies found that Chinese offshore wind energy resources are mainly concentrated in the eastern coastal areas with huge development and utilization potential (Zhang et al., 2011; Davidson et al., 2016; Yuan, 2016). However, due to the limitations of grid connection conditions and operation and maintenance technologies (Sahu, 2018; Bosch et al., 2019), the cost of offshore wind power is still higher than that of the developed countries referred above.

2.2. Effect of Covid-19 pandemic on renewable energy investment

With the outbreak of COVID-19 pandemic, the global development of renewable energy has encountered serious challenges (Broto and Kirshner, 2020; Kuzemko et al., 2020; Steffen et al., 2020). Firstly, governments in different countries have taken policy measures to limit the movement of persons across regions or countries, and make reasonable arrangements for firms to resume work to control the spread of COVID-19 pandemic. For renewable energy power sector, these policies may increase the finance burden of renewable energy enterprise and delay the investment of renewable energy power projects (Rosenbloom and Markard, 2020; Hosseini, 2020). Secondly, the COVID-19 pandemic may strike the supply chains of renewable energy manufacturing, which have slowed down the transition to the renewables (Sovacool et al., 2020; Yoshino et al., 2020). Thirdly, the suspended import and export of renewable energy power equipment among different countries caused by COVID-19 pandemic has delayed the renewable energy power grid-connection and increases the risk of renewable energy investment (Gillingham et al., 2020). Thus, it's generally considered that the COVID-19 pandemic has a negative effect on the current investment of renewable energy.

2.3. The impact of green finance on renewable energy investment

Green finance is a new type of finance instrument proposed to solve environmental problems, and it is the embodiment of finance innovation in the field of renewable energy (Barbier, 2020). With the development of green finance, different finance policy instruments have been proposed to promote renewable energy investment, such as carbon pricing, tradable green certificate and green credit. The positive effect of green finance on the investment of renewable energy has long been confirmed, especially for the wind energy (Hafner et al., 2020) and biomass energy (Falcone and Sica, 2019). Specifically, the green finance policies could accelerate the substitution of traditional energy with renewable energy by providing direct or indirect economic incentives, and lower the overall cost of the renewable energy power (He et al., 2019; Hafner et al., 2020; Bourcet and Bovari, 2020).

2.4. Research gap

Different from previous studies, the contribution of this paper is twofold. First, the recent researches mainly focused on analyzing the potential of cost reduction of offshore wind power based on the distribution of offshore wind resource in China. However, there are few relevant studies focusing on the cost of offshore wind power based on the actual investment and operation costs data in China. In fact, due to the differences of economic development and offshore wind resource among different regions in China, the disparity in the costs of offshore wind power projects is significant, and the COVID-19 pandemic may further amplify this disparity. Therefore, in order to depict the cost evolution of Chinese offshore wind power in more comprehensive way, we calculate the LCOE of offshore wind power based on a complete sample of offshore wind power projects implemented from 2014 to 2020 in China, and especially we analyze the impact of Covid-19 on cost evolution of offshore wind power, which has never been explored to our best knowledge.

Second, this study quantifies the effect of green finance on counteracting the adverse effects of COVID-19 pandemic on offshore wind power investment, and especially the effect of the carbon pricing, tradable green certificate and green credit are systematically evaluated, which can provide important implication for the future policy design to promote the renewable energy investment under the COVID-19 pandemic.

3. Methodology

Levelized Cost of Electricity (LCOE) is a measure of the average cost of power generation, which is calculated as the total cost associated with building and operating a power-generating project divided by the total electricity output over the lifetime. Now it is a widely used indicator for comparing electricity costs from different energy technologies (Ouyang and Lin, 2014; Tu et al., 2019a). LCOE can also be regarded as a minimum price at which electricity must be sold in order to break even over the lifetime of the project.

The LCOE is calculated when the present value of the total discounted revenues () is equivalent to the total discounted cost during the lifetime of the systems over N years. The Net Present Value (NPV) is as follow,

Table 1
List of studies on offshore wind power cost evaluation.

Region	Time	Data sources	Cost	Key factors	References
US	2012	Level 4 wind farm	0.14–0.32 ($/kWh)	Tax rate, O&M cost	Chu and Majumdar (2012)
UK	2012–2030	10 wind power projects	0.18–0.11 (£/kWh)	Discount rate, capacity factor	Levi et al. (2015)
Global	2014–2050	IEA	0.19–0.10 ($/kWh)	Capacity factor, discount rate, O&M cost	Wiser et al. (2016)
EU	2000–2015	46 wind power projects	0.10–0.25 (€/kWh)	Capacity factor, resource potential	Voormolen et al. (2016)
Chile	1979–2014	Resource potential	0.10–0.11 ($/kWh)	Initial cost, capacity factor, discount rate	Mattar and Guzmán-Ibarra (2017)
Canary Islands	2014	Resource potential	0.18–0.26 (€/kWh)	Power generation, grid connection cost	Rosenbloom and Markard (2020)
Global	2000–2018	IRENA	0.13–0.13 ($/kWh)	Capacity factor, unit investment cost	IRENA (2020)
US	–	Resource potential	0.12 ($/kWh)	Investment cost, O&M cost, discount rate	Bosch et al. (2019)
UK			0.07 ($/kWh)		
Japan			0.09 ($/kWh)		
Denmark	–	Resource potential	0.09–0.17 (€/kWh)	Investment cost, O&M cost, discount rate	Kuzemko et al. (2020)
China	–	Zhejiang Putuo 6# wind project	0.56 (CNY/kWh)	Investment cost, operation hour, lifetime	Wang (2019)

$$NPV = \sum_{i=1}^{N} Cash(i)\%(1+d)^{-i} = 0 \quad (1)$$

in which d is the discount rate, $Cash(i)$ is the cash flow in year i, which can be represented as follow,

$$Cash(i) = E(i)\%P + D - I - O\&M(i) - L(i) - T(i) \quad (2)$$

Specifically, $E(i)$ is the annual electricity production in year i which can be determined by the capacity (Q), the capacity factor (CF), the utilization rate of offshore wind turbine and the maximal available utilization hours in a standard year (8760h), i.e. $E(i) = Q\%CF\%8760\%\theta^i$; P is the on-grid price of wind power, with the assumption of a constant price over the project lifetime. This price is determined when the total NPV, including prepaid investment and debt, capital cost, O&M cost as well as loan payment and tax, is equal to zero. I is the investment costs of project; $O\&M(i)$ is the operation and maintenance (O&M) costs and $T(i)$ is the tax cost of project in year i, including Value Added Tax (VAT), Income Before Tax (IBT) and education and urban construction surtax. Moreover, the loan from bank is assumed as 80% of the investment cost, i.e. the debt $D = 0.8I$. Accordingly, the loan payment $L(i)$ with loan period t (Davidson et al., 2016) can be represented as

$$L(r) = \frac{D\%r\%(1+r)^t}{(1+r)^t - 1} \quad (3)$$

The LCOE is defined as the break-even electricity price for NPV to equal zero, under which an investor would receive a return proportional to the discount rate of the investment. Thus, based on Eqs. (1)–(3), we can get the LCOE,

$$LCOE = \left(I + \sum_{i=1}^{N} \frac{O\&M(i) + L(r) + T(i) - D}{(1+d)^n}\right) \Bigg/ \left(\sum_{i=1}^{N} \frac{Q\%CF\%8760\%\theta^i}{(1+d)^n}\right) \quad (4)$$

In this paper, we consider the green finance in the calculation of LCOE. In general, green credit, carbon pricing and tradable green certificate are three representative green finance instruments. Firstly, offshore wind power plant investors can obtain a preferential loan interest rate, r_g, through green credit provided by commercial banks and the loan payment, $L(r_g)$, will decrease as shown in Eq. (3). Secondly, under the carbon pricing policy, offshore wind power investors can sell the issued certified emission reduction (CERs) at year i, ER_i, and obtain emissions reduction revenues, i.e. $R_c(i) = P_c\%ER_i$, with carbon price P_c. Thirdly, under the tradable green certificate (TGC) policy, offshore wind power investors can sell the issued green certificates in TGC market and get additional revenues, i.e. $R_{TGC}(i) = P_{TGC}\%E(i)$, with TGC price P_{TGC}. Therefore, the LCOE shown in Eq. (4) can be re-wrote as follow,

$$LCOE = \left(I + \sum_{i=1}^{N} \frac{O\&M(i) + L(r_g) + T(i) - D - R_c(i) - R_{TGC}(i)}{(1+d)^n}\right) \Bigg/ \left(\sum_{i=1}^{N} \frac{Q\%CF\%8760\%\theta^i}{(1+d)^n}\right) \quad (5)$$

4. Data description

In this Section, we describe in detail the data used to calculate the LCOE of offshore wind power projects including data sources, investment costs, power generation, operation and management costs and other financial parameters. Moreover, feed-in tariffs of offshore wind power and the green finance policy are introduced in Section 4.6 and 4.7.

4.1. Data sources

Data in this paper is derived principally from Environmental Assessment Report (EAP) and Wind Turbine Tender Documents (WTTD) of offshore wind power projects. Specifically, we collect the detail finance and technical data of offshore wind power projects from EAP and WTTD, including the construction date of the projects, bid price of wind turbine, investment costs, capacity, loan interest rate, etc. As shown in Fig. 2, by the end of Jun. 2020, 97 offshore wind power projects located in Guangdong, Fujian, Jiangsu, Zhejiang, Shanghai, Liaoning and Shandong provinces have been included in the dataset. The total cumulative capacity of these projects is 28.24 GW, which accounts for 91% of the total capacity of approved offshore wind power projects from 2014 to 2020. Consequently, the dataset is a good representation of China's offshore wind power sector.

4.2. Investment cost and bid price

Investment costs of offshore wind power projects consist of offshore wind turbine costs, installation costs of wind power facilities, design and construction costs, as well as other miscellaneous expenses (Sherman et al., 2020). Fig. 3 shows the unit investment costs of offshore wind power projects from 2014 to 2020. As shown in Fig. 3(a), the unit investment costs reduce from 23829.20 CNY/kW in 2007–17260.30 CNY/kW in 2019, with a 27.57% decrease. However, with the outbreak of Covid-19 pandemic in Jan. 2020, the average bid price of offshore wind turbine is increasing from 6312.04 CNY/kW in 2019–6955.90 CNY/kW in 2020, i.e. 10.2% increase, as shown in Fig. 3(b). Driven by the increasing of wind turbine bid price, the average unit investment cost is 20327.77CNY/kW in 2020 compared to 17260.30CNY/kW in 2019, with a 17.41% increase. It implies that the Covid-19 leads to higher wind turbine bid prices and consequently higher investment costs.

4.3. Power generation

The annual power generation of offshore wind project will be determined by the capacity, the capacity factor, and the maximal available utilization hours in a standard year (8760h). In particular, due to the impact of ocean environmental, such as high temperature, high humidity, high salt fog, operating efficiency of offshore wind turbine will decrease year by year (Sherman et al., 2020). Therefore, we use the degradation rate to depict the effect of ocean environmental factors on the generation efficiency of offshore wind turbine. In this paper, we assume the utilization rate as 97% (Shafiee et al., 2015). Moreover, by comparing the location of offshore wind power projects with Chinese offshore wind resource distribution map shown in Sherman et al. (2020), the capacity factor for all offshore wind power projects are determined, and the offshore wind power generation of all the projects is estimated.

4.4. Operation and management cost

Operation and maintenance (O&M) costs include operation costs, management costs, and other expenses. Due to limited data availability for the O&M costs for offshore wind projects in our dataset, it's assumed that the average operational and maintenance costs of the offshore wind

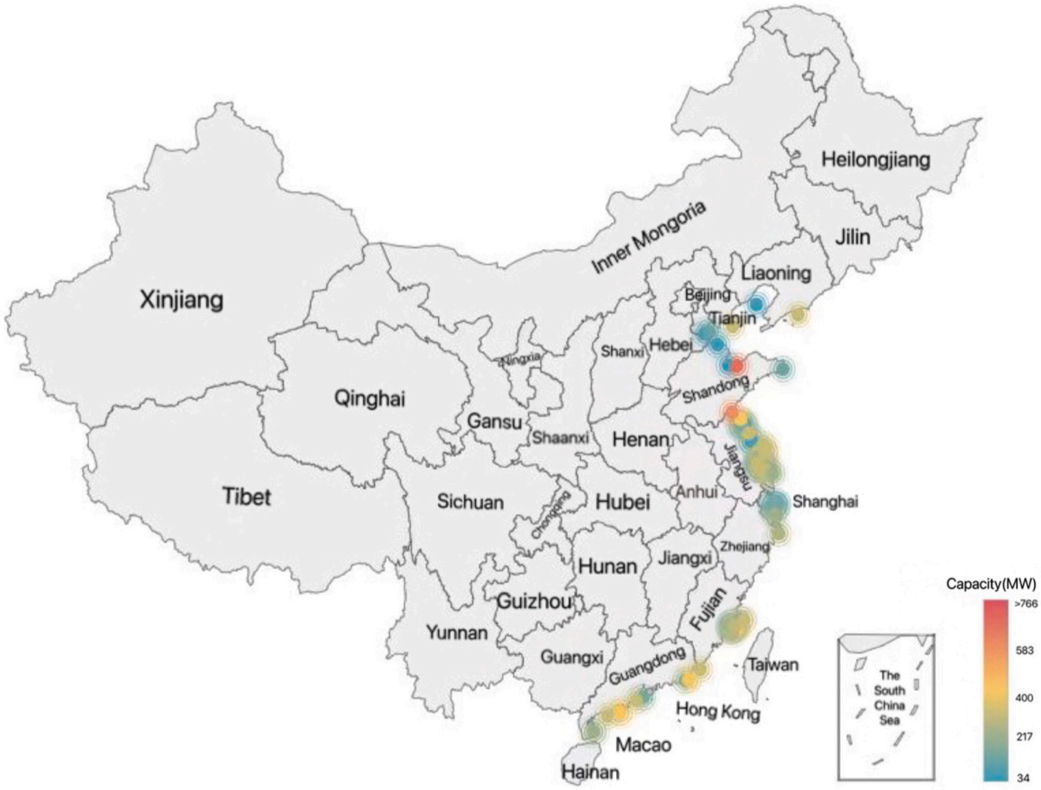

Fig. 2. The distribution of the offshore wind power projects in China.

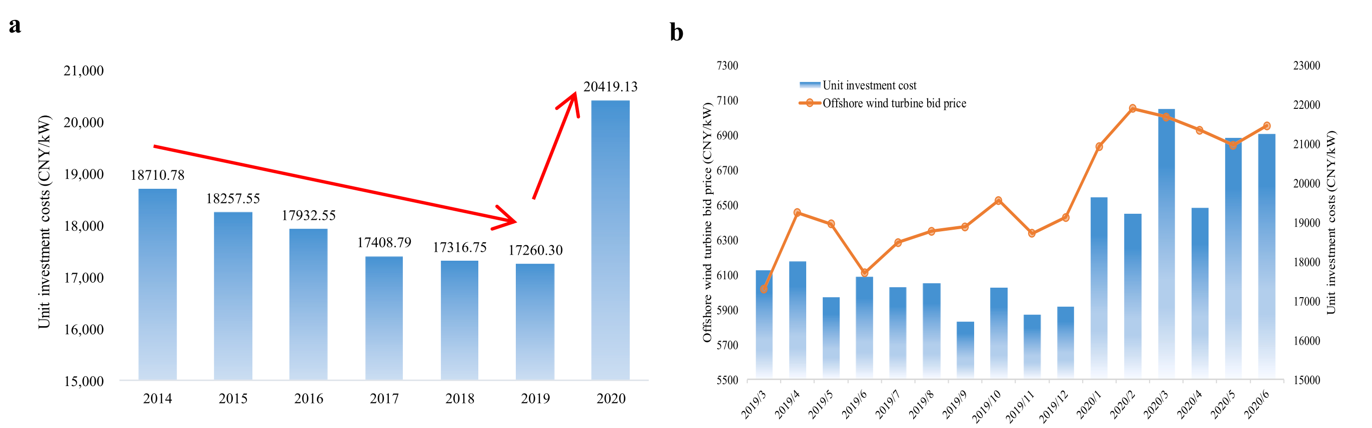

Fig. 3. The investment costs of offshore wind power from 2014 to 2020.

power projects was 0.15CNY/kWh according to IEA (2011) and IRENA (2020), respectively.

4.5. *Financial parameters*

One of significant input for the LCOE is the interest rate of commercial loan from bank. According to the guiding interest rate for energy projects published by central bank,[2] the annual loan interest rate for all offshore wind power projects is set as 4.9%, and the annual loan payment are assumed to remain constant over 15-year period in this study.

Another key parameter for estimating the LCOE is the discount rate, which reflects the technology- and time-specific cost of capital (Schmidt et al., 2019). Based on Egli et al. (2018), Wang (2019) and Liu and Xu (2020), the discount rate is set as 6.50% in this paper.

Table 2
The feed-in tariffs for offshore wind power in China.

Type	Feed-in tariffs (CNY/kWh)	Time
offshore wind power	0.85	2014.6
	0.80	2019.7
	0.75	2020.1

Date Source: NDRC (2014; 2019).

4.6. *Feed-in tariffs*

Feed-in tariff (FIT) is an effective policy instrument to improve the

[2] Data source: http://www.pbc.gov.cn/.

profitability of offshore wind power projects (Ouyang and Lin, 2014). The NDRC first issued the FIT policy of offshore wind power in 2014. Based on NDRC (2014), the on-grid price of offshore wind power is 0.85CNY/kWh. In order to promote the technological progress of offshore wind power sector, NDRC reduced the on-grid price of offshore wind power to 0.80CNY/kWh and 0.75CNY/kWh in 2019 and 2020 (Table 2).

4.7. Green finance

In general, green finance refers to the finance policy instrument providing concessional finance for project investment and operation in the fields of environmental protection, energy conservation, renewable energy, green transportation and building (He et al., 2019). Among them, green credit, carbon pricing and tradable green certificate are three representative policy instruments. Green credit is the policy instrument that commercial banks provide preferential loan to support the investment in low-carbon industries (Yang et al., 2020). Since China Banking Regulatory Commission (CBRC) published the green credit guidelines in 2012, the scale of green credit expanded rapidly in China. Based on the "statistical report on the loan investment of finance institutions" published by China central bank, the scale of green credit increased from 5.20 trillion CNY in 2013 to 9.00 trillion CNY in 2018, and the renewable energy sector gets about 23% of total green credit in 2018 (CBRC, 2019). In order to analyze the effectiveness of green credit policy, we choose 8 preferential loan interest rates in our analysis according to Liu et al. (2017), which are 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% lower than the benchmark loan interest rate (4.9%) in Section 5.

Carbon pricing policy is another green finance policy instrument to support the development of offshore wind power. With the implementation of the Chinese nation-wide carbon emission trading market in 2017 (NDRC, 2017a), offshore wind power plant investors can sell the issued certified emission reduction (CERs) and obtain emissions reduction revenues. The emission reduction revenues can offset part of the power generation cost of offshore wind power. Based on the experience from the pilot carbon emission trading markets in China, we set the carbon price as between 10 and 150CNY/t CO_2 in our analysis in Section 5, which is approximately the range of carbon price variation in the China's carbon trading pilots.[3]

As an emerging green finance policy instrument, tradable green certificate (TGC) has been introduced since 2017 in China (NDRC, 2017b). Unlike the FIT policy, TGC is a market-based policy which can provide incentive for various consumers to buy renewable energy power in electricity market (Tu et al., 2020). Specifically, renewable power generators can sell the issued green certificates in TGC market and get additional revenues from renewable energy power generation. In this situation, part of the generation costs of offshore wind power can be offset by these revenues from TGC sales. By June of 2020, the number of issued TGCs for wind power in China is 5,681,112, and the trading volume is 37,750. Moreover, the prices of TGCs for wind power fluctuate greatly, which ranged from 128.60 CNY to 273.70 CNY. In this paper, we set the TGC price as between 130 and 270 CNY, which is approximately the same as the range of TGC price variation in the China's tradable green certificate market.[4]

5. Results and discussion

Based on the methodology described in Section 3 and the data from Section 4, we calculate the LCOE of offshore wind power projects constructed from 2014 to 2020 and analyze the impact of Covid-19 pandemic on the profitability of offshore wind power projects by comparing the LCOE and FIT in Section 5.1. Next, we discuss the effectiveness of the green finance policy to reduce the LCOE of offshore wind power projects in Section 5.2. Considering the coexistence of the policy instruments in practice, the effect of the policy mix of green finance policy on improving the profitability of offshore wind power projects is also analyzed.

5.1. Impact of Covid-19 on the LCOE of offshore wind power projects

The costs of electricity generation from offshore wind projects from 2014 to 2020 are shown in Fig. 4. As shown in Fig. 4(a), the average LCOEs of the wind power decrease from 0.86 CNY/kWh in 2014 to 0.72 CNY/kWh in 2019, i.e. 16.17% decrease, mainly as a result of the learning effect (Arrow, 1962). While, since the outbreak of Covid-19 pandemic, the production of offshore wind turbine was disturbed and even disrupted, which makes the output of the wind turbine decreased, and pushed up the price of offshore wind turbine. Thus, the average LCOE in 2020 increased to 0.79 CNY/kWh accordingly, i.e. 10.84% increase compared to that in 2019. In more detail, as shown in Fig. 4(b), in 2019 20 projects' LCOEs are lower than the FIT (0.75CNY/kWh), meaning that most projects are profitable; while among the total 19 projects implemented in 2020 after the outbreak of Covid-19 pandemic, there are only three projects whose LCOEs are lower than the FIT, and in other words, only 3 or 16% of the projects are expected to be profitable. In addition, there is significant disparity among different regions in the effect of Covid-19 pandemic, and the average LCOEs of projects located in Jiangsu, Fujian, Guangdong and Zhejiang increased by 3.25%, 12.34%, 11.89% and 20.15%, respectively. Overall, the results indicate that the Covid-19 pandemic has a significantly negative effect on the profitability of offshore wind projects. Actually, according to IEA (2021), COVID-19 pandemic had hindered the construction and operation of offshore power projects. On one hand, the isolation measures of COVID-19 have restricted the movement of offshore power project workers and delayed the project construction schedule. On the other hand, the outbreak of COVID-19 pandemic has leaded to great uncertainty of future cash flow, and investors may reduce investment in offshore wind power projects due to uncertain demand and limited budgets. In addition, as the supply chain of offshore wind equipment is more globalized, the ongoing spread of COVID-19 pandemic around the world has increased the price volatility of offshore wind power equipment (Gillingham and Knittel, 2020). To sum up, the cost of offshore wind power projects may become higher with the outbreak of COVID-19 pandemic.

5.2. LCOE of offshore wind power projects with single green finance policy

In order to decrease the LCOE and improve the profitability of offshore wind power projects, as explained in Section 4.7, green finance policy can provide low-cost finance and additional revenues for investment and operation of offshore wind power projects to offset the increasing LCOE of offshore wind power projects due to COVID-19 pandemic. Fig. 5 shows the LCOEs of offshore wind power projects with different green finance policies, in which the 19 lines represent the LCOEs of 19 offshore wind power projects constructed in 2020. a. As shown in Fig. 5, the LCOEs of 19 offshore wind power projects in 2020 range from 0.68 CNY/kWh (Changle Area C offshore wind project) to 0.86 CNY/kWh (Bandaonan III offshore wind project) in the Baseline scenario. The average and median LCOEs of 19 offshore wind power projects in 2020 are 0.79 CNY/kWh and 0.79 CNY/kWh, respectively. By comparing the LCOEs with FIT in 2021 (0.75 CNY/kWh), only 3 offshore wind power projects can be profitable. Under the carbon pricing policy, offshore wind power plant investors can sell the issued certified emission reduction (CERs) and obtain emissions reduction revenues to offset the increasing LCOE of offshore wind power projects. As shown in Fig. 5(a), the average LCOE of 19 offshore wind power

[3] Data source: http://k.tanjiaoyi.com/.

[4] Data source: http://www.greenenergy.org.cn/.

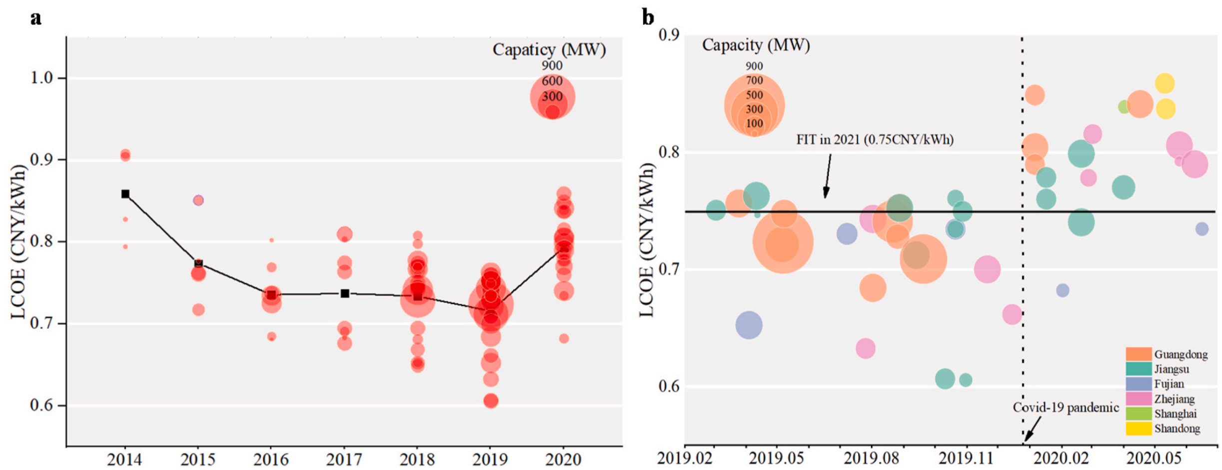

Fig. 4. The LCOE of offshore wind power projects from 2014 to 2020.

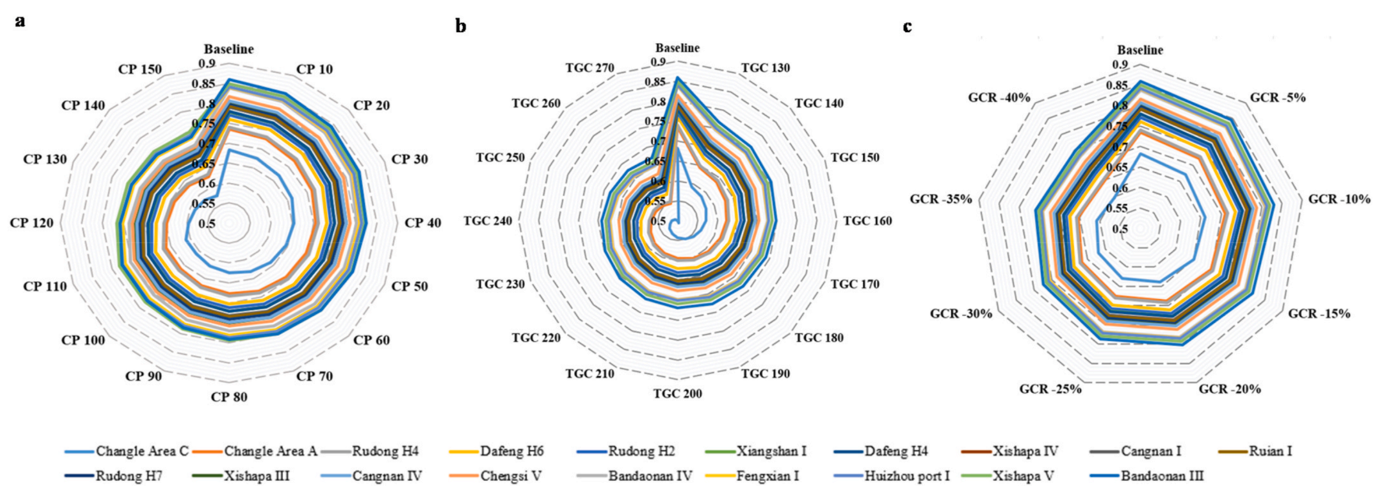

Fig. 5. The effect of carbon pricing (CP) (a), tradable green certificate (TGC) (b) and green credit (GCR) (c) policies on LCOEs reduction of offshore wind projects in 2020. (The lines in this radar map show the LCOEs of 19 offshore wind power projects. The radius of each radar map shows the LCOE of offshore wind power. The indicators of each radar map show the scenarios with different carbon prices, TGCs prices and decrease of loan interest rate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

projects in 2020 decreases from 0.79 CNY/kWh to 0.76 CNY/kWh, and the number of the profitable projects increase from 3 to 7, with carbon price increasing from 0 to 50 CNY/t CO_2, i.e. the average carbon price in China's emission trading pilots. With the carbon price reaching 100 CNY/t CO_2, the carbon price observed in Beijing and Shenzhen emission trading pilots, the average LCOE will further decrease to 0.72 CNY/kWh, and the number of the profitable projects increases to 14 accordingly.

Under tradable green certificate policy, offshore wind power plant investors can sell the TGCs and obtain additional TGCs revenues to offset the increasing LCOE of offshore wind power projects. As shown in Fig, 5 (b), the average LCOE decreases from 0.79 CNY/kWh to 0.70 CNY/kWh, and the number of the profitable projects increase from 3 to 16, with TGC price increasing from 0 to 130 CNY, i.e. the minimal TGC price observed in China's TGC market. With the TGC price reaching 170 CNY, i.e. the average TGC price in China's TGC market, the average LCOE will further decrease to 0.67 CNY/kWh, and all the 19 offshore wind power projects in 2020 will be profitable, accordingly.

Under the green credit policy, offshore wind power plant investors can obtain a preferential loan interest rate by green credit provided by commercial banks, and the loan payment will decrease. As shown in Fig. 5(c), the average LCOE decreases from 0.79 CNY/kWh to 0.74CNY/kWh, and the number of the profitable projects increase from 3 to 11, with benchmark loan interest rate decreasing by 20%, i.e. the average long-term loan interest rate published by 21 commercial banks in China. With the benchmark loan interest rate decreasing by 40%, the minimal long-term loan interest rate published by 21 commercial banks in China, the average LCOE will further decrease to 0.69 CNY/kWh, and all the 19 offshore wind power projects in 2020 will be profitable, accordingly.

To sum up, the results confirm that the green finance policies, i.e. carbon pricing, tradable green certificate and green credit policy are effective to lower the LCOE and improve the profitability of offshore wind power projects. Further, by comparing the LCOEs with the three green finance policies, we find that the LCOEs of offshore wind power projects decrease from 0.79 CNY/kWh to 0.76, 0.70 and 0.74 CNY/kWh, with the average level of carbon price (50 CNY/tCO_2), TGC price (130 CNY) and loan interest rate (3.92%), respectively.

5.3. LCOE of offshore wind power projects with policy mix

The effect of green finance policy mix on promoting the LCOE reduction of offshore wind power projects in 2020 is also explored, and Fig. 6, presents the LCOE distribution of the 19 projects under different policy scenarios. Specifically, Fig. 6(a) shows the LCOEs of 19 offshore wind power projects in 2020 with the policy mix of green credit and carbon pricing. Under the benchmark loan interest rate (GCR -0% scenario), the LCOE ranges from 0.68 CNY/kWh to 0.86 CNY/kWh, and the

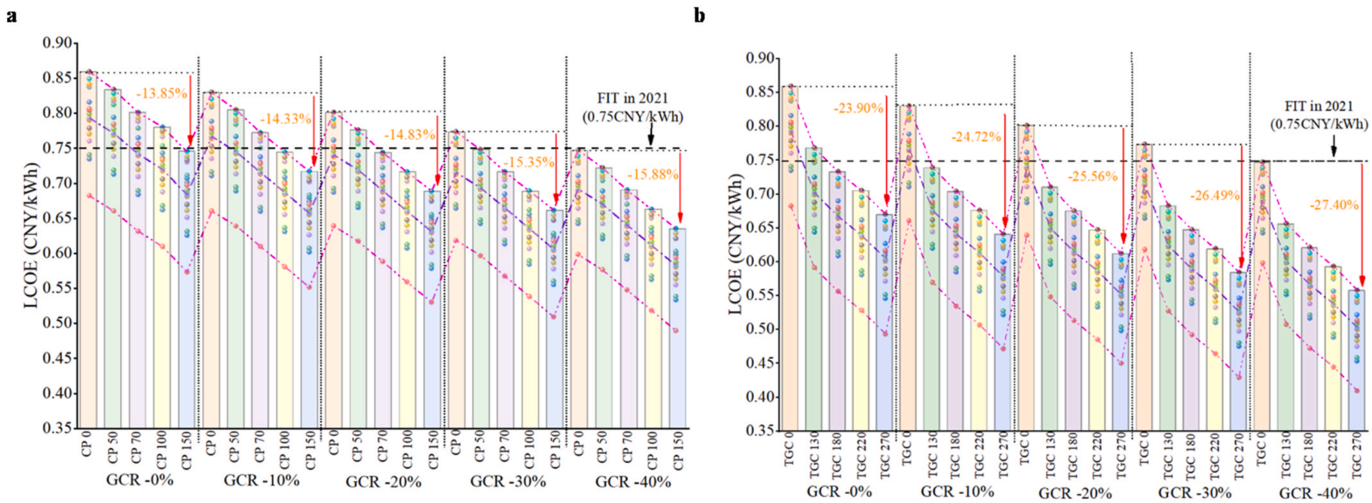

Fig. 6. The effect of green finance policy mix on LCOEs of offshore wind projects in 2020. The histogram shows the maximum LCOE of all offshore wind power projects with different carbon prices (CP), TGCs prices and green credit (GCR). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

average LCOEs decreases from 0.79 CNY/kWh to 0.68 CNY/kWh, i.e. 13.85% decrease, with carbon price increasing from 0 CNY/t CO_2 (CP 0 scenario) to 150 CNY/t CO_2 (CP 150 scenario). While with the benchmark loan interest rate decreasing by 10% (GCR -10% scenario), 20% (GCR -20% scenario), 30% (GCR -30% scenario) and 40% (GCR -40% scenario), the average LCOEs under the carbon price of 50 CNY/t CO2 (CP 50 scenario), i.e. the average carbon price in China's carbon trading market, are 0.76 CNY/kWh, 0.73 CNY/kWh, 0.70 CNY/kWh, 0.68 CNY/kWh and 0.66 CNY/kWh, with 4.62%, 4.78%, 4.94%, 5.12% and 5.29% compared to the average LCOE without carbon pricing policy (CP 0 scenario), the number of profitable offshore wind power projects in 2020 is 7, 13, 16 and 19, respectively. In addition, the average LCOEs under the carbon price of 150 CNY/t CO2 (CP 150 scenario), which is the maximal carbon price in China's carbon trading market, are 0.66 CNY/kWh, 0.63 CNY/kWh, 0.60 CNY/kWh and 0.58 CNY/kWh, corresponding to the decrease of 14.33%, 14.83%, 15.35% and 15.88% compared to the LCOE without carbon pricing policy (CP 0 scenario) and all offshore wind power projects will be profitable. The result shows that the green credit policy can enhance the policy effectiveness of carbon pricing policy and accelerate LCOE reduction of offshore wind power projects.

Similar to Fig. 6(a) and (b) shows the LCOEs of 19 offshore wind power projects in 2020 under the policy mix of green credit and tradable green certificate policy, the LCOE ranges from 0.68 CNY/kWh to 0.86 CNY/kWh and only 3 offshore wind power projects will be profitable under the CCR -0% scenario. With the benchmark loan interest rate decreasing by 0% (GRC -0% scenario), 10% (GCR -10% scenario), 20% (GCR -20% scenario), 30% (GCR -30% scenario) and 40% (GCR -40% scenario), the average LCOEs under the TGC price of 130 CNY (TGC 130 scenario), i.e. the average TGC price in China's TGC market, are 0.70 CNY/kWh, 0.68CNY/kWh, 0.65 CNY/kWh, 0.62 CNY/kWh and 0.60 CNY/kWh, corresponding to the decreases of 11.50%, 11.90%, 12.32%, 12.75% and 13.19% compared to the LCOE without TGC policy (TGC 0 scenario), the only 3 offshore wind power projects cannot be profitable under GRC -0% scenario, respectively. In addition, the average LCOEs under the TGC price of 270 CNY (TGC 270 scenario), i.e. the maximal TGC price in China's TGC market, are 0.60 CNY/kWh, 0.58 CNY/kWh, 0.55 CNY/kWh, 0.53 CNY/kWh and 0.50 CNY/kWh, corresponding to the decreases of 23.90%, 24.72%, 25.56%, 26.49% and 27.40% compared to the LCOE without TGC policy (TGC 0 scenario), and all offshore wind power projects will be profitable, respectively. It also indicates the percentage of LCOEs reduction under TGC prices of 207 CNY (TGC 270 scenario) is increasing with the benchmark loan interest rate decreasing by 0%–40%. The result also shows that the green credit policy can also strengthen the policy effectiveness of TGC policy and accelerate LCOE reduction of offshore wind power projects.

5.4. *Sensitivity analysis*

For the policy makers, what they concern about is the required carbon prices and TGC prices to keep the wind power project profitable. However, the effect of the green finance policy on the wind power cost and profitability may also be affected by some key parameters such as wind turbine utilization efficiency, offshore wind power grid-connection cost and offshore wind resource condition (Schmidt et al., 2019; Sherman et al., 2020; Tu et al., 2019b), and the critical prices may be different with varying parameter. Thus the required carbon prices and TGC prices to make all the projects profitable under different assumptions of the parameter setting are calculated, as shown in Table 3.

Firstly, the instability of offshore wind power would be a key concern for the plant operator, and it may lead to higher O&M costs (Tu et al., 2019a; Schmidt et al., 2019). In the sensitivity analysis, we calculate the required carbon price and TGC prices to make all the offshore wind power projects profitable with alternative O&M cost. We choose the lower and the higher cases of O&M cost as 0.1 CNY/kWh and 0.2 CNY/kWh (IEA, 2014). As shown in Table 3, the average LCOE of offshore wind power increases from 0.74 CNY/kWh to 0.85 CNY/kWh with the O&M cost increasing from 0.10 CNY/kWh to 0.20 CNY/kWh. This means that the increasing O&M costs due to instability of offshore wind power grid-connection has a significate effect on the LCOE. To

Table 3
Sensitivity analysis of key parameters.

Parameters	Value	Average LCOE (CNY/kWh)	Required carbon price (CNY/t CO_2)	Required TGC price (CNY)
O&M costs (CNY/kWh)	0.10	0.74	62.24	75.52
	0.12	0.76	94.93	107.72
	0.15	0.79	143.97	156.01
	0.20	0.85	185.59	236.51
Utilization rate (%)	90	1.13	673.46	685.18
	95	0.88	284.22	296.19
	97	0.79	143.97	156.01
	99	0.71	12.21	24.34
Capacity factor (%)	30	1.06	487.02	498.82
	35	0.92	272.55	284.51
	40	0.79	143.97	156.01
	45	0.76	41.52	53.64

further explore the profitability of offshore wind power projects, we compare the LCOEs of all the19 offshore wind power projects in 2020 with the FIT, i.e. 0.75 CNY/kWh. It is shown that the required carbon price to make all the offshore wind power projects profitable should be 62.24 CNY/t CO_2, 94.93 CNY/t CO_2, 143.97 CNY/t CO_2 and 185.59 CNY/t CO_2, with the O&M cost being 0.1 CNY/kWh, 0.12 CNY/kWh, 0.15 CNY/kWh and 0.2 CNY/kWh, and the critical TGC prices should be 75.52 CNY, 107.72 CNY, 156.01 CNY, and 236.51 CNY. Thus, the required carbon price and TGC price are sensitive to the varying O&M cost, and higher carbon prices and TGC prices are necessary to make the offshore wind power projects profitable with higher O&M cost.

In addition, utilization rate reflects the wind turbine utilization efficiency of offshore wind power driven by the technological progress, which has attracted much attention from investors and government. According to Sherman et al. (2020), the utilization rate is assumed to fall between 90% and 99%, and the effect of the utilization rate on the LCOE and the critical carbon prices and TGC prices with different utilization rates are presented in Table 3. With the utilization rate increasing from 90% to 99%, the average LCOE of 19 offshore wind power projects in 2020 decreases from 1.13 CNY/kWh to 0.71 CNY/kWh. This indicates that a higher utilization rate also leads to lower LCOE. By comparing the LCOEs of all the offshore wind power projects in 2020 with the FIT, it is found that the required carbon price (TGC price) to make all the offshore wind power projects profitable are 673.46 CNY/t CO_2, 284.22 CNY/t CO_2, 143.97 CNY/t CO_2 and 12.21 CNY/t CO_2 with the utilization rate being 90%, 95%, 97% and 99%, and the critical TGC prices are 685.18 CNY, 296.19 CNY, 156.01 CNY, 24.34 CNY, respectively. Thus, the carbon pricing and TGC policies seems to be more effective to promote the offshore wind power investment with higher utilization rate.

Finally, the capacity factor represents the offshore wind resource condition which is uncertain and may affect the LCOE of offshore wind power projects (Sherman et al., 2020; Tu et al., 2020). According to (IRENA, 2020), the capacity factor is assumed to range from 30% to 45%. As shown in Table 3, the average LCOE of offshore wind power decreases from 1.06 CNY/kWh to 0.76 CNY/kWh with the capacity factor increasing from 30% to 45%. Thus a higher capacity factor leads the LCOE to becoming lower. By comparing the LCOEs of all offshore wind power projects in 2020 with the FIT, the required carbon price to make all offshore wind power projects profitable are 487.02 CNY/t CO_2, 272.55 CNY/t CO_2, 143.97 CNY/t CO_2 and 41.52 CNY/t CO_2, and the critical TGC prices are 498.82 CNY, 284.51 CNY, 156.01 CNY and 53.64 CNY with the capacity factor being 30%, 35%, 40% and 45%, respectively. Thus, the carbon pricing and TGC policies are more effective to promote the offshore wind power projects investment with a higher capacity factor.

6. Conclusion and policy implication

To promote the energy system transition and achieve the carbon emission mitigation target, it is necessary to develop the offshore wind power. However, the offshore wind turbine industrial chain has been disturbed and even disrupted by the COVID-19 pandemic, which pushes up the production cost and leads to the shortage of offshore wind turbine supply. In this situation, the investment cost and generation cost of offshore wind power has increased significantly after the outbreak of the COVID-19 pandemic, and the profitability of offshore wind power may get worse. As an emerging policy instrument, green finance policy may offset part of the increase of generation cost and improve the profitability of offshore wind power projects. In this work, it is aimed to explore whether and to what extent the green finance policy can counteract the adverse effect of COVID-19 pandemic on the profitability of offshore wind power and promote the offshore wind power investment. To this end, we calculate the LCOEs of 97 offshore wind power projects implemented in the period of 2014–2020 and quantify the impact of COVID-19 pandemic on the LCOE of offshore wind power projects by comparing the LCOEs of the projects implemented before and after the COVID-19 pandemic. Then, the green finance policy (i.e. carbon pricing, tradable green certificate and green credit) effect on the LCOEs and the profitability of offshore wind power projects is evaluated by incorporating the policy into the calculation of the LCOEs. The results can provide important implication for the policy makers to further improve the green finance policy system to promote the development of the offshore wind power after the COVID-19 pandemic.

Our results show that the average LCOEs of offshore wind power projects have decreased significantly, from 0.86 CNY/kWh in 2014 to 0.72 CNY/kWh in 2019, i.e. 16.17% decrease. While, since the outbreak of COVID-19 pandemic, the offshore wind turbine prices have been pushed up, and accordingly the average LCOEs in 2020 increased by 9.72% compared to that before COVID-19 pandemic. Thus it can be concluded that COVID-19 pandemic indeed has negative impact on the investment of renewable energy i.e. offshore wind power. More important, this negative impact may be long-lasting before COVID-19 pandemic being completely controlled, especially given the global second outbreak of COVID-19 pandemic. Thus, besides the expedient measures, a long-term strategic policy framework may be necessary to counteract the negative impact of the COVID-19 pandemic on the investment of renewable energy and promote the sustainable development of the renewable energy and whole energy system transition.

Green finance polices, e.g. carbon pricing, tradable green certificate and green credit, can increase the future cash flows or reduce financial cost during the project lifetime, which will lower the overall LCOE of offshore wind power and improve the profitability of the projects. However, since the green finance policy system in China is still in the early stage of development, and the single policy instrument may not be enough to support the offshore wind power investment currently and in short term future. Thus, in order to assure the effectiveness and feasibility of green finance policies, the policy mix which combine the two or three of them together may be necessary in short term future. In addition, the FIT is declining during the past years, and to keep the offshore wind power investment profitable after the COVID-19 pandemic, the government can slow down the pace of the FIT decline.

The effectiveness of the green finance policy to address the COVID-19 pandemic will be influenced by some key uncertain factors, i.e. the operation cost, utilization rate of offshore wind turbine and the capacity factor. Specifically, with the lower O&M costs, higher utilization rate of offshore wind turbine and higher capacity factor, the critical values of green finance policy will be lower. These key uncertain factors are closely related to the future technology development of the offshore wind power, and may also differ in different regions. This result has important policy implication for the policy makers. Specifically, the differentiated policies may be necessary to promote the development of offshore wind power in different regions of China. In addition, the learning effect plays a key role in decreasing the cost of wind power, which is determined by the learning rate and the cumulative capacity in future (Tu et al., 2019b). To further lower the cost offshore wind power and improve the effectiveness of the green finance policy, it is necessary to promote technological progress and the diffusion of the offshore wind power technology.

In view of these results, we recommend two-stage policy strategy. In short term, government should promote the participation of offshore wind power in national carbon emission trading market, and increase the coverage of green credit to support the investment of offshore wind power projects. Especially with the impact of COVID-19 pandemic, the profitability of offshore wind power firms will be weakened in short term. Thus, government should promote the offshore wind power to participate in national-wide carbon market and offset part of the generation cost of offshore wind power. Meantime, green credit will help offshore wind power projects investors to get low cost loans and the profitability of offshore wind power will be further improved.

In the long run, the R&D investment in should be increased, to promote the technological progress of offshore wind sector. Despite that the downward trend of Chinese offshore wind power cost has gradually emerged, there are still many challenges to achieve grid parity for Chinese offshore wind power with traditional coal-fired power, such as high operation and maintenance cost and construction investment cost (Zhang et al., 2020). According to our findings, the O&M costs, utilization rate and capacity factor of offshore wind power projects are three key factors affecting the effectiveness of green finance polices. Government can provide R&D subsidy and tax exemption, to promote offshore wind power firms to increase R&D investment, and encourage the overall technological innovation of the offshore wind power industry, so that the utilization efficiency can be improved and the investment cost and O&M costs offshore wind power will be further reduced. In this situation, the grid parity for renewable energy with traditional coal-fired power can be achieved earlier (Tu et al., 2019b, 2020; Zhou et al., 2020; Zhang et al., 2021), which can contribute more to achieving China's carbon neutral target.

Credit author statement

Qiang Tu:Methodology, Writing – original draft, Jianlei Mo: Conceptualization, Writing – original draft, Supervision, Zhuoran Liu: Visualization, Investigation, Chunxu Gong: Visualization, Investigation, Ying Fan: Reviewing and Editing.

Declaration of competing interest

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

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