Environmental Science and Pollution Research (2021) 28:52329–52344
https://doi.org/10.1007/s11356-021-14275-w

RESEARCH ARTICLE

The influencing factors and hierarchical relationships of offshore wind power industry in China

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Received: 7 January 2021 / Accepted: 30 April 2021 / Published online: 19 May 2021

Abstract
As a new and cost-effective renewable energy power generation technology, offshore wind power is getting more and more attention. The development of offshore wind power industry is affected by policy-making, technology management, resources and environment, market supply and demand, and the relationship among the influencing factors is complex. This paper analyzes the factors that affect offshore wind power industry from a unique and comprehensive perspective. Fourteen factors are selected and interpretative structural model (ISM) is established to study the relationship between the influencing factors of offshore wind power industry. The results show that 14 influencing factors can be divided into five levels: the first level is the surface factors, including the economic incentive policy, operation mechanism, industrial chain, energy market mechanism, investment, and financing mechanism; the second and third levels are the intermediate factors, including generation cost, operation management, and offshore wind power technology; the fourth and fifth levels are deep-seated factors, including development planning and grid price, site selection, R&D investment, environmental protection policy, and offshore wind power supply. Deep-seated factors have a direct impact on the intermediate factors, the intermediate factors have an important impact on the surface factors, and the surface factors directly affect the development of offshore wind power industry. The influence of the 14 factors selected in this paper on offshore wind power industry is from bottom to top, from deep to shallow.

Keywords Offshore wind power · China · Influencing factor · Interpretative structural model · Policy review

Introduction

On December 12, 2020, in the climate ambition summit, President Xi Jinping announced that by 2030, the CO_2 emissions from China's gross domestic product will drop by more than 65% compared with 2005. The proportion of non-fossil energy to primary energy consumption will reach 25%, and the total installed capacity of wind power and solar power will reach 1200 GW. The declaration further improves the bottom-line standard of CO_2 emission reduction target and clearly puts forward the target of installed capacity of wind power and solar power for the first time (New China Net 2020).

Responsible Editor: Roula Inglesi-Lotz

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China's commitment to achieve carbon neutrality by 2060 and increase the national contribution to CO_2 emission reduction will play a positive role in strengthening the domestic determination of low-carbon transformation and the confidence of global climate governance, but it also faces huge challenges. In recent years, China's wind power development has made great achievements, especially the offshore wind power. In 2020, the new installed capacity of wind power in China reached 71.67 million kilowatts, including 68.61 million kilowatts for onshore wind power and 3.06 million kilowatts for offshore wind power (NEA 2021). Offshore wind power is set to grow globally to 228 GW by 2023 and potentially to 1000 GW by 2050 (International Renewable Energy Agency 2019). The increasingly prominent position of offshore wind power in renewable energy makes in-depth analysis of offshore wind power industry necessary. However, a drawback of wind as an energy source lies in its high variability (Kisvari et al. 2020), especially for offshore wind power (Bains et al. 2020). It is urgent to study the relevant factors affecting offshore wind power industry. Therefore, this paper studies the factors influencing the development of offshore wind power industry and the relationship between them, aiming to figure out the mechanism of these factors on offshore wind power industry and provide meaningful suggestions for the development of offshore wind power industry and promote the development of offshore wind power in China and the world.

The research perspectives affecting China's offshore wind power industry mainly involve resources, technology, market, policy, etc., but most of the perspectives are relatively single, and there is no in-depth decomposition of each perspective. So, there is a lack of analysis on the interaction between the influencing factors and the influence degree of each factor on the development of offshore wind power industry. This paper intends to use the ISM model to analyze the structure and hierarchy of the influencing factors of China's offshore wind power industry and explore the surface, intermediate, and deep factors which affect the offshore wind power industry.

The contributions of this paper are as follows: Firstly, it proposes a factor set influencing the development of offshore wind power industry from the dimensions of policy, technology, resources, and market and describes the characteristics of each segmentation factor, so as to clarify the correlation between each factor. Secondly, this paper analyzes the structure and hierarchy of the factors affecting the offshore wind power industry with the ISM model and explores the action path of each factor and analyzes the influence degree of each factor. Thirdly, based on the influence degree of each factor, this paper puts forward policy recommendations to promote the sound and rapid development of China's offshore wind power industry.

The rest of the article consists of six sections. The "Literature review" Section is the literature review, which mainly introduces some factors affecting the offshore wind power industry. The "Development status of offshore wind power" section introduces the development status of offshore wind power in the world and China and the relevant policies of offshore wind power in China. The "Methodology" section is methodology, which describes the modeling steps of the interpretative structural model in detail. The "The influencing factors of offshore wind power industry in China based on ISM model" section shows how to apply ISM to the research of the influencing factors of China's offshore wind power industry. The "Results and discussions" section is the result analysis of the model operation and discussions. The "Conclusions" section is the conclusions and policy implications based on the "Results and discussions" section.

Nomenclature

Abbreviations	
A	Adjacency matrix
a_{ij}	Effect value of S_i on S_j
CDM	Clean development mechanism
COVID-19	Corona Virus Disease 2019
CWEA	China Wind Energy Association
GIS	Geographical Information Systems
GW	Gigawatt
GWEC	Global Wind Energy Council
I	Identity matrix
ISM	Interpretative structural model
LCOE	Levelized cost of energy
M	Reachability matrix
MCDM	Multi-criteria decision-making
MW	Megawatt
NDRC	National Development and Reform Commission
NEA	National Energy Administration
P	Reachable set
Q	Antecedent set
R&D	Research and development
S	The system factor set
S_i	The ith influencing factor in S
S_j	The jth influencing factor in S
TWh	Terawatt hour
VAT	Value-added Tax
yuan/kWh	Yuan per kilowatt hour

Literature review

Around the globe, government and legislative authorities at the local, regional, national, and international levels are highly concerned about the environmental impacts and risk factors that influence the energy paradigm (Nazir et al. 2020b). In the past two decades, with global energy, resources, and environmental problems becoming more and more prominent, especially global climate change, wind energy has stood up as a cost-effective source of energy. It is endorsed as having the emission-free ability, green, and is also subsidies by state support and credit benefits for taxes (Nazir et al. 2020c). What's more, it has become one of the fastest developing renewable energy in the world with the joint efforts of all countries (Guo et al. 2019). Wind energy stands out in the process of energy transformation because of its abundant reserves, clean and efficient advantages. Wind power is divided into onshore wind power and offshore wind power. Onshore wind power appeared earlier and its technology is relatively mature. Compared with onshore wind power, offshore wind power has the advantages of abundant wind energy resources, wind farm close to the energy load center, wide sea surface available area, and no land occupation. Ocean captures and stores huge amounts of energy, which could satisfy five times of world energy demand (Chen et al. 2018). The development of offshore wind power is an effective guarantee for China to realize the national energy structure adjustment. Therefore, the development and utilization of offshore wind power have been paid more and more attention. However, there are some problems in the development of offshore wind power, such as lack of technical strength, high generation cost, and lack of reasonable planning. In recent years, offshore wind power technology has made new breakthroughs. A decreasing trend in the cost of initial capital investment and the levelized cost of energy (LCOE) for offshore wind-power generation developments is projected to continue (O'Kelly 2019). In 2020, many countries around the world set "green energy transformation" as the focus of future economic development, resulting in a sudden increase in the number of offshore wind power projects under construction and to be built (Li 2021). With the rapid development of global offshore wind power industry, the installed capacity is advancing by leaps and bounds, and the single unit capacity is also growing. The Corona Virus Disease 2019 (COVID-19) that has spread across the world has had a concussion on the energy industry: The construction schedule is postponed; the investment environment of the recession market is affected; in 2020, the electricity demand in some areas is expected to drop by 10%. However, the development cycle of offshore wind power is long. To a large extent, it will not be affected by the short-term impact of the epidemic on the industrial chain like onshore wind power (Sun 2020). Therefore, offshore wind power is bound to play an important role in the future world energy structure.

China has become the global leader in wind power, its wind power development has greatly promoted the growth rate of global wind power, and it has become an indispensable force in global wind power development (Zhang et al. 2020). China has more than 18,000 km of continental coastline. In the offshore area within the 5–25 m water depth line, the installed capacity at 50 m above sea level is about 200 GW, and that above 70 m is about 500 GW (Min et al. 2016). And Yang et al. (2017) have proved that the southeast region of China is particularly rich in offshore wind energy resources. China's offshore wind power potential is huge.

By combing the relevant literatures on the development of offshore wind power, it can be concluded that scholars study the factors influencing the development process of offshore wind power industry through the following aspects: First, policy-making. The development of offshore wind power will be affected by many policies, such as land use regulation, energy and environmental policy, economic incentive policy, and on grid price policy (Tu 2019; Liu et al. 2015). In particular, renewable energy policies also have an impact on the development of offshore wind power (Papiez et al. 2019). The promulgation of relevant policies will also have an impact on the technical innovation, operation and maintenance cost, and installed capacity of offshore wind power and then affect the development process of offshore wind power (Reichardt and Rogge 2015; Nguyen and Chou 2019; Cao 2018). Although China has promulgated a series of policies to promote the development of offshore wind power industry and achieved certain results, it is not difficult to find that there are still some problems in China's industrial policies, such as unclear planning, low administrative efficiency, imperfect competitive allocation system construction, and insufficient financial support (Zhang 2019). Second, technical management. The high cost of technology research and development, high investment risk, and high energy price are the main reasons for the development difficulties of offshore wind power. Among them, the performance of wind turbines plays a key role in the breakthrough of offshore wind power technology (Tahir et al. 2020). What's more, the wind turbine with higher rated power produced higher energy output (Allouhi et al. 2017). In the field of offshore wind power and, in contrast to more developed countries, China still has a problem with both a weak technical support system and underdeveloped technologies (Zhang et al. 2018). There are few "highly cited" patents in China's offshore wind power industry, and the patent value is not high. The length of the patent reference chain is generally short, the inheritance of main technology flow is poor, the key technology path is monotonous, and the technical breakthrough is difficult (Zheng 2017). Third, resources and environment. First of all, considering the development cost, operation revenue forecast, wake effect, and other factors, the selection of offshore wind farm sites is a very complex problem (Wu et al. 2019; Cranmer et al. 2017). Tercan et al. (2020) provided a solution to the problem of offshore wind power location. It combined multi-criteria decision-making (MCDM) methods and geographical information systems (GIS) and was implemented in Cyclades (Greece) and in the sea area of the İzmir region (Turkey). MCDM methods and satellite technology for identifying suitable areas of wind power plants have become increasingly popular in site selection decision-making (Shao et al. 2020; Nezhad et al. 2020). Then, a precise assessment of wind resources is considered of paramount significance for the construction of offshore wind farms (Murthy and Rahi 2017; Guo et al. 2019). Ranthodsang et al. (2020) presented an offshore wind resource assessment and offshore wind power feasibility analysis on the western coast of Thailand. Accurate and reliable wind speed forecasting is also vital in power system scheduling and management (Peng et al. 2020). And high-quality wind data is essential for the whole wind energy assessment process (Zhao et al. 2019). China has a lot of potential offshore wind energy resources to be developed. Under the high-cost scenario forecast, it can provide 1148.3TWh of energy in a cost-competitive way, and under the low-cost scenario forecast, it can provide 6383.4TWh of energy, which is equivalent to 36% to 200% of the total coastal energy demand after 2020 (Sherman et al. 2020). Fourth, market supply and demand. With an increase in cooperation for wind farm development, the development became more international and with more frequent alliances

(Dedecca et al. 2016). Offshore wind power project has a large amount of investment, and the demand for funds is relatively concentrated. The funds are mainly solved through internal financing and external financing (Zhang et al. 2015). The financing cost of offshore wind power investment can be reduced by broadening direct financing channels, improving private financing mechanism, introducing insurance policies to encourage offshore wind power enterprises, and establishing effective international reinsurance channels (Zhang and Huang 2018). At present, China's offshore wind power is in the stage of high-speed development, and the offshore wind power market has broad space and promising prospects (Xu et al. 2019). Facing the fierce market competition, China's offshore wind power should take "innovation" as the core and "cost reduction" as the goal, so as to better adapt to the current development of offshore wind power (Ji et al. 2019).

China is the world leader in wind energy, producing more than a third of the world's capacity (Nazir et al. 2020a). But the research on the influencing factors of offshore wind power industry is very scarce. Based on the above four aspects, the 14 influencing factors of this paper are identified from literatures and expert interviews.

Development status of offshore wind power

International situation

At present, the total capacity of global offshore wind power exceeds 35 GW, increasing by 106% in the past 5 years. In 2020, the new installed capacity of global offshore wind power exceeded 6 GW, which was second only to that in 2019. As shown in Fig. 1, China's offshore wind power has led the world for three consecutive years, with a new installed capacity of 3.06GW, accounting for 50.43% of the world's new installed capacity. Europe has maintained steady growth, accounting for most of the remaining new capacity. Specifically, the annual new capacity of the Netherlands is second only to China, reaching 1493 MW; Belgium (706 MW), the UK (483 MW), and Germany (237 MW) also have new capacity; the new floating offshore wind power installation is only from Portugal (17 MW). As shown in Fig. 2, the cumulative installed capacity of China's offshore wind power exceeds that of Germany, second only to the UK, becoming the second-largest offshore wind power market in the world.

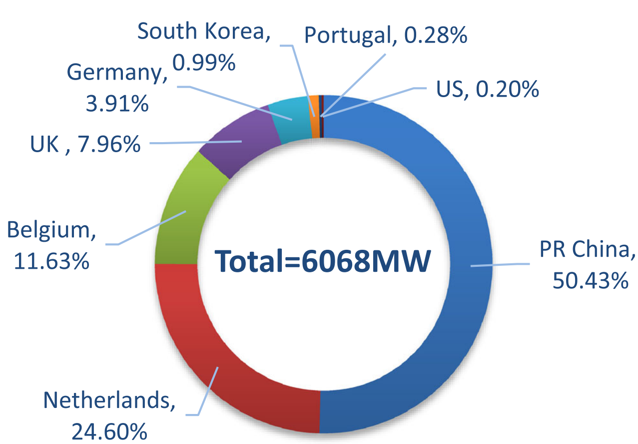


Fig. 1 Global annual offshore wind installations in 2020 (Data from Global wind report 2021 (Global Wind Energy Council (GWEC) 2021))

At present, Europe is still the largest offshore wind power market in the world, but the Asia Pacific region also pays more attention to offshore wind power. On December 15, 2020, Japan established the long-term goal of "10 GW by 2030 and 30-45 GW by 2040" for offshore wind power (CWEA 2020). South Korea announced that "by 2030, South Korea's offshore wind power scale will reach 12GW, striving to become one of the top five offshore wind power countries in the world" (European offshore wind power 2020). In addition, the Biden government actively seeks to develop the state and company of offshore wind power industry and also vigorously develop the offshore wind power industry of the USA (Mackenzie 2020).

Chinese situation

Figure 3 shows the installed capacity of offshore wind power in China from 2010 to 2020. Only in 2011 and 2013 did the annual new installed capacity decline. Since 2013, the annual new installed capacity has been growing. Especially in recent years, China's offshore wind power industry is developing rapidly.

COVID-19 has formed a large-scale spread in early 2020, and many industries have suffered from adverse effects. However, the global offshore wind power industry still maintains a sustained growth trend during the epidemic period.

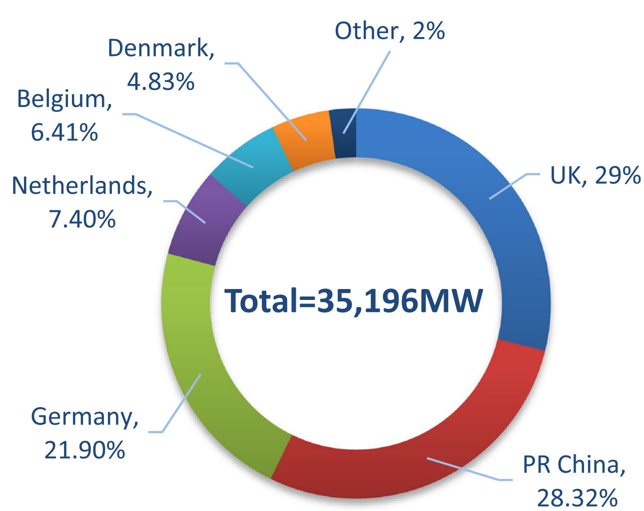
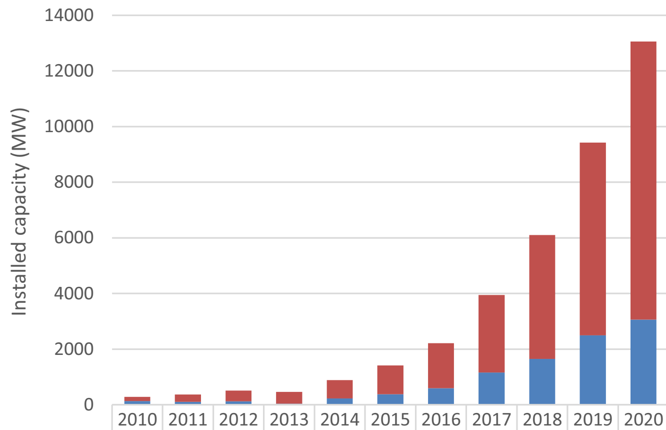


Fig. 2 Global cumulative offshore wind installations by end of 2020. (Data from Global wind report 2021 (Global Wind Energy Council (GWEC) 2021))



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Accumulated installed capacity	153	262	389	428	658	1035	1627	2788	4443	6936	9996
Newly added installed capacity	136	109	127	39	230	377	592	1161	1655	2493	3060

Fig. 3 China's offshore wind power capacity in 2010–2020. Note: The data on the newly added and cumulative installed capacity of China's offshore wind power in each year are all from the Global Wind Energy Report of the GWEC over the years (Global Wind Energy Council (GWEC) 2019, 2020, 2021)

China's offshore wind power industry is even less affected by the epidemic.

The Chinese government attaches great importance to the significance of offshore wind power. As shown in Table 1 (Xu et al. 2021), in order to encourage and guide the healthy and sustainable development of offshore wind power and realize energy structure adjustment, the state has issued a series of planning policies to provide support and guidance for the development of offshore wind power. From the perspective of electricity prices, China has also issued a series of policies. On June 5, 2014, the National Development and Reform Commission (NDRC) issued the "Notice on Offshore Wind Power Feed-in Tariff Policy," stipulating that offshore wind power projects which put into operation before 2017 (excluding 2017) had a feed-in tariff of 0.85 yuan/kWh, and the on-grid electricity price for projects in intertidal zone was 0.75 yuan /kWh. Since then, until 2019, in order to encourage the development of offshore wind power, the benchmark price of offshore wind power had remained unchanged. On May 21, 2019, the NDRC issued the "Notice on Improving the Policy for Wind Power Feed-in Tariffs." It is clear that "for offshore wind power projects approved before the end of 2018, if all units are connected to the grid before the end of 2021, the on grid price at the time of approval shall be implemented; for all units connected to the grid after 2022, the guiding price in the year of connection shall be implemented". To catch up with the feed in tariff deadline at the end of this year, China's offshore wind power construction boom is expected to continue in 2021.

Methodology

Warfield pioneered the ISM method in 1973 (Wang et al. 2020). Warfield explored the methodological questions of how frameworks of understanding and valuing could be developed for complex societal situations collectively. Warfield pointed out that the key dilemma in this exploration was that the rate of societal change was faster than the rate at which people can perform effectively in problem-solving and goal-setting situations. His explorations have yielded a way around this dilemma and an impressive theory of idea management (Warfield 1978). The basic theory of ISM is the reconstruction theory of graph theory, which belongs to static qualitative model. ISM has some limitations. First of all, there is no feedback loop between the levels, so we can only see the effect from the bottom to the top; second, the subjectivity is too strong, which depends on people's experience judgment to a certain extent, but this is also the inevitable disadvantage of all qualitative methods. However, compared with other quantitative methods, ISM still has irreplaceable advantages. It can present the fuzzy relationship with a clear structure model, so that people can more intuitively understand the complex relationship; and it is especially suitable for the system analysis with many variables, complex relationship between variables and unclear structure, and can also be used for the ranking of schemes. For example, "multiple regression" is a very classic method to study the relationship between variables. It can study the influence of a series of factors on a variable, but there is a certain subjectivity in the process of variable selection. In the face of many variables, "multiple regression" is very difficult to deal with. Some data are necessary but not available, which will make the "multiple regression" research unable to advance.

The interpretative structural model decomposes a complex system into several sub-system elements and constructs a multi-level hierarchical structure model by combining people's practice, knowledge and experience, and computer assistance (Jia 2020). Using interpretative structural model to analyze, we can find out the surface direct influencing factors, the middle indirect influencing factors, and the deep fundamental influencing factors from many influencing factors and

Table 1 Policy review of offshore wind power in China (Xu et al. 2021)

Theme	Name	Issuer	Year	Objectives	Reference
Electricity price	"Notice on the on-grid tariff policy for offshore wind power"	NDRC	2014	The on-grid tariff for offshore wind power projects put into operation before 2017 (excluding 2017) is 0.85 yuan per kilowatt-hour, and the on-grid tariff for intertidal wind power projects is 0.75yuan per kilowatt-hour. At the same time, it is encouraged to determine offshore wind power project development owners and feed-in tariffs through market competition methods such as concession bidding.	CWEA (2014)
	"Notice of the National Development and Reform Commission on Adjusting the Benchmarking On-grid Tariff of Photovoltaic Onshore Wind Power"	NDRC	2016	Offshore wind power benchmark tariffs will not be adjusted; prices determined by market competition methods such as bidding, the part within the benchmark on-grid tariffs (including desulfurization, denitrification, and dust removal tariffs) for local coal-fired units will be settled by the local provincial power grid; the part that exceeded will be settled by the state The Renewable Energy Development Fund provides subsidies.	NDRC (2016)
	"Notice on relevant requirements for wind power construction management in 2018"	NEA	2018	From the date of issuance of this notice, all offshore wind power projects with unidentified investment entities shall be allocated and determined on-grid power prices through competition. The provinces (autonomous regions and municipalities) that have issued the 2018 wind power construction plan and the offshore wind power projects that have determined the investment subject can continue to advance the original plan in 2018. From 2019 onwards, all provinces (autonomous regions, municipalities) offshore wind power projects should all be configured and determined on-grid tariffs through competition.	NEA (2018)
	"Notice on Actively Promoting the Work Related to Unsubsidized Parity of Wind Power and Photovoltaic Power Generation"	NDRC and NEA	2019	Policy-based cross-subsidies will be reduced or exempted for the nearby direct trade of renewable energy power that is included in the pilot project. Provincial-level power grid companies assume the responsibility of purchasing electricity for parity grid projects and low-price grid-connected projects, and sign long-term fixed-price electricity purchase and sale contracts with wind power and photovoltaic power generation project units (many in 20 years), such projects are not required to participate in electricity market-oriented transactions (except for nearby direct transaction pilots and distributed market transactions) according to the local coal-fired benchmarking grid tariffs set by the state at the time of project approval.	NDRC and NEA (2019)
	"Notice on Improving the On-grid Tariff Policy for Wind Power"	NDRC	2019	The benchmark on-grid tariff for offshore wind power will be changed to a guideline price. All newly approved offshore wind power projects will determine the on-grid tariff through bidding. For offshore wind power projects that have been approved before the end of 2018, if all units are connected to the grid before the end of 2021, the approval will be implemented If all units are connected to the grid in 2022 and beyond, the guidance price for the grid connection year will be implemented; the newly approved offshore wind power guidance price that meets the plan and is included in the fiscal subsidy annual scale management will be adjusted to 0.8 yuan/kWh in 2020. Adjusted to 0.75 yuan/kWh, the on-grid electricity price determined through	NDRC (2019b)

Table 1 (continued)

Theme	Name	Issuer	Year	Objectives	Reference
				competition for newly approved offshore wind power projects shall not be higher than the above-mentioned guide price.	
Planning	"Notice on the National Offshore Wind Power Development and Construction Plan (2014–2016)"	NEA	2014	There are 44 projects included in the National Offshore Wind Power Development and Construction Plan (2014–2016), with a total capacity of 10.53 million kilowatts, which should be approved within the validity period (2 years).	NEA (2014)
	"Thirteenth Five-Year Plan for Wind Power Development"	NEA	2016	During the 13th Five-Year Plan period, the construction of offshore wind power will be actively and steadily promoted, focusing on Jiangsu, Zhejiang, Fujian, Guangdong, and other provinces. By 2020, the scale of offshore wind power construction in the four provinces will reach more than 1 million kilowatts. The scale of wind power construction will reach 10 million kilowatts, and the cumulative grid-connected capacity will reach 5 million kilowatts or more.	(NEA 2016)
	"Administrative Measures for Offshore Wind Power Development and Construction"	NEA& State Oceanic Administration	2016	It puts forward specific requirements for the administrative organization and management and technical quality management for offshore wind power development planning, project approval, use of sea areas and islands, environmental protection, construction, and operation.	NEA, State Oceanic Administration (2016)
	"Industrial Structure Adjustment Guidance Catalog (2019 Edition, Draft for Comment)"	NDRC	2019	It is divided into three categories: encouraged, restricted, and eliminated type. There are 4 wind powers in encouraged type, namely wind power, and photovoltaic power generation complementary system technology development and application, 2.5 MW and above offshore wind turbine technology development and equipment manufacturing, offshore Wind farm construction and equipment manufacturing, gearboxes for wind power over 2.0 MW.	NDRC (2019a)
	"Notice on matters related to the construction of wind power and photovoltaic power generation projects in 2020 (draft for comments)"	Comprehensive Department of National Energy Administration	2020	Require provinces whose grid-connected capacity and start-up scale have exceeded the planned targets to suspend the competitive allocation and approval of offshore wind power projects in 2020, provinces mentioned above can consult the list of three types of projects that are publicly announced grid-connected projects by the end of 2020, construction by the end of 2020, and completion by the end of 2021, reasonably take control of the moves and timing, and organize construction in an orderly manner.	Comprehensive Department of National Energy Administration (2020)

complex factor chains (Xue and Liu 2008). The explanatory structure model plays an important role in system engineering, which is the middle part of the transition from conceptual model to quantitative model. It is widely used in systems that are difficult to quantify directly and has been successfully applied in risk management (Li et al. 2007), power demand (Xu et al. 2009), and other fields, and its modeling steps are as follows (Xu et al. 2009; Wang and Kang 2017; Mathiyazhagan et al. 2013; Xu and Zou 2020). The flow-process diagram of the ISM model is shown in Fig. 4.

Step 1: Determine the system factor set. Collect all the components related to the system, and classify and arrange them to form a set containing n elements, which is determined as the system factor set S, which is recorded as:

$$S = \{S_i | (i = 1, 2, \cdots, n)\} \tag{1}$$

Step 2: Establish a concept system. Associate each element in the system factor set with other (n-1) elements to judge whether there is a direct binary relationship between them, which can be expressed as:

$$a_{ij} = \begin{cases} 1 & (S_i \text{ has an effect on } S_j.) \\ 0 & (S_i \text{ has an effect on } S_j.) \end{cases} \tag{2}$$

0 (S_i has no effect on S_j)

Step 3: Form an adjacency matrix. Arranging all the direct binary relations to obtain an n-order matrix, which is called adjacency matrix A and expressed as $A = (aij)M \times N$.

Step 4: Calculate the reachability matrix. A is a direct binary relationship between elements. After transmission, some elements may establish an indirect influence relationship. Find out all the indirect transmission relationships and get the reachability matrix M, whose calculation formula is:

$$(A + I) \neq (A + I)^2 \neq \cdots \neq (A + I)^m = (A + I)^{m+1} = M \tag{3}$$

According to the operational rule of Boolean algebra, A is first added with identity matrix I, and then multiplied by itself. When the result of multiplication will not change again, the M obtained at this time is the reachability matrix.

Step 5: Hierarchical division. Find the reachable set P and antecedent set Q of all elements. If $P(S_i) \cap Q(S_i) = P(S_i)$, this element is a high-level element, the elements meeting this condition are of the same level, and so on, different hierarchical levels are obtained.

Step 6: Generate a hierarchical topology diagram. After the hierarchical division is completed, the directed connection graph is drawn, which can directly and clearly represent the hierarchical structure of the system.

The influencing factors of offshore wind power industry in China based on ISM model

Applicability analysis

There are three bases for using ISM method in this paper: (1) offshore wind power industry is a complex system involving cross knowledge of energy, economy, and other aspects. ISM

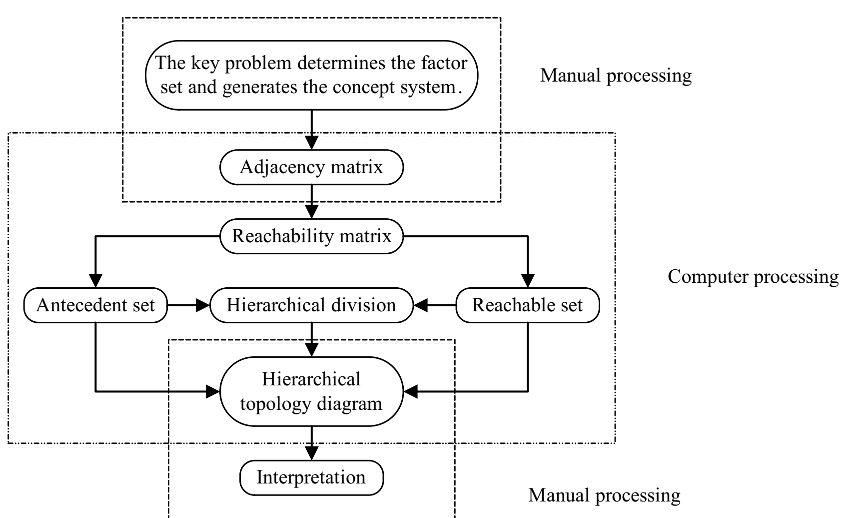


Fig. 4 Flow-process diagram of ISM model

is suitable for the interpretation and analysis of dynamic systems with many variables, complex relationships, and fuzzy structure. It can decompose a complex system into several subsystems with the help of researchers' practical experience and professional knowledge (Shen et al. 2021). (2) Offshore wind power industry is affected by many factors such as policy, technology, resources and environment, and market supply and demand. ISM can classify, identify, and select the key factors affecting offshore wind power industry, and deeply analyze the characteristics and hierarchical relationship of each key factor. (3) Compared with the empirical analysis of other influencing factors, ISM can continuously supplement the arguments according to the research progress, ensure the timeliness, strictness, and saturation of the data, and enhance the persuasiveness of the research conclusions (Liu 2017).

Determination of the influencing factors set

According to GWEC's data (GWEC 2021), in 2020, China's new installed capacity of offshore wind power reached 3060 MW, ranking the first in the world. The cumulative installed capacity reached 9996 MW, ranking the second in the world. China's offshore wind power has not only made great achievements in the installed capacity but also made a great breakthrough in technology. On July 12, 2020, China's first 10-MW offshore wind turbine was successfully connected to the grid for power generation at Three Gorges Group, Fujian Fuqing, Xinghua Bay Phase II offshore wind farm. The grid-connected power generation marks that China has independent design, research and development, manufacturing, installation, debugging, and operation capabilities of 10 MW large-capacity offshore wind turbines. It also marks a historic progress for China's wind power development capabilities and a great achievement in realizing the localization of major offshore wind power equipment (China Three Gorges Group Corporation 2020). In recent years, although China's offshore wind power industry has made great progress, it is still in the exploratory development stage, facing the constraints of policy, technology, environment, and market. There are still many problems to be solved. The site selection of offshore wind farm is a key step in the development of offshore wind power, which involves a lot of planning, and needs the coordination from provincial functional departments to local municipal government functional departments (Polaris wind power network 2018); offshore wind power and ecological environment are important factors for the location of wind farm. Wind turbine is the lifeblood of wind power generation. In the face of harsh marine environment, the reliability of wind turbine will be greatly reduced, resulting in high operation and maintenance costs of offshore wind power. Michiel et al. (2019) discovered that the cost of operation and maintenance stage accounts for about 30% of the total cost of offshore wind power generation. This has greatly hindered the large-scale development of offshore wind power industry. From the perspective of the industrial chain, there is no obvious difference between offshore wind power and onshore wind power, which can be divided into three parts from bottom to top: wind farm operation, wind turbine manufacturing and wind turbine parts manufacturing (China Investment Advisory Network 2018). The operation of the industrial chain has a great impact on the development of the whole offshore wind power industry: the operation of wind farms is affected by policy factors, and it also has a direct impact on the cost of power generation; wind turbine manufacturing is affected by policy factors and R&D input costs, and controlling the cost of wind turbine manufacturing technology is the key to reduce the cost of offshore wind power generation.

There are many and complex factors influencing offshore wind power industry, which are affected by economic development, policy situation, technological innovation, resource environment, market supply and demand, etc. In this paper, through literature retrieval method, the factors that can affect offshore wind power are obtained, and then through expert consultation method, the influencing factor set is further determined, including 14 factors: development planning, on-grid electricity price, economic incentive policy, environmental protection policy, operation mechanism, operation management, offshore wind power technology, offshore wind resource supply, site selection, power generation cost, R&D investment, industrial chain, energy market mechanism, investment, and financing mechanism. The direct binary relationship among the influencing factors is shown in Table 2.

Adjacency matrix and reachability matrix

The 14 influencing factors listed in Table 2 and their direct binary relations are expressed by formula (2), and a matrix A of 14×14 is obtained, which is the adjacency matrix of the influencing factor set, as shown in Table 3.

Run the program after inputting the adjacency matrix in Matlab2018a software. When iterating for five times, the matrix reaches a stable state, then exit the loop and get the reachability matrix, arrange the reachability matrix in ascending order according to rows, adjust the column direction accordingly, and divide the hierarchy to get the reachability matrix with clear hierarchy, as shown in Table 4.

Results and discussions

Matrix decomposition results

Hierarchical decomposition is based on the analysis of antecedent set, reachable set, and their intersection set. The antecedent set Q is the set of factors that can influence S_i through direct or indirect conduction. Reachable set P is the set of

Table 2 List of factors affecting the development of China's offshore wind power industry

Category	Influence factor	Serial number	Feature description	Direct influencing factors
Policy formulation	Development planning	S_1	Refers to the plans and arrangements made by governments at all levels and relevant institutions for China's offshore wind power industry. Including industrial layout, technology research and development, key project construction, safeguard measures, etc.	S_3, S_6, S_{12}
	On-grid tariff	S_2	Refers to the measured price when the power grid purchases the power of the power generation enterprise and the electricity quantity is connected to the main grid. The benchmark on-grid tariff of offshore wind power in China is now the guide price, and the newly approved on-grid tariff is determined through competition.	S_6, S_{12}
	Economic incentive policy	S_3	Refers to a series of economic policies and measures implemented by the government to promote and guarantee the development of offshore wind power. It mainly includes financial subsidies, investment credit concessions, tax concessions for value-added tax (VAT) and income tax reduction and exemption, etc.	S_{14}
	Environmental protection policy	S_4	It refers to a series of economic policies and measures implemented by the government to realize ecological civilization and sustainable development. It has a certain impact on the energy consumption structure.	S_7, S_{11}
	Operating mechanism	S_5	This refers to the general name of some international and domestic systems and activities closely related to the development of offshore wind power. It mainly includes clean development mechanism (CDM), carbon emission trading mechanism, renewable energy quota trading mechanism and its supporting green certificate trading mechanism, etc.	
Technical management level	Operations Management	S_6	The general term for the management of the planning, organization, implementation, and control of the whole operation process of offshore wind power projects. Including site selection in the early stage of power generation project, equipment selection, operation after production, etc.	S_{10}, S_{12}
	Offshore wind power technology	S_7	Refers to the related technologies of offshore wind power industrialization, involving piling and installing wind turbines, wind resources storage, and other links.	S_{10}, S_{13}
Resource and environment level	Supply of offshore wind resources	S_8	Refers to the available energy of offshore wind resources for offshore wind power generation.	S_9
	Site selection	S_9	Refers to the site selection of offshore wind farms, which needs to consider wind resources, power generation costs, technical difficulties, and other issues.	S_6
	Power generation cost	S_{10}	Refers to the cost generated in the process of electric energy production, which is mainly composed of fixed assets investment cost and management operation cost.	S_3
	R&D investment	S_{11}	Refers to the input cost of research and development of offshore wind power-related technologies. It reflects the core competitiveness of offshore wind power industry and is influenced by macro-economy.	S_7, S_{10}
Market supply and demand level	Industrial chain	S_{12}	It consists of wind resources supply, related wind turbines, power generation equipment supply, power generation enterprises, and downstream power grid enterprises.	S_{13}
	Energy market mechanism	S_{13}	Refers to the mechanism by which China's energy resources are allocated through market competition. It mainly consists of supply, demand mechanism, price formation mechanism, competition mechanism, and risk mechanism.	S_{12}, S_{14}
	Investment and financing mechanism	S_{14}	Refers to the investment and financing mechanism for offshore wind power industry or enterprise. Offshore wind power involves many factors, large investment scale, and high investment risk.	S_3, S_{12}

Note: The influencing factors in this paper are sorted out according to the literatures (Xu et al. 2009; Wang and Kang 2017; Luo et al. 2016) and investigation and interview

Table 3 Adjacency matrix *A*

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
S_1	0	0	1	0	0	1	0	0	0	0	0	1	0	0
S_2	0	0	0	0	0	1	0	0	0	0	0	1	0	0
S_3	0	0	0	0	0	0	0	0	0	0	0	0	0	1
S_4	0	0	0	0	0	0	1	0	0	0	1	0	0	0
S_5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_6	0	0	0	0	0	0	0	0	0	1	0	1	0	0
S_7	0	0	0	0	0	0	0	0	0	1	0	0	1	0
S_8	0	0	0	0	0	0	0	0	1	0	0	0	0	0
S_9	0	0	0	0	0	1	0	0	0	0	0	0	0	0
S_{10}	0	0	1	0	0	0	0	0	0	0	0	0	0	0
S_{11}	0	0	0	0	0	0	1	0	0	1	0	0	0	0
S_{12}	0	0	0	0	0	0	0	0	0	0	0	0	1	0
S_{13}	0	0	0	0	0	0	0	0	0	0	0	1	0	1
S_{14}	0	0	1	0	0	0	0	0	0	0	0	1	0	0

factors that can be reached by conducting S_i directly or indirectly (Wang et al. 2017). According to the *M*, the reachable set *P*, antecedent set *Q*, and their intersection set are shown in Table 5.

Directed graph of hierarchical structure

Enter the reachability matrix in Matlab2018a and run the program, and the hierarchical decomposition can be calculated as shown in Table 6. Hierarchical division is to better understand the hierarchical relationship between various factors in the system and the influence degree of each factor. The top-level represents the ultimate goal of the system, and the lower level is the reason for the upper level. The bottom factors are the root cause of system motion.

Table 4 Reachability matrix *M*

	S_3	S_5	S_{12}	S_{13}	S_{14}	S_{10}	S_6	S_7	S_1	S_2	S_9	S_{11}	S_4	S_8	
S_3	1	0	1	1	1	0	0	0	0	0	0	0	0	0	1
S_5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
S_{12}	1	0	1	1	1	0	0	0	0	0	0	0	0	0	
S_{13}	1	0	1	1	1	0	0	0	0	0	0	0	0	0	
S_{14}	1	0	1	1	1	0	0	0	0	0	0	0	0	0	
S_{10}	1	0	1	1	1	1	0	0	0	0	0	0	0	0	2
S_6	1	0	1	1	1	1	1	0	0	0	0	0	0	0	3
S_7	1	0	1	1	1	1	0	1	0	0	0	0	0	0	
S_1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	4
S_2	1	0	1	1	1	1	1	0	0	1	0	0	0	0	
S_9	1	0	1	1	1	1	1	0	0	0	1	0	0	0	
S_{11}	1	0	1	1	1	1	0	1	0	0	0	1	0	0	
S_4	1	0	1	1	1	1	0	1	0	0	0	1	1	0	5
S_8	1	0	1	1	1	1	1	0	0	0	1	0	0	1	

Establishment and analysis of ISM

It can be seen from the hierarchical structure model (Table 6 and Fig. 5) that the influencing factors of offshore wind power industry can be divided into five levels.

First, all the influencing factors ultimately point to five factors: economic incentive policy (S_3), operation mechanism (S_5), industrial chain (S_{12}), energy market mechanism (S_{13}), and investment and financing mechanism (S_{14}) through different ways and means. Therefore, these five factors are the direct causes affecting the offshore wind power industry, which are surface factors. Compared with other renewable energy sources, the generation cost of offshore wind power is higher and the development is more difficult, which leads to greater investment risks. In this case, the economic incentive policies composed of financial subsidies, tax incentives, electricity price subsidies, and investment incentives, as well as the operation mechanism composed of clean development mechanism, carbon emission trading mechanism, renewable energy quota trading mechanism, and its supporting green certificate trading mechanism are particularly important to ensure the operation and promotion of offshore wind power industry. This is also a significant "high push" effect. The decision-making of the state and relevant departments determines the implementation and resource allocation of offshore wind power industry. Economic support directly stimulates industrial development, and operation mechanism is the driving force of industrial development. In addition, industrial chain, energy market mechanism, investment, and financing mechanism also have a direct impact on the development of offshore wind power industry. The supply and demand of the market is the best signal for the development of offshore wind power industry. Good market supply and demand relationship

Table 5 Table of reachable set, antecedent set, and their intersection set

S_i	$P(S_i)$	$Q(S_i)$	$P(S_i) \cap Q(S_i)$
S_1	1,3,6,10,12,13,14	1	1
S_2	2,3,6,10,12,13,14	2	2
S_3	3,12,13,14	1,2,3,4,6,7,8,9,10,11,12,13,14	3,12,13,14
S_4	3,4,7,10,11,12,13,14	4	4
S_5	5	5	5
S_6	3,6,10,12,13,14	1,2,6,8,9	6
S_7	3,7,10,12,13,14	4,7,11	7
S_8	3,6,8,9,10,12,13,14	8	8
S_9	3,6,9,10,12,13,14	8,9	9
S_{10}	3,10,12,13,14	1,2,4, 6,7,8,9,10,11	10
S_{11}	3,7,10,11,12,13,14	4,11	11
S_{12}	3,12,13,14	1,2,3,4,6,7,8,9,10,11,12,13,14	3,12,13,14
S_{13}	3,12,13,14	1,2,3,4,6,7,8,9,10,11,12,13,14	3,12,13,14
S_{14}	3,12,13,14	1,2,3,4,6,7,8,9,10,11,12,13,14	3,12,13,14

Table 6 Hierarchical decomposition of factors

Hierarchy	Influencing factor
First level	S_3, S_5, S_{12}, S_{13}, S_{14}
Second level	S_{10}
Third level	S_6, S_7
Fourth level	S_1, S_2, S_9, S_{11}
Fifth level	S_4, S_8

can make the offshore wind power industry maintain sustainable and stable development.

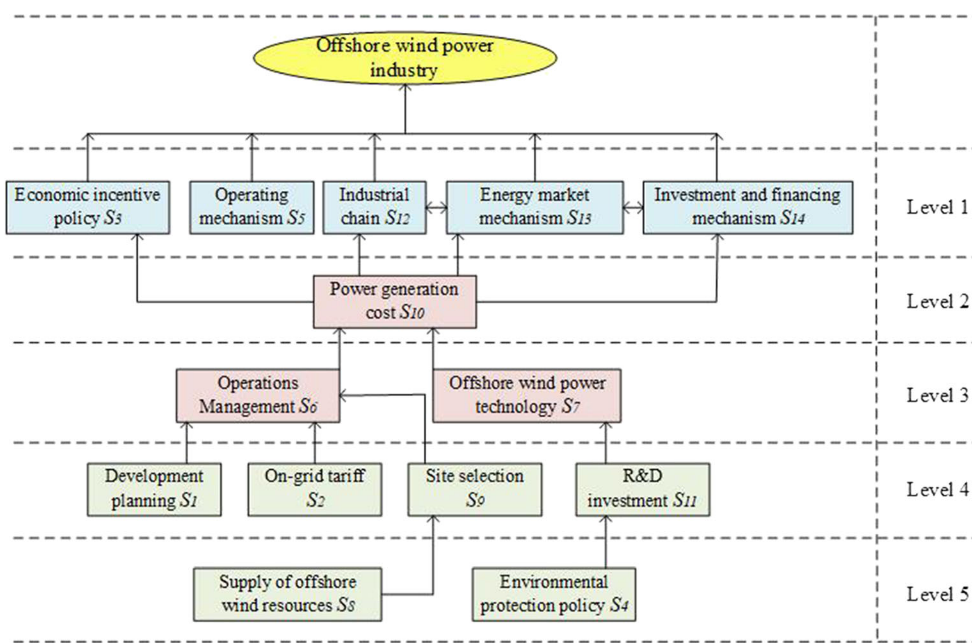
Secondly, three factors, namely, power generation cost (S_{10}), operation management (S_6) and offshore wind power technology (S_7), are intermediate factors. Among them, operation management and offshore wind power technology are important factors that affect the supply of offshore wind power. The level of professional technology and operation management determine the development quality of the supply side of offshore wind power industry. And power generation cost is an important factor that affects the demand of offshore wind power. The higher the generation cost, the higher the electricity price. And high electricity prices will lead to a reduction in demand. On the other hand, if the offshore wind power project can achieve better operation and management and make continuous progress in offshore wind power technology, it will definitely reduce the power generation cost of offshore wind power, thus better developing the offshore wind power industry.

Thirdly, development planning (S_1), on-grid electricity price (S_2), site selection (S_9), R&D investment (S_{11}), environmental protection policy (S_4), and offshore wind resources supply (S_8) are all deep-seated factors affecting offshore wind power industry. Development planning policy and environmental protection policy affect the layout and progress of the whole offshore wind power industry. Development planning policy helps to promote the offshore wind power industry in an orderly manner, while environmental protection policy can play a very good incentive role for the offshore wind power industry. The supply of offshore wind resources determines the site selection, and it is also a necessary condition for the development of offshore wind power industry. But this factor is often ignored. Therefore, the assessment of offshore wind resources should be paid more attention. The input cost of R&D is a part of the total cost, which is an indispensable financial support for technology improvement. At the same time, it affects the grid price.

Conclusions

As a kind of green energy, offshore wind power industry has made great achievements in recent years and stands out in renewable energy. Due to the abundant offshore wind energy resources, there is of great development potential for offshore wind power. However, the offshore wind power industry has encountered new bottlenecks, so it is necessary to deeply analyze the influencing factors of offshore wind power industry development. ISM model is a method to analyze the hierarchical relationship between influencing factors. Firstly, the influencing factor set of offshore wind power industry must be determined. Offshore wind power industry is affected by many factors, such as economic development, policy situation, technological innovation, resource environment, and

Fig. 5 Hierarchical topology diagram of influencing factors of offshore wind power industry



market supply and demand. Through literature search and expert consultation, 14 influencing factors were identified. By analyzing the 14 factors with the ISM model, these factors can be divided into five levels. Among them, the factors in the first level classified as the surface factors, including economic incentive policy (S_3), operation mechanism (S_5), industrial chain (S_{12}), energy market mechanism (S_{13}), and investment and financing mechanism (S_{14}). The factors in the second and third level classified as the intermediate factors, including power generation cost (S_{10}), operation management (S_6), and offshore wind power technology (S_7). The factors in the fourth and fifth level classified as the deep-seated factors. They include six factors: development planning (S_1), on-grid electricity price (S_2), site selection (S_9), R&D investment (S_{11}), environmental protection policy (S_4), and offshore wind resources supply (S_8).

China's offshore wind power industry is now in a critical period of development. On the one hand, China's offshore wind resources are very rich, and offshore wind power has good ecological and social benefits, and offshore wind power occupies an irreplaceable absolute dominant position in renewable energy; On the other hand, offshore wind power still has some technical problems and inevitable uncertainties such as climate, which makes the economy of offshore wind power in renewable energy at a disadvantage. There are many factors affecting the development of offshore wind power industry, including objective environmental factors and artificial factors. The surface factors and deep-seated factors need to be paid close attention in order to clear the obstacles for the development of offshore wind power industry.

According to the influencing factors, the policy recommendations are shown as follow:

First, at the level of policy support, the policy system of offshore wind power industry should be improved. China's offshore wind power industry has not yet reached the mature stage, so the government needs to formulate corresponding supportive policies. The policies of offshore wind power industry should cover development planning, on-grid tariff, technology research and development, taxation, subsidies, investment and financing, etc. For example, in terms of technology research and development, increase research and development funds for key technologies such as offshore wind power generators, blades, and unit converters, or encourage key technology development by providing discount loans and establish subsidies for offshore wind power machinery purchase; another example is to further improve credit policies and increase preferential efforts in offshore wind power investment and financing; carry out rolling development planning, regularly check whether the plan is completed, and make timely and reasonable adjustments to the plan.

Second, at the level of technology management and resource environment, decision-makers should pay more attention to wind resources assessment and site selection; develop more offshore wind power projects suitable for construction, investment, and operation and stop projects with insufficient or extremely unstable wind resources in time; more attention should be paid to R&D investment of offshore wind power. Technology is the primary productivity of offshore wind power industry and plays a key role in the better development of offshore wind power.

Third, at the level of market supply and demand, government departments should guide the whole offshore wind power industry chain to develop healthily and encourage enterprises to invest and finance offshore wind power projects, so as to speed up the development of offshore wind power industry, and guide the supply and demand mechanism, price formation mechanism, competition mechanism and risk mechanism to ensure the large-scale and commercial promotion of offshore wind power industry.

Availability of data and materials All data generated or analyzed during this study are included in this published article.

Author contribution All authors contributed to the study conception and design. Data collection and analysis were performed by K.Y and G.Z. The first draft of the manuscript was written by Y.X and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was funded by the National Natural Science Foundation of China (71774105), Program for the Innovative Talents of Higher Education Institutions of Shanxi (PTIT), and Program for the Philosophy and Social Sciences Research of Higher Learning Institutions of Shanxi (2020W061). The authors would also like to acknowledge great thanks to anonymous reviewers for their valuable comments which largely improve the academic quality of this paper. The usual caveats apply.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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