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Offshore wind power policies and green total factor productivity: empirical evidence from coastal China

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Introduction: Green and high-quality development requires the transformation and upgrading the energy structure. As a clean and efficient new energy, the development of offshore wind power is related to the achievement of green development and the realization of the dual carbon goals.

Methods: Based on the perspective of green total factor production, this study aims to explore the impact of offshore wind power policies (OWPPs) on green and high-quality development. Taking 11 coastal areas of China from 2004 to 2020 as samples, this paper empirically tested the impact of OWPPs on green total factor productivity (GTFP) by using propensity score matching difference-in-differences method (PSM-DID).

Results and discussion: The results show that OWPPs have a significant positive impact on GTFP. The robustness test further verifies the results, and the provincial difference is significant. By stimulating technological innovation and reducing energy intensity, OWPPs have improved GTFP, but increasing marketization level is a long way off.

KEYWORDS
offshore wind power policies, green total factor productivity, SBM-GML model, difference-in-differences, propensity score matching, green development

Highlights

- Scientifically investigating the causality between OWPPs and GTFP in costal China for the first time.
- SBM-GML model and more comprehensive indicators are used to measure GTFP.
- OWPPs have significantly promote the GTFP in the pilot regions, specifically by influencing the technology change component of the GTFP.
- Heterogeneity exists between the GTFP of OWPPs and the regions.
- Technological innovation and energy intensity are mechanisms, marketization level faces numerous challenges.

1 Introduction

Energy consumption caused by global economic growth is the main cause of environmental deterioration. In order to improve the energy structure, enhance environmental quality, and promote efficient energy production and green development are imperative (Acemoglu et al., 2012). Offshore wind power is a clean, efficient, and renewable source of energy that can effectively reduce carbon emissions (IRENA, 2018). By 2040, global investment in offshore wind energy is expected to reach one trillion US dollars, and the capacity of offshore wind power will increase by a factor of 15 (IEA, 2019). In the context of "Marine potestatem" and "Dual carbon", OWPPs have emerged in an endless stream. The concepts of green, low-carbon, clean, and others have been repeatedly emphasized. A range of interventions, including administrative controls, development planning, pricing and tax policies, spatial planning, and scientific research support (Liu et al., 2023), have been implemented to promote green transformation and development. It will count much in future policy decisions to understand the relationship between OWPPs and green development in the past. The year 2012 was crucial to the development of OWPPs in China. During that year, the central government emphasized, in March, July, and September, the importance of following the principles of deep-sea offshore layout, providing scientific demonstration and planning for offshore wind power, expediting the construction of offshore wind power bases, and acknowledging the important contribution of the offshore wind energy industry to the development of new energy. It was the macro-planning of OWPPs at a national level for the first time in China. With the guidance of macro planning, support measures began to be implemented. Firstly, the implementation of tendering for offshore wind power projects can promote the development of offshore wind power through market competition in the early stage of industry development, which helps to reduce the development costs and improve the development efficiency of offshore wind power (Xu et al., 2015). Secondly, the government provides certain financial support and tax relief for enterprises, which promotes the establishment of offshore wind power demonstration projects and provides experience and technical support for the commercial development of offshore wind power (Wei et al., 2014). Additionally, by improving wind power equipment standards and industrial monitoring systems, the government encourages technological innovation in offshore wind power and energy system reform, which is also conducive to the development and maturity of China's offshore wind power technology.

According to Lokshin and Mohnen (2012) and Jin et al. (2018), government subsidies are designed to encourage companies to develop green technology, and in the case of offshore wind power, price setting is an important element of the policy system. In 2014, the government formulated the feed-in tariff for offshore wind power non-tendered projects, and offshore wind power entered the era of centralized subsidies. With national subsidies, the net present value and internal rate of return of offshore wind power plants are high, thereby reducing oil imports, carbon dioxide emissions, and external costs during operation, resulting in substantial social and economic effects (Zountouridou et al., 2015). Nevertheless, excessive financial subsidies will hinder the progress of green technology and add to the government's financial burden. In May 2019, the government explicitly changed the benchmark on-grid electricity price of offshore wind power to a guidance price and all newly approved offshore wind power projects determined the on-grid electricity price through competition, marking the official entry of China's offshore wind power industry into the era of bidding, thus preparing for the exit of central subsidies in the future. The following year, China's Ministry of Finance, National Development and Reform Commission, and National Energy Administration jointly announced that, effective 2022, the central government would no longer subsidize new offshore wind power projects, in order to promote technological progress and achieve electricity parity. Under the coordinated effect of macro-policies and supporting measures, China's cumulative installed capacity of offshore wind power has exceeded 30 GW as of the end of 2022, ranking first globally. However, there is limited research that systematically evaluates the true benefits of OWPP development, especially in terms of green development. Therefore, the main focus of this article is to examine whether, and how, OWPP affects green development.

GTFP is an essential indicator to measure reginal green development. Numerous studies have proved that GTFP can correctly handle the relationship among economic development, resource utilization, and environmental protection (Chen and Golley, 2014; Song et al., 2018). This is an important path to sustainable development and green economic development (Chen et al., 2018). Current studies on GTFP focus on three categories: technological flows, economic flows, and government information flows (Zhang et al., 2021). Research on its influencing factors mainly focused on technological progress (Zhang, 2015; Wang, 2017), environmental regulations (Lei and Wu, 2019; Cao et al., 2020), market allocation (Zhang et al., 2019), production factors (Männasoo et al., 2018; Rath et al., 2019), industrial structures, and economic development models (Li and Lin, 2017), etc. Technological innovation is positively correlated with GTFP (Du and Li, 2019), which makes the frontier of green production shift outwards, improves output efficiency, promotes the development of energy saving and emission reduction technologies, and thus promotes the coordinated development of economy and environment (Cheng et al., 2018). Implementing this approach is vital for countries globally to achieve energy efficiency, environmental sustainability, and green development (Shao et al., 2021; Sun et al., 2021). Industrial structure upgrading and diversification also contribute to pollution reduction and industrial innovation (Eswaran and Kotwal, 2002; Zhang et al., 2014; Dong et al., 2020), and improve GTFP across the board. At the same time, an appropriate level of economic development (Li and Liao, 2020), reasonable introduction of foreign investment(Xu et al., 2019), and and improvement of marketization (Li and Gao, 2016) are also conducive to the improvement of GTFP. Generally low technical proficiency (Zhang, 2021), inefficient environmental management (Shao et al., 2016), irrational industrial structures (Feng et al., 2019), and and blind introduction of foreign capital (Naz et al., 2019) threaten high-quality green development. In the past decade or so, China has grown from scratch to become the world leader in offshore wind power development, and economic development has gradually abandoned the "GDP-only theory". However, no research has been devoted to exploring the relationship between OWPPs and GTFP, and it remains unclear whether OWPP contributes to GTFP in terms of innovation, as well as energy and marketization aspects. As an important part of renewable energy, OWPPs will obscure the actual benefits of China's sustainable development policy if it does not deeply explore the impact of OWPPs on GTFP. Therefore, this paper uses panel data covering 11 coastal regions in China from 2004 to 2020, and SBM-DEA model and global Malmquist-Luenberger productivity index (GML) are used to measure GTFP. With more comprehensive indexes are selected from the non-expected output, green development measured more scientifically. Applying the PSM-DID method to integrate OWPPs and GTFP into a unified analytical framework, the green development effect of OWPPs and its mechanism are explored to provide meaningful suggestions for the development of the offshore wind power industry, which in turn contributes to the world's green and low-carbon production.

This study has several main contributions: first, the result add to the important literature on the green development benefits of OWPPs (Gibbs and Jensen, 2022). In particular, new empirical evidence is provided for uncovering the value of GTFP in OWPPs, as GTFP is considered to be an important component of sustainable development (Lyu et al., 2023; Lee and Lee, 2022).

Second, to the best of our knowledge, so far, the green development effects of OWPPs have not been systematically and critically examined in China. There is no doubt that OWPPs are key policies for green transformation (Poulsen and Lema, 2017). While there are many energy and environmental science studies with a focus on OWPPs in China (Tu et al., 2021; Chen et al., 2023), economics studies focusing on OWPPs are rare. The approach taken in this study can be effectively applied to assess the impact of traditional energy and environmental policies.

Third, the mechanisms through which OWPPs take effect are identified as promoting the technological innovation and reduce energy intensity (Shi et al., 2023; Fan et al., 2022), while to promote the level of marketization faces challenge, this study has employed more rigorous methodologies to support this perspective. Furthermore, new ideas for comprehending how to better exploit the positive externalities of OWPPs are provided from a regional perspective, which is significant for the development of offshore wind power in emerging economies.

2 Research hypothesis

The impact of government on the progress of green technology is significant, and the policy environment is crucial for its development (Chava et al., 2013; Feng and Li, 2021; Yu and Cai, 2021). There are two guiding policies for green development. First, general policies, including government subsidies policies (Aerts and Schmidt, 2008) and government support policies (Doh and Kim, 2014; Guo et al., 2016). Second, pilot policies, including carbon trading pilot policies (Chen et al., 2021; Du et al., 2021; Liu et al., 2021), low-carbon city (Tian et al., 2021), and smart city pilot policies (Bundgaard and Borras, 2021). Compared with these pilot policies, the guidance principles and goals of OWPPs are more focused on energy conservation and emission reduction and green innovation, which may have a more profound impact on green development. Previous research on the essential topic of offshore wind power and green development has mainly focused on the field of energy and environmental engineering science. Poulsen and Lema (2017) took the offshore wind energy industry in China and Europe as examples and identified its role in the green transition through life cycle analysis. Zhang and Wang (2022) reviewed the development of offshore wind power generation and offshore wind turbine basic technologies in China, and proposed that more use of offshore wind power generation may be one of the solutions for energy saving and sustainable environment in the long run. The application of new turbines has made wind energy more promising, competitive and cleaner (Rashedi et al., 2012). However, OWPPs research based on economic perspective is still lacking. In spite of some studies have focused on the economic aspects of green development of offshore wind power (Wieczorek et al., 2013; Shah et al., 2021; Jang et al., 2022), the assessment of green development effects is still one-sided. Therefore, this study adopts an index to comprehensively measure green development, namely GTFP, to directly reflect the green development effect of OWPPs.

OWPPs have policy and technological innovation attributes with Chinese characteristics. As it belongs to the national macro-policy, it fully reflects macro-target orientation of the central government's and the initiative of local governments in the pilot process. At the same time, with green low-carbon and technological innovation as the pilot principle of policy construction, under the guidance of the central government, local governments actively try and fuly mobilize the green development incentive mechanism of local officials. The series of measures and policy subsidies of offshore wind power promoted by pilot policies are expected to effectively stimulate the vitality of green high-quality development and improve GTFP. Therefore, this paper proposes the following hypothesis:

Hypothesis 1. The adoption of OWPPs would promote GTFP

Innovations in wind power have two externalities: knowledge spillover and cleanliness, which can reduce firms' innovation initiative (Khan et al., 2019) and encourage them to continuously invest in existing knowledge and technologies rather than exploring new solutions (Zhao et al., 2020). Considering the high risks of wind power innovation, supportive policies can offset R&D costs and reduce firms' risk perception (Wang et al., 2020). The long-term support measures of OWPPs have increased wind power enterprises' revenue estimates and improved their enthusiasm for developing new products, technologies, and ideas (Zhao et al., 2020). With the continuous advancement of offshore wind power technology, the central government is gradually reducing subsidies for offshore wind power until complete withdrawal. Therefore, wind power companies need to enhance technological innovation within a limited timeframe, expand the frontier of green production, improve output efficiency, and quickly respond to the relative increase in operating costs in the short term. This helps to increase the supply of clean energy, reduce air pollution, alleviate environmental pressure through agency costs (Lacerda and Bergh, 2020), and thereby improve GTFP. Based on this, this paper proposes the following hypothesis:

Hypothesis 2. The promotion of GTFP is realized by the effect of OWPPs on the technological innovation

With the enhancement of economic viability, the development of marketization has become an inevitable trend for offshore wind power. The project development and management mechanism centered on market competition can effectively promote technological progress and cost reduction, stabilize investment returns (Zhang, 2021). The participation of renewable energy in market trading mechanisms is also beneficial for breaking down market and administrative barriers, expanding the scale of green electricity transactions, and fully reflecting the environmental value of renewable energy. It has been revealed that effective market mechanisms and well-crafted regulations are capable of significantly promoting the total factor productivity of industries as stated by Zhang and Du (2020). However, from the perspective of the input indicators of GTFP, the decrease in offshore wind energy costs has also reduced the electricity cost for high energy consuming enterprises in the region, thereby improving their profit margin. This induces the allocation of capital, labor and other production factors to high energy consuming industries to some extent, and promotes the trend of blind investment expansion in high energy consuming industries, which weakens the role of the market in promoting green production. Furthermore, the "pollution sanctuary effect" in China may inhibit GTFP growth, as mature markets make firms more competitive and reckless in scaling up (Andersen, 2017), generating more energy consumption and pollution emissions in the process. Thus, the influence of marketization level on GTFP is unclear and worth investigating. Based on the above analysis, this paper proposes the following hypothesis:

Hypothesis 3. OWPPs can enhance the level of marketization which in turn increases GTFP

Offshore wind power is an effective means of achieving a low-carbon energy transition (Hof et al., 2020; Chang et al., 2021), and is one of the most preferred technologies for achieving low carbon energy transition (Roberts et al., 2018; Devine-Wright and Wiersma, 2020). Offshore wind power plays a crucial role in lowering energy intensity. On one hand, offshore wind energy utilization can reduce reliance on traditional energy sources such as coal and oil (Li et al., 2022), and it has the characteristics of renewable, clean, low-carbon, and environmental protection, which can improve the energy structure and increase energy utilization efficiency, thereby reducing total energy consumption (Normann, 2017; van der Loos et al., 2020). On the other hand, developing offshore wind power is conducive to achieving the transformation and upgrading of the economic structure in coastal areas, driving the development of high-end equipment manufacturing industry, and promoting the sustainable growth of the marine industry economy (Velenturf, 2021). Therefore, the energy effect of offshore wind power is quitely consistent with the expected direction of the input and output indicators of GTFP, which is conducive to reducing environmental pollution and promoting the improvement of GTFP. In summary, this article proposes the following hypothesis:

Hypothesis 4. OWPPs reduce the energy intensity and then raise GTFP

3 Methodology

3.1 Measurement of GTFP

The calculation of traditional total factor productivity (TFP) rarely considers resource and environmental constraints as well as non-radial and non-angular issues in the model, and there are also shortcomings such as linear programming infeasibility and non-transferability in ML index. In light of the limitations of existing studies, this paper builds upon the ideas presented by Oh (2010) and Zhao et al. (2022), adopting the SBM-DEA model and the GML index to accurately and dynamically measure regional GTFP. Based on the application of SBM directional distance function, the efficiency measurement error caused by ignoring non-radial relaxation variables can be effectively avoided.

First, we construct a global production possibility set. The K province is regarded as the DMU_K, and it is assumed that the DMU_K adds N elements to inputs $x=(x_1,\ldots,x_n)\in R_N^+$ to obtain M expected outputs $y=(y_1,\ldots,y_n)\in R_M^+$ and I kinds of undesirable outputs $b=(b_1,\ldots,b_n)\in R_I^+$, then the input and output of the DMU_K stage t are expressed as (x_k^t, y_k^t, b_k^t), and the global production possibility set $P^G(x)$, which emphasizes consistency and comparability of production frontiers, is expressed as:

$$P^G(x) = \left\{ \begin{array}{l} (y^t, b^t): \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t \geq y_{km}^t, \forall m;\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t = b_{ki}^t, \forall i; \\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t \leq x_{kn}^t, \forall n;\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t = 1, z_k^t \geq 0, \forall k \end{array} \right\} \tag{1}$$

Where z_k^t is the weight assigned to each cross-section. If z_k^t is greater than or equal to zero, it indicates constant returns to scale, and if $\sum_{k=1}^{K} z_k^t = 1, z_k^t \geq 0, \forall k$, it indicates variable returns to scale.

Secondly, drawing on the research of Yang et al. (2015) this paper defines the global SBM directional distance function that accounts for non-expected outputs as follows:

$$\begin{gathered} \vec{S}_V^G(x_{k'}^t, y_{k'}^t, b_{k'}^t; g^x, g^y, g^b) = max \frac{\frac{1}{N}\sum_{n=1}^{N}\frac{S_n^x}{g_n^x} + \frac{1}{M+1}\left(\sum_{m=1}^{M}\frac{S_m^y}{g_m^y} + \sum_{i=1}^{1}\frac{S_i^b}{g_i^b}\right)}{2} \\ s.t. \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^t, \forall n \\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^t, \forall m \\ \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \forall i \\ \sum_{k=1}^{K} z_k^t = 1,\ z_k^t \geq 0,\ \forall k; s_m^y \geq 0, \forall m; s_i^b \geq 0, \forall i \end{gathered} \tag{2}$$

Equation (2) involves direction vector (g^x, g^y, g^b), the elements of which respectively demonstrate the direction of the reduction of input, the increase of desired output, and the decrease of non-desired output. Slack variables (s_n^x, s_m^y, s_i^b) are also introduced, where the elements indicate the input redundancy, shortfall of the desired output, and excess of the non-desired output. Afterwards, we utilize the GML index for further evaluating the growth of GTFP.

$$GTFP_t^{t+1} = \frac{1 + \vec{S}_V^G(x^t, y^t, b^t; g^x, g^y, g^b)}{1 + \vec{S}_V^G(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b)} = EC_t^{t+1} \times TC_t^{t+1} \tag{3}$$

$$EC_t^{t+1} = \frac{1 + \vec{S}_V^t(x^t, y^t, b^t; g^x, g^y, g^b)}{1 + \vec{S}_V^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b)} \quad (4)$$

$$TC_t^{t+1} = \frac{1 + \vec{S}_V^G(x^t, y^t, b^t; g^x, g^y, g^b)/1 + \vec{S}_V^t(x^t, y^t, b^t; g^x, g^y, g^b)}{1 + \vec{S}_V^G(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b)/1 + \vec{S}_V^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; g^x, g^y, g^b)} \quad (5)$$

Where $\vec{S}_V^G(x^t, y^t, b^t; g^x, g^y, g^b)$ and $\vec{S}_V^t(x^t, y^t, b^t; g^x, g^y, g^b)$ represent the SBM directional distance function, which are constructed based on the surface of the global frontier and the current period frontier, respectively. A GTFP index >1 indicates an increase in GTFP; a GTFP value <1 indicates a decrease in GTFP, and a value of 1 signifies stable GTFP. The two components of GTFP are efficiency change (*EC*) and technology change (*TC*), which change in the same way as GTFP.

3.2 DID method

To address the endogeneity issue, we utilize panel data from 11 coastal provinces in China from 2004 to 2020, with 2012 as the policy turning point, and employ the DID method to examine the causal relationship between OWPPs and GTFP. In view of the time differences in the implementation of OWPPs in coastal areas, it is necessary to consider the province and time fixed effects of regional samples. The model is formulated as follows:

$$\text{Ln}(GTFP_{it}) = \alpha + \beta OWPPs_{it} + \gamma Controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (6)$$

Specifically, the dependent variable, $\text{Ln}(GTFP_{it})$, represents the natural logarithm of the green total factor productivity of province i at time t. The constant term α is also included. The virtual variable, *OWPPs*, represents the offshore wind power policies pilots, while the estimation of the net impact of OWPPs implementation on GTFP in the pilot area is represented by β through difference-in-differences estimation. The control variable is denoted by "*Controls*". Provincial fixed effects are represented by μ, time fixed effects are represented by η, and the random disturbance term is represented by ε.

3.3 Mechanism test model

To further explore the impact mechanism of OWPPs on GTFP, this study takes into consideration the research conducted by Liu et al. (2020), Zhang (2021) and Ji and Tang (2022), the study selects technological innovation, marketization level, and energy intensity as mechanism variables to examine the extent to which OWPPs impact GTFP through these mechanisms. Considering the application bias of the mediating and moderating effects model (Jiang, 2022), and referring to the majority of the literature's mechanism testing approach, the mechanism test model of this papaer is established based on Equation (6):

$$M_{it} = \alpha_0 + \delta OWPP_{it} + \theta \text{Control}_{it} + \lambda_i + \tau_t + \xi_{it} \quad (7)$$

M_{it} is the matrix vector comprising mechanism variables, including technological innovation (Patent), marketization level (Mak), and energy intensity (EI), while λ_i and τ_t represent fixed effects of province and time, respectively. Furthermore, ξ_{it} is the random disturbance term, and the rest of the variables are consistent with Equation (6).

3.4 The proposed integrated model for impacts of OWPPs on GTFP

This study presents a research framework to investigate the influence of OWPPs on GTFP and its mechanisms based on the hypothesis and model settings from the previous section.The model proposed in this paper includes three components (Figure 1):

In Step 1, we measure GTFP using SBM-DEA and GML index, and consider OWPPs as a virtual variable.

In Step 2, we employ the DID method to investigate the impact of OWPPs on GTFP, and conduct robustness tests to ensure the accuracy of the estimation results. These tests include replacing the dependent variable, PSM-DID, parallel trend tests, and placebo tests.

Step 3 analyzes the mechanisms behind the impact of OWPPs on GTFP. To this end, we include three mechanism variables, namely technological innovation, marketization level, and energy intensity.

4 Data

4.1 Data sources

Considering the non-randomness of OWPPs implementation and the availability of data, we use panel data of 11 coastal provinces in China from 2004 to 2020. According to the cumulative installed capacity of offshore wind power in each province by the end of 2020, the 11 coastal provinces are classified into the experimental group: Jiangsu, Guangdong, Fujian, Liaoning, Zhejiang provinces and Shanghai city, while the control group was Hebei, Shandong, Guangxi, Hainan provinces and Tianjin city. At the same time, in order to eliminate the impact of inflation, all nominal indexes were based on 2004 and adjusted to constant prices according to the annual price indexes of each province. Carbon emission data was calculated according to IPCC. Other data sources used in this study comprise the China Statistical Yearbook, China Statistical Yearbook On Environment, China Energy Statistical Yearbook, as well as the CNRDS and Wind databases. We processed 11 valid provincial samples and obtained 187 valid "province-year" observations based on data availability.

4.2 Variables

4.2.1 Dependent variable

In order to calculate the GTFP, two types of indicators are required: inputs and outputs. Labor input is captured based on the number of employees at the end of the year in each province, capital

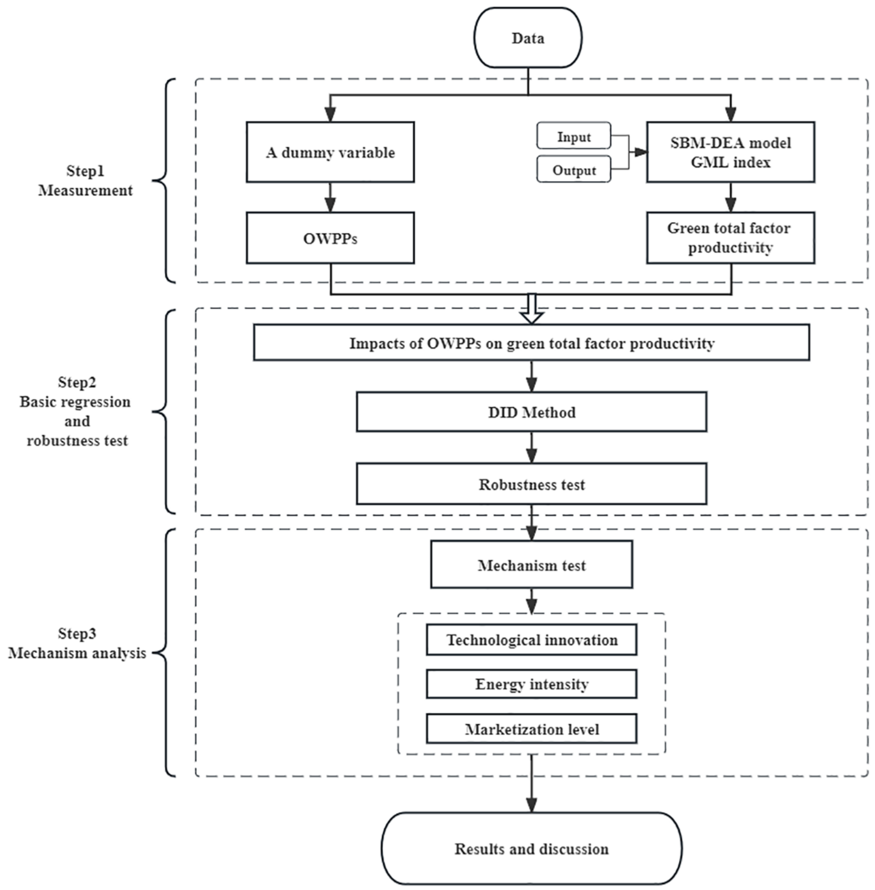

FIGURE 1
The proposed integrated model for impacts of OWPPs on GTFP.

input is estimated using the perpetual inventory method with reference to the work of Zhang (2008), and energy input is represented by the total energy consumption in each region. Two types of outputs were considered: expected output and unexpected output. Expected output was measured by the actual GDP of each province in 2004 after eliminating the price factors while unexpected output captures industrial wastewater, industrial sulfur dioxide, general industrial solid waste, and industrial dust emissions. To avoid the interference of reverse causal relationships on policy effect identification, the dependent variable was advanced by one period, given the use of the GML index to lose the base period sample, and the lag effect of policy. Additionally, to avoid the influence of extreme values and better comply with the assumptions of a classical linear model, the GTFP is log-transformed in the present study. The above treatment also applies to the decomposition term of GTFP – EC and TC.

4.2.2 Independent variable

The independent variable examined in this study is OWPPs, represented as a dummy variable. For reference (Xu et al., 2021), in conjunction with the focus of this research, among the 14 measures affecting the development of OWPPs, we selected the OWPPs as the first macro plan of basic policy (2012) to encode the independent variable, which is the deep factor affecting OWPPs. Specifically, the policy implementation year and the pilot areas in subsequent years are coded as 1, while other years are coded as 0.

4.2.3 Control variables

To control for the impact of OWPPs on GTFP, the present study supplements the core variables with other explanatory factors proposed by Wang and Liu, 2015 and Chen (2016), including the level of economic development, industrial structure, population density, human capital, environmental regulation, Internet development level, and foreign direct investment level. The level of economic development (LnGDP) is measured by the natural logarithm of GDP at constant prices. The industrial structure (IS) reflects the proportion of secondary industry, which consumes more energy, leads to more pollution, and results in a lower GTFP level in the region. In this study, the ratio of the value added of the tertiary industry to the secondary industry is used to measure the degree of industrial structure (Wu et al., 2023). Population density (LnPopd) is measured as the natural logarithm of the ratio of permanent population to administrative area. With the increase of population density, the demand for green development also increases due to the considerations of renewable resources and a cleaner environment. Furthermore, regions with higher population density tend to be more prosperous and better capable of promoting green development. The present study measures human capital (Edu) by the average years of schooling per capita. The accumulation of human capital can enhance public environmental awareness and accumulate innovative talents, which promotes GTFP improvement. The impact of environmental regulations (ER) on corporate performance has been debated. Two different perspectives prevail: "compliance costs" and "innovation compensation." The former believes that environmental regulations increase cost pressure on enterprises, having a negative impact on the long-term performance and productivity of enterprises (Dean and Brown, 1995). The latter believes that environmental regulations would induce companies to upgrade their technology, which is beneficial to enhancing environmental performance and productivity (Porter and van der Linde, 1995). Therefore, the impact of environmental regulations on GTFP needs rigorous validation, and the present study employs the ratio of industrial pollution control investment to industrial value-added introduced by Fan and Mu (2017) to measure environmental regulation. Moreover, Internet development level (Internet) is measured as the ratio of the number of internet users to the total population living in the region. Regions with advanced Internet technology can stimulate industry growth via the "Internet Plus" model, attract technical and innovative talents, and accelerate green and high-quality development. The present study measures foreign direct investment (FDI) as the ratio of foreign direct investment to GDP in RMB units using actual exchange rates. Two contradictory effects of foreign direct investment on GTFP exist: on one hand, it can introduce advanced production technology, promote enterprise production efficiency, and enhance GTFP growth; on the other hand, it may worsen pollution and undermine local environmental regulation through the transfer of high-energy-consuming and high-polluting enterprises.

4.2.4 Mechanism variables

In order to further study the influence mechanism of OWPPs on GTFP, three mechanism variables were selected in this paper combined with the previous research hypotheses. Referring to Ji and Tang (2022), we introduced energy intensity (EI) as a measure of the ratio between total energy consumption and actual GDP. In order to study the impact of technological innovation on GTFP more effectively, Patent outputs rather than R&D inputs are used in this paper to reflect the level of regional technological innovation (Brunel, 2019; Chen et al., 2021). The marketization level (Mak) was measured by NERI index (Fan et al., 2011).

Table 1 provides descriptive statistics of the primary variables.

5 Empirical results

5.1 Benchmark regression analysis

According to Hypothesis 1, this study employs the DID method to estimate the parameters in Equation (3), and Table 2 presents the benchmark regression outcomes. All six columns of the table consider control variables. Specifically, Columns (1), (3), and (5) control for provincial fixed effects, while Columns (2), (4), and (6) further adjust for time fixed effects. Based on the estimation outcomes in Column (2), after controlling for both-way fixed effects, the OWPPs have a significantly positive impact on GTFP at the 1% level. This indicates that if a region transits from non-OWPPs to OWPPs, its GTFP will increase by an average of 6.2%, thereby verifying Hypothesis 1. Moreover, from estimating the regression outcomes from Columns (3) to (6), it is evident that OWPPs have a significantly negative influence on efficiency change, while having a significantly positive influence on technology change, indicating that OWPPs primarily affect the technology change component of GTFP.

Irrespective of whether fixed effects are carried out or not, the coefficient of Logarithm of Gross Domestic Product (LnGDP) with Industrial Structure (IS) is significantly positive, indicating that the economy promotes green development, and the more developed the economy of a region, the higher its GTFP. As the proportion of industries with high added-value, high technological content, and high innovation in the economic structure increases, the advancement of industrial structure fosters the transformation of the modern economic development model and plays a crucial role in enhancing GTFP. In the above model, the coefficient of Environmental Regulation (ER) is presently not significant, as is also observed in Wang et al. (2020) study. Wang's work shows that the impact of environmental regulation on GTFP at the 0.05, 0.90, and 0.95 quantiles is not significant. Nevertheless, it decreases at each quantile and within a specific range, thereby verifying the Porter hypothesis to some extent. This can be attributable to the U-shaped correlation between ER and GTFP (Wang et al., 2018), for which the inflection point of positive and significant impacts has not yet arrived. After controlling for two-way fixed effects, the coefficient of Internet is significantly positive, indicating that the continued development of the Internet can improve GTFP, which resonates with the research results of Li and Liao (2020). The advancement of the Internet provides a platform and channels for sharing resource information, breaking down the administrative barriers caused by regional differences, and supports the implementation of the new development concept. Furthermore, the coefficient of Foreign Direct Investment (FDI) is significantly positive, and it remains significant after adjusting for time fixed effects, supporting that the higher the FDI, the higher the level of green development. The reason is that FDI offers the host country with advanced green technology, thus enhancing the cleanliness of production and the efficiency of resource utilization (Girma et al., 2008), thereby verifying the "pollution halo" hypothesis. However, LnPopd and Edu do not significantly influence GTFP in statistics. This may be because the population density of coastal areas is relatively high, and the way of measuring human capital cannot truly reflect the enhancement of environmental awareness and the accumulation of innovative talents that are expected to provide.

TABLE 1 Descriptive statistics.

Variables	Symbol	Measured methods	Mean	Min	Max
Green Total Factor Productivity	LnGTFP	The measured data mainly include inputs and outputs, which are measured using SBM-DEA and GML indices, and are taken as log.	0.002	−0.568	0.910
Efficiency Change	LnEC	Logarithm of the GTFP efficiency decomposition term.	−0.088	−0.993	0.582
Technology Change	LnTC	Logarithm of the GTFP technical decomposition term	0.038	−0.487	0.486
Offshore Wind Power Policies	OWPPs	For the pilot province, the year of policy implementation and subsequent years are set as 1, and the rest years are set as 0.	0.289	0.000	1.000
Economic Development Level	LnGDP	Logarithm of the constant price of GDP.	9.853	6.709	11.615
Industrial Structure	IS	Ratio of added value of tertiary sector to added value of secondary sector.	1.095	0.557	3.162
Population Density	LnPopd	Logarithm of the ratio of resident population to administrative area.	6.286	5.258	8.275
Human Capital	Edu	Years of schooling per capita.	9.263	7.492	12.915
Environmental Regulation	ER	Ratio of total investment in industrial pollution control to the value added of industrial output.	0.003	0.000	0.013
Internet level	Internet	Ratio of the number of Internet users to the total resident population in the region.	50.572	12.000	83.000
Foreign Direct Investment	FDI	Ratio of foreign direct investment to GDP.	0.036	0.002	0.121
Energy Intensity	EI	Ratio of total energy consumption to real GDP.	−0.381	−1.182	0.716
Technological Innovation	Patent	Total number of green invention patents and green utility model patents granted.	5.146	0.009	52.808
Marketization level	Mak	NERI Marketization Index.	2.058	1.461	2.485

The minimum value of GTFP occurs in 2019-2020, which is reasonable considering the severe impact of the novel coronavirus pneumonia outbreak on regional development.

5.2 Parallel trend test

Adopting the DID approach essentially requires the satisfaction of the parallel trend assumption (Kahn et al., 2015). Therefore, before its implementation, we conducted further tests to determine whether the OWPPs exhibit a lag effect on the outcome. Following Li and Gao (2016), we applied the event analysis method to investigate the dynamic effect of policy implementation. We replaced the virtual variable OWPPs in Equation (6) with virtual variables that represent the periods before and after the policy implementation. All other variables were held constant. The estimation equation is expressed as follows:

$$\mathrm{Ln}(GTFP_{it}) = \alpha_0 + \prod_{\mathrm{k}\geq -4}^{4} \alpha_k T_k + \lambda Control_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (8)$$

T_0 represents a virtual variable that represents the year of OWPPs implementation. When K<0, it indicates K years prior to the implementation of the policy, and when K>0, it indicates K years after the implementation. The results demonstrate that there were no significant differences observed between the experimental and control groups before the policy implementation. Hence, it indicates the satisfaction of the parallel trend assumption. Figure 2 visually illustrates the GTFP trend of the treatment group affected by OWPPs, as compared to the control group not influenced by it. It is observed that the implementation of OWPPs cased a lag effect on the GTFP, with the delay of three periods.

5.3 Robustness test

5.3.1 PSM-DID

As a quasi-natural experiment, the OWPPs face the challenge of selecting a representative sample. To enhance the sample quality and reliability of the results, this study utilizes the Propensity Score Matching method to match the sample, with GDP, industrial structure, population density, human capital, environmental regulation, Internet level, and foreign direct investment being the matching variables. The caliper value is limited to a range of 0.01 using the radius matching method. Figure 3 illustrates the core density graph of the propensity scores before and after matching. The overlapping of the propensity scores of the treatment and control groups in Figure 3 accords with the common propensity score assumption. After matching, the distribution trend of the treatment group becomes consistent with that of the control group.

TABLE 2 Benchmark regression.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	f_LnGTFP	f_LnGTFP	f_LnEC	f_LnEC	f_LnTC	f_LnTC
OWPPs	0.022	0.062***	−0.245***	−0.083**	0.207***	0.073***
	(1.43)	(3.46)	(−10.36)	(−2.78)	(19.16)	(7.61)
LnGDP	0.039***	0.049***	0.042***	0.031	0.002	0.018
	(3.42)	(3.27)	(3.35)	(1.61)	(0.22)	(1.58)
IS	0.439***	0.636***	0.252*	0.542***	−0.011	−0.082
	(6.04)	(6.27)	(1.80)	(4.75)	(−0.08)	(−0.98)
Lnpopd	−2.494*	−3.241	−1.347	−4.576***	−0.471	2.409***
	(−1.88)	(−1.68)	(−0.86)	(−3.30)	(−0.54)	(3.91)
Edu	−0.080***	−0.023	0.031	0.056	−0.093***	0.055**
	(−3.26)	(−0.22)	(0.73)	(0.57)	(−4.06)	(2.74)
ER	6.752	6.274	3.024	20.484***	4.861	−13.013***
	(1.50)	(1.24)	(0.68)	(4.22)	(1.48)	(−5.21)
Internet	−0.002	0.005*	−0.005*	0.003	0.004	0.003***
	(−1.51)	(1.98)	(−2.01)	(1.17)	(1.75)	(3.54)
FDI	2.504***	2.531**	0.294	1.274	1.542*	0.906**
	(3.72)	(2.28)	(0.55)	(1.14)	(1.83)	(2.15)
Constant	0.342	0.000	−0.329	0.000	0.609***	0.000
	(1.44)	(.)	(−0.83)	(.)	(4.02)	(.)
Observations	176	176	176	176	176	176
R-squared	0.157	0.264	0.0843	0.380	0.174	0.560
Number of groups	11	11	11	11	11	11
Province FE	YES	YES	YES	YES	YES	YES
Year FE	NO	YES	NO	YES	NO	YES

t-statistics in parentheses.
***p<0.01, **p<0.05, *p<0.1.

The regression results are presented in column (1) of Table 3, which indicates that OWPPs remain significantly positive at a 1% level of significance even after regressing the matched sample, confirming the robustness and consistency of the previous regression conclusion.

5.3.2 Alternate dependent variable

Considering the realistic background of continuous growth of carbon emissions, and drawing on the practice of (Chen, 2010) et al., we added carbon dioxide emissions into the model with unexpected output on the basis of the above, recalculated the inter-provincial GTFP and took it as a substitute variable. The regression results are presented in column (2) of Table 3, taking into account two-way fixed effects. The estimated coefficients are highly positive and significant higher than the the baseline estimates. This indicates that OWPPs still significantly improve regional GTFP after considering carbon emission as the undesirable output, and the results are robust and indicate that OWPPs have emission reduction effect.

5.3.3 Placebo test

To minimize the influence of extraneous variables on the relationship between the outcome variable and the OWPPs, a robustness test was performed in this study, utilizing a counterfactual hypothesis. In particular, interaction terms were chosen at random, and the DID regression analysis was performed to assess the extent of the coefficient's variation from the baseline estimate, based on a false OWPPs variable. To prevent the estimation results being affected by insignificant and rare events and to improve the randomness of policy impacts across different areas, this process was repeated 500 times in this study. The distribution of the kernel density of the control group's estimated coefficient, randomly generated 500 times, is presented in Figure 4. It can be observed

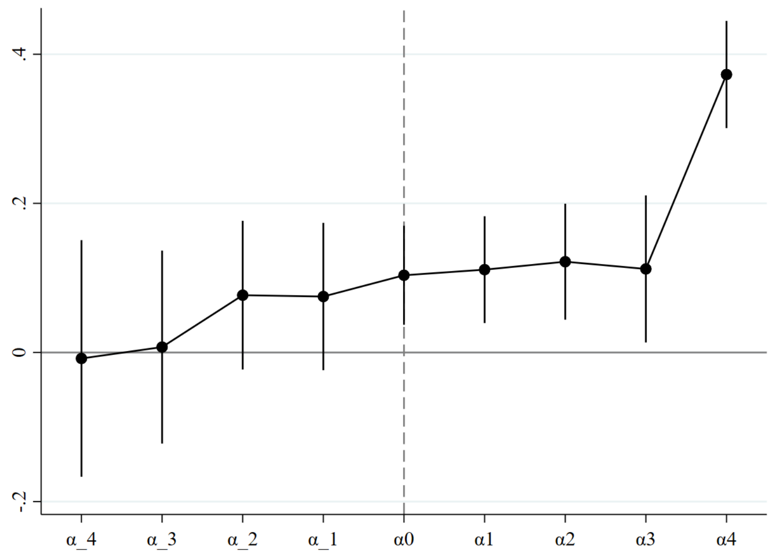

FIGURE 2
Parallel trend test.

that the beta estimates assigned at random are mostly focused around 0, signifying that there is no influence from other random factors on the key findings of this study, and that the estimation results based on the DID regression analysis in the baseline regression model are not basically influenced by any accidental factors.

5.4 Heterogeneity analysis

In order to explore the provincial heterogeneity of OWPPs development, samples were specific to each province of the experimental group for grouping regression. Table 4 shows the grouping regression results. The findings suggest that OWPPs have a positive and significant impact on the GTFP of Guangdong, Jiangsu, and Fujian provinces, highlighting a strong causal relationship. In contrast, we find no significant impact of OWPPs on the GTFP of Zhejiang Province, Liaoning Province.There is a slight negative correlation in Shanghai. Several reasons account for these discrepancies. Firstly, Guangdong, Jiangsu, and Fujian are among China's strongest and relatively strong economic provinces, having experienced rapid development and high concentrations of innovative elements. These factors provide an ideal economic foundation for the effective implementation of OWPPs, contributing towards the improvement of GTFP via aggregation

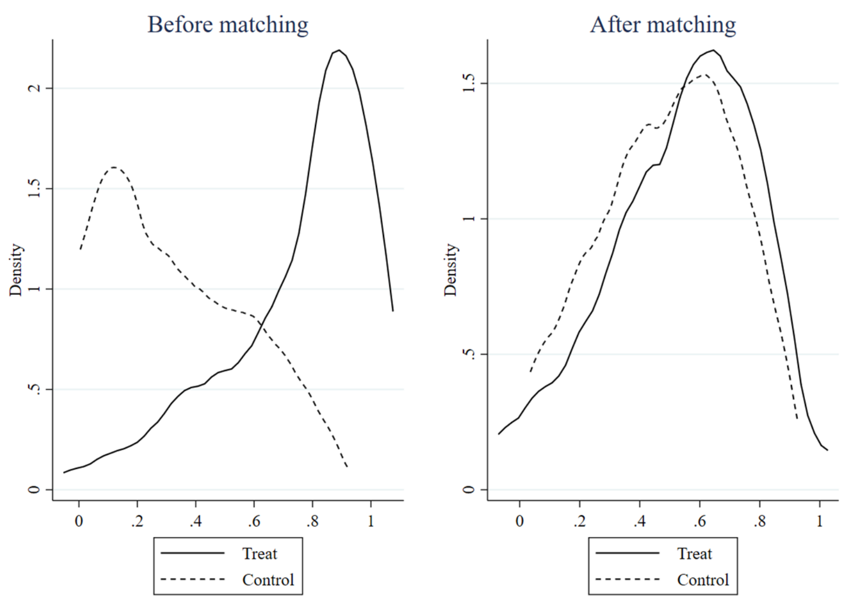

FIGURE 3
Propensity score match.

TABLE 3 Robustness test.

VARIABLES	PSM-DID	Substituting explained variables
	f_LnGTFP (1)	f_LnGTFP (2)
OWPPs	0.151***	0.089***
	(3.98)	(3.16)
Constant	−3.942***	0.000
	(−5.57)	(.)
Controls	YES	YES
Observations	68	176
R-squared	0.559	0.268
Number of groups	10	11
Province FE	YES	YES
Year FE	YES	YES

t-statistics in parentheses.
***p<0.01, **p<0.05, *p<0.1.

and emission reduction effects. Secondly, Compared with provinces where OWPPs have a significant effect, the cumulative installed amount of offshore wind power in Zhejiang and Liaoning is low, which leads to the delay of their green transformation and development. Experience shows that these areas do not lack the conditions to develop OWPPs and are expected to achieve economic rise through green development, but this requires local governments to strengthen their awareness of green governance. Thirdly, The accumulated installed amount of offshore wind power in Shanghai is also not high but shows a slight negative correlation. The potential reason is that the actual conversion effect of OWPPs in this region is not good, and the development of offshore wind power may have a threshold effect. To sum up, due to the difference in resource allocation and economic development scale in different provinces, the demand for GTFP is also quite different, and the empirical results are also different.

5.5 Mechanism analysis

To further verify the impact of OWPPs on green total factor productivity through incentivizing technological innovation, enhancing marketization, and reducing energy intensity, we conducted a mechanism test. The regression results are presented in Table 5.

5.5.1 Technology innovation mechanism

Column (1) indicates that OWPPs significantly promote technological innovation. Specifically, OWPPs' feed-in tariff policy subsidy is gradually declining, which encourages enterprises to increase the research and development of key technologies such as offshore wind turbines, blades, and unit inverters within a limited time, so as to reduce operation and maintenance costs, improve economic efficiency and promote the greening of economic production process, promote the promotion of GTFP. Therefore, H2 is supported.

5.5.2 Marketization level mechanism

The results of column (2) indicate that the OWPPs significantly suppressed the market level at a 1% significance level. This is due to the dominance of a fixed grid price and subsidy system in the development of OWPPs in the past decade, with high government subsidies that deviate from the market supply and demand relationship. Consequently, this limits the ability of offshore wind

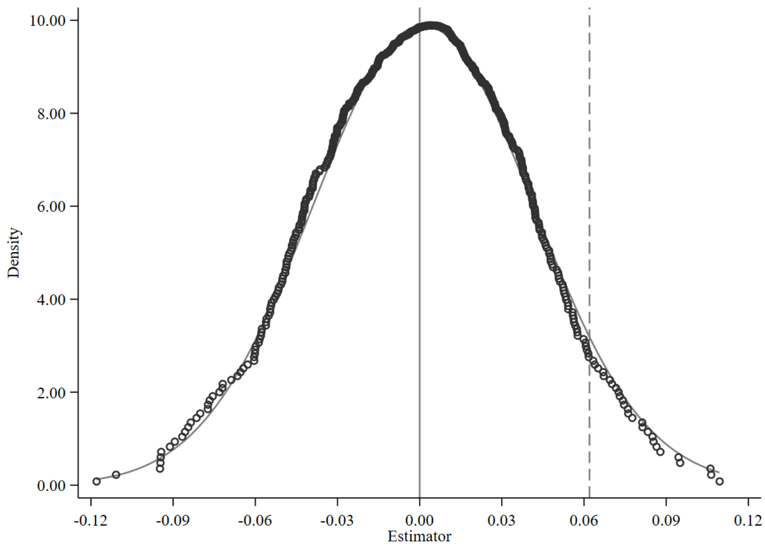

FIGURE 4
Distribution for coefficients of treat (placebo test).

TABLE 4 Heterogeneity analysis.

	(1) Shanghai	(2) Guangdong	(3) Jiangsu	(4) Zhejiang	(5) Fujian	(6) Liaoning
VARIABLES	f_LnGTFP	f_LnGTFP	f_LnGTFP	f_LnGTFP	f_LnGTFP	f_LnGTFP
OWPPs	−0.176	0.361***	0.081**	0.097	0.146***	0.020
	(−1.59)	(5.25)	(2.91)	(1.02)	(3.40)	(0.41)
Constant	7.211	−11.650**	0.000	4.382**	0.000	1.759
	(1.16)	(−2.47)	(.)	(2.55)	(.)	(0.53)
Controls	YES	YES	YES	YES	YES	YES
Observations	96	96	96	96	96	96
R-squared	0.383	0.289	0.291	0.291	0.270	0.266
Number of groups	6	6	6	6	6	6
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

t-statistics in parentheses.
***p<0.01, **p<0.05, *p<0.1.

power companies to adapt to the power market, leading to a lack of cost constraints and an expanding subsidy gap. This hinders offshore wind power companies from making optimal production capacity decisions, distorts resource allocation, restricts the growth of GTFP, and negates the predicted hypothesis (H3).

5.5.3 Energy intensity mechanism

The coefficient of OWPPs is -0.090 in column (3), and this value is significantly negative at a 1% level, indicating that OWPPs effectively reduced energy intensity during the sample period. On one hand,with the continuous development of OWPPs, clean offshore wind power has improved energy structuring and regional emission reductions capacity by replacing part of traditional energy sources. On the other hand, due to its proximity to the energy load center, the industrial correlation effects of OWPPs reduce enterprise energy consumption, improves energy utilization efficiency and thus,promotes GTFP in coastal areas. This finding supports H4.

TABLE 5 Mechanism analysis.

	(1)	(2)	(3)
VARIABLES	f_Patent	f_Mak	f_EI
OWPPs	6.207***	−0.049***	−0.090***
	(4.54)	(−2.84)	(−5.37)
Constant	−260.899***	−2.656***	3.706***
	(−4.19)	(−3.40)	(4.85)
Controls	YES	YES	YES
Observations	176	176	176
R-squared	0.721	0.848	0.977
Number of groups	11	11	11
Province FE	YES	YES	YES
Year FE	YES	YES	YES

t-statistics in parentheses.
***p<0.01, **p<0.05, *p<0.1.

6 Discussion

GTFP is an effective and comprehensive indicator to measure the green development of the economy in the new era. The pursuit of green development has become the inevitable path of economic development nowadays. As one of the fastest-growing renewable energy sources, the study of the green development effect of OWPPs and its mechanism has far-reaching practical significance. This study finds that OWPPs strongly contribute to green development, which is similar to the findings of Chen et al. (2023). Unlike case studies with a one-sided focus on the emission reduction and energy saving aspects of green development, the use of panel data and the constructs of SBM-DEA and GML index for GTFP capture the green development effect of OWPPs more broadly and effectively. It is worth noting that the green development effect of the OWPPs lags behind by 2–3 years, and there are two main possible reasons for this. For one thing, the deployment and coordination of local government's offshore wind power construction concepts, target principles, development planning, workable design, construction and building, and safeguards, which in principle have a construction cycle of between 2 and 3 years. For another 2 years after the base period, the central government started to provide stable subsidies for wind power enterprises, and offshore wind power ushered in a rapid development. This shows that the impact of OWPPs on green development has a lag effect, but at the same time, local governments and enterprises may be more "rational people" than we think.

Interestingly, compared with Chen (2010) and Liu et al. (2021), we find that the growth of GTFP is mainly due to the improvement of TC rather than EC, which is consistent with the latter view after using more comprehensive indicators to measure green development in non-expected outputs. The reason for this is that China's total factor productivity has been dependent on technology change in a single-wheel drive mode for a long time (Li and Liu, 2015). The introduction of new industries in pilot areas has enhanced the level of green science and technology in the region. However, the optimization of resource allocation has been overlooked, hindering the growth of GTFP. Therefore, to achieve the sustainable development of the regional economy, the improvement of GTFP should be transformed to a dual-wheel drive of technology change and efficiency change.

OWPPs promote green development by enhancing technological innovation and reducing energy intensity. Compared with Shi et al. (2023) who used a fixed effects model, we construct a DID analysis on this basis, which provides stronger support for this view. Unlike the energy and engineering science perspective of Fan et al. (2022), our findings provide new evidence in the field of economics. On the one hand, OWPPs gather innovative factors in the same geographical space, making full use of the scale effect generated by the clustering of innovative factors to reduce the production and transaction costs of enterprises, encourage them to research and develop more energy-saving and emission-reduction technologies in production activities, transform traditional industries, and further improve GTFP. At the same time, the aggregation of information elements has produced knowledge spillover effects, and strengthened the communication and collaboration between enterprises in the energy industry. Advanced production technology and management concepts improve the level of production research and development and management of enterprises, thereby improving enterprise productivity. Offshore wind power is a knowledge-intensive, low-pollution, low-consumption, high-output industry. Economies of scale, high innovation factor concentration, and knowledge spillover promote the improvement of GTFP. On the other hand, the decline in energy intensity in industrialized countries over the past few decades has been mainly caused by improvements within the production sector (Li and Lin, 2014) and (Huang et al., 2017), which means that the decline in energy intensity is not due to a shift in the economic structure to cleaner sectors. OWPPs are the exact model of clean energy transformation (Poulsen and Lema, 2017). Its strong development can effectively reduce the dependence on traditional energy and the undesirable output of environmental pollution, improve the utilization efficiency of clean energy, and thus increase GTFP. It is of great significance for the region to gradually realize the goal of "dual carbon" and high-quality energy development by taking carbon emission dual control as the starting point.

Contrary to expectations, this study does not find that the OWPPs promote green development by facilitating marketization for the time being, but this is not surprising when one corresponds this finding to the inhibitory effect of EC on GTFP, as described above, and relates it to the history of the policy's development. Globally, governments that coordinate market economies tend to utilize policy tools to encourage investment and shared risk in the earlier, more precarious stages of OWPPs' development (Rentier et al., 2023), and China is not an exception. During the past decade, OWPPs, which were propelled by subsidies, created a market that lack of competition, resulting in issues like idle capacity, weak operating efficiency, and unwise expansion (Liu et al., 2023). The mismatch of resources has hindered the process of industry marketization and blocked efficiency changes. Consequently, the integration of offshore wind power with the entire electricity marketization faces several challenges (Kirkegaard and Caliskan, 2018). Fortunately, the development of Chinese offshore wind power industry does not lack the prerequisites for smooth transition. With the OWPPs on-grid tariff transitioning from a fixed price to a bidding system and the elimination of the central subsidy policy, the conditions surrounding the construction of Chinese offshore wind power have significantly transformed, and the industrial development will shift to market drive, give full play to the decisive role of market allocation of resources, and reduce transaction costs, investment risks, and energy costs with a more perfect market mechanism. This is compatible with sustainable development in the process of marketization. When the market competition of offshore wind power matures, the relationship between OWPPs' green development effect and marketization will fundamentally change.

The findings in this paper make a useful contribution to the study of OWPPs, which is gradually becoming a hot topic for sustainable policy research around the world. More specifically, the findings provide new empirical evidence on the role of OWPPs in promoting green development. OWPPs are not unique to China, on the contrary, it is Europe that was the earliest developer of offshore wind, but is now witnessing the rise of Northeast Asian countries led by China (Mathews et al, 2023). The evaluation framework and insights provided in this paper have entended the OWPPs of China and could provide a strong reference for offshore wind policy in emerging developing countries. For developed countries or regions, it is necessary to construct an evaluation framework suitable for the green development conditions of the country or region based on the particular operational dynamics of offshore wind power development.

It should be noted that the OWPPs are important tools for promoting green development in regions. From a micro perspective, how OWPPs affect the green development of enterprises should also be explored in subsequent studies. From a data perspective, further research will include the latest data. From a methodological perspective, in addition to the application of econometrics, complex analysis considering multiple factors coupling can also be utilized, such as time-varying qualitative comparative analysis or time-difference qualitative comparative analysis (Nie et al., 2022).

7 Conclusion

In this study, By viewing the OWPPs as a quasi-natural experiment, we apply the PSM-DID model to assess the impact of OWPPs on green development. The SBM-DEA model and GML index are utilized to construct the GTFP as a measure of green development. The results show that the relevant policies significantly promote green development after the pilot extension, and the lag of the effect is obvious with significant provincial differences. Green development mainly benefits from technological changes rather than efficiency improvements. This finding can be understood in terms of technological innovation, energy intensity, and marketization level. Our findings will guide and promote high-quality development with green as the universal form.

First of all, promoting OWPPs can stimulate green development dividends. Policymakers should expedite the consolidation of further insights from offshore wind power test programs, and establish universal and diversified best practices promptly to attain the overarching policy objective. From fixed feed-in tariffs with central subsidies to competitive tariffs with local subsidies, regions are supposed to accelerate the pace of offshore wind power construction and promote green development through gradual transformation.

Secondly, at the level of technological innovation, the local government should increase financial investment in science and technology to enhance the output ratio of R&D investment, promote large-scale production, and develop regional deep-sea wind farms to advance intelligent industrial development. It can be stated that technological innovation is the primary productive force of the offshore wind power industry and plays a crucial role in its development. At the level of energy utilization and transformation, policymakers should consider promoting systematic absorption and utilization in the energy consumption field and diversifying energy systems to enhance overall energy utilization. Addressing the energy revolution and ensuring clean energy consumption while adhering to the principle of "grasping the key and promoting step by step," is essential. Promoting the development of a diversified energy portfolio that includes "offshore wind power +" is an inevitable choice for China to achieve its "dual-carbon strategy."

Thirdly, in terms of marketization, the development of offshore wind power still has a considerable distance to cover. It is vital to promote the virtuous cycle of offshore wind power. This can be achieved by encouraging industrial layout clustering, ensuring parity of on-grid electricity pricing, and localizing policy subsidies. These measures could promote market competition, optimize resource allocation, and accelerate the transformation of improving green total factor productivity, which involve a shift from the single-wheel drive of technology change to the dual-wheel drive of technology change and efficiency change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JZ: Conceptualization, Methodology, Data curation, Software, Formal analysis, Visualization, Validation, Project administration, Writing – original draft, Funding acquisition. ZW: Supervision, Writing – review & editing. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1251787/full#supplementary-material

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