THE RESPONSE OF EUROPEAN OFFSHORE WIND POWER TO NATIONAL GREENHOUSE GAS EMISSIONS AND THE RESULTING ENVIRONMENTAL BENEFITS

by

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Renewable energy represents a pathway towards sustainable development and reducing dependence on fossil fuels for the international workforce. Following the Russo-Ukrainian conflict, the EU has been intensifying its transition towards clean energy, reaffirming its net-zero emissions goal. Under this goal, accelerating the development of renewable energy has become a necessity. Wind power holds a significant position among the EU's RES. Due to the high population density in the EU, offshore wind power, compared to onshore wind power, experiences faster wind speeds and more stable wind sources, making the boost of offshore wind energy a major development trend for the EU's new energy initiatives. The results indicate a significant positive correlation between offshore wind power generation and greenhouse gas emissions. On average, for every 100 million tons of GHG emissions, the EU should achieve an annual power generation of 3148.11 GWh through offshore wind power and increase the cumulative installed capacity of national offshore wind power to 768045 MW. In combination with the EU's carbon trading system and the carbon price and emission reduction effects of offshore wind power proposed by some scholars, an installed capacity of offshore wind power approximately accounts for 2.69% of the EU's emission reductions, potentially generating an economic benefit of 21825 billion euros.

Key words: *EU, cumulative installed capacity of offshore wind power, offshore wind power generation, environmental benefits, economic benefits, GHG reduction, carbon pricing*

Introduction

Europe, as an energy-intensive continent, heavily relies on imported energy. Coupled with its recent endeavors to lead the global response to climate change, it is currently facing global challenges such as the depletion of local energy resources, rising fuel costs, and disruptions in the energy supply chain [1]. Particularly since the outbreak of the Russo-Ukrainian conflict in 2022, the global traditional energy supply chain has been forced to readjust. The EU, as a major purchaser of Russian energy, where Russian oil and natural gas hold significant positions in its energy structure. According to data from the U.S. Energy Information Administration (EIA) and the EU's statistical office, before the Russo-Ukrainian

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conflict, the EU's imports of natural gas and oil from Russia accounted for about 25.23% and 44.69% of its total imports, respectively. Against this backdrop, the EU proposed the RePower EU plan in May, aimed at accelerating the development of renewable energies such as wind and solar power. Due to the cost-effectiveness and broad development prospects of wind power generation, it has become the main direction for the clean energy transition of many European countries. The European offshore wind industry has transformed Europe from an energy-dependent continent into an energy exporter [2]. Compared to traditional fuels, wind energy, as a renewable source, generates no emissions, thus significantly reducing the total amount of air pollutants. Moreover, in the past decade, the cost of wind power generation has significantly decreased, whereas the costs of traditional energy sources, especially oil and gas, have increased dramatically [3], stimulating overall growth in the wind power industry in Europe and around the world.

Existing research has confirmed that, in addition to the aforementioned minimal environmental impact, offshore wind power has stronger wind resources compared to onshore wind power. The increase in wind speed leads to a 150% increase in the power generation of offshore wind turbines, and the capacity factor of wind farms has increased from around 25% to 40% [4] (The capacity factor of offshore wind turbines can reach 40% [5]). Compared to PV power generation, offshore wind power also has advantages, as it can serve as an important supplement to PV power generation during the night and in the less sunny winter season [6]. Furthermore, offshore wind power consumes much less water throughout its entire lifecycle [7], compared to coal, and does not rely on large amounts of freshwater resources like traditional energy sources, thereby reducing significant health impacts [4]. Additionally, compared to onshore wind power, offshore wind offers stronger and more persistent winds, thus enhancing the production efficiency of wind power and achieving a more favorable rate of CO_2 elimination. Research by Snyder and Kaiser [4] has argued that offshore wind power has all the advantages of onshore wind power, with very low carbon emissions throughout its lifecycle, and emissions of mercury, NO_x, and sulfur oxides can be considered negligible. Studies by, Owens and Chapman [8] and Reimers *et al*. [9] have demonstrated that the GHG emissions from onshore and offshore wind power are similar, and compared to onshore wind power, offshore wind power has a smaller environmental impact. Some scholars have found that when the EU-27 installs 65 GW of wind power capacity, the installation share of offshore wind farms is nearly 2.23%, which can avoid the emission of 108 million tons of CO_2 annually, equivalent to reducing emissions from over 50 million cars on European roads [6]. Research by Reimers *et al*. [9] found that parameters of power generation (*i.e.*, average wind speed, technical availability) have a significant impact on GHG emissions, with average wind speed having the greatest impact on overall GHG emissions. A decrease in average wind speed reduces power generation, thereby significantly increasing GHG emissions. The extension of technical life shows great potential for reducing GHG emissions, while distance from shore and water depth have a smaller impact on GHG emissions. Moreover, Snyder and Kaiser [10] have argued that since the power generated is proportional to the square of the wind speed (the power of the wind is proportional to the cube of the wind speed [11]), the development of a country's offshore wind is positively correlated with its latitude, and also believed that wind power installation and generation may be positively correlated with population density. High population density to some extent hinders the development of onshore wind power, which is usually the cheapest RES. Due to the high population density in Europe, there is limited space for expanding onshore wind energy production, hence European countries have developed offshore wind power the most [10]. Moreover, offshore wind power is physically closer to major coastal population centers, thereby eliminating the need for expensive high-voltage transmission [4]. Additionally, surveys in Denmark, a leading country in the development of offshore wind power in the EU, have shown that the public has a more positive attitude towards offshore wind power than onshore wind power [12].

Beyond serving as a new energy source to replace traditional energy for energy conservation and emission reduction, offshore wind power also brings significant economic benefits. As a global leader in net-zero emissions, the EU has the most comprehensive carbon trading system to date. Therefore, the carbon reduction brought by offshore wind power can provide the EU with economic benefits in addition to environmental benefits. In April 2013, under the EU carbon trading system, the price of emission allowances per ton of CO_2 equivalent was 2.75 €, which rose to 5 € by 2016, although still below the EU's projected 30 € [13]. A UK government report provided low, medium, and high carbon prices for 2050 of 117 €/tCO_2, 234 €/tCO_2, and 351 €/tCO_2, respectively [13]. According to the EU's forecast, the average cost of carbon trading system price policies per ton of CO_2 reduction is 52 €, far lower than other policies, because it promotes a relatively wide range of mitigation measures, transitioning to cleaner generating fuels and improving the energy efficiency of the electricity and large industrial sectors [6]. The European offshore wind industry has significantly reduced the electricity generation costs of oil fuels and reduced CO_2 emissions. According to estimates by the European Wind Energy Association, offshore wind power can achieve 85-90% of the GHG reduction targets by 2050 [2]. Compared with traditional coal-fired power plants, offshore wind power plants have a potential storage capacity utilization rate 10.68 times higher and a comprehensive environmental efficiency of CO_2 emissions 9.93 times higher over an estimated 25-year operating life. Therefore, for offshore wind farm power generation, the energy efficiency benefits value of CO_2 emissions is higher than that of fossil fuel energy production [15]. Compared to fossil fuel power generation, offshore wind power projects have lower variable costs, as wind power generation does not require fuel costs [16], and thus do not experience price fluctuations like oil, natural gas, biomass energy, nuclear energy, and coal power generation. Moreover, the offshore wind power industry does not have to worry about turbine noise like the onshore industry. Therefore, the offshore industry can use larger turbines. Due to economies of scale, these larger turbines will make offshore wind power more economically attractive [4]. These advantages will all drive the development of EU offshore wind power. The continued expansion of offshore wind power installation will also enable offshore wind power costs to continue to decline, making it more cost-effective compared to thermal power generation [17]. Therefore, this study aims to explore the power generation and installed capacity of offshore wind power in EU countries in recent years, as well as the environmental and additional economic benefits it brings, in order to provide theoretical support for the development of offshore wind power and energy transformation in EU countries.

Research methodology

This study selects major EU countries based on their offshore wind power installed capacity and power generation. The data on installed capacity and power generation of various EU countries primarily come from the Global Renewable Energy Agency, while GHG emissions data for European countries such as Germany and the Netherlands are sourced from the EU Statistical Office. The population density and per capita arable land area of the relevant countries are obtained from the World Bank. To ensure the uniformity of the data, all the datasets used in the analyses are from the year 2021.

Simple data processing is carried out using Excel 2016. Graphs are produced with Origin 2017, and linear fitting and significance analysis are performed. Correlation analysis is used to identify the relationships between offshore wind power installed capacity, power generation, and environmental factors such as per capita arable land area and population density. The Performance Analytics package in R-3.5.1 is applied for correlation analysis using the R language (version 4.1.3) to determine the significance of these relationships.

Results

Current status of wind power and offshore wind power in Europe

Current status of wind power in Europe

According to data from the Global Renewable Energy Agency, wind power generation remains the second largest RES, trailing only hydropower. Even before the Russo-Ukrainian conflict, EU countries placed a high emphasis on developing renewable energy. After the outbreak of the conflict and the resulting pain from disruptions in the energy supply chain, the EU initiated the RePower EU plan to accelerate the development of renewable energy, focusing on the rapid deployment of renewable energy installations and increasing the proportion of renewable energy in its electricity structure.

Indeed, the EU has always been a strong advocate for renewable energy. In terms of installed capacity, the EU's cumulative wind power installed capacity led the world until 2014, when it was surpassed by China. Nevertheless, by 2022, the EU's cumulative wind power installed capacity reached 203.54 GW, accounting for 22.64% of the global wind power installed capacity. In terms of power generation, the EU's wind power generation led the world until 2017, and even after being surpassed by China in 2018, it remained the second largest globally. In 2021, the EU's wind power generation was 387,026 GWh, approximately 21.05% of the global total.

Structure of wind power installation and generation in the EU

Due to its lower environmental impact and more stable wind resources, both the installed capacity and power generation of offshore wind in the EU have shown an upward trend. From the perspective of power generation, it increased from 8152 GWh in 2013 to 47804 GWh in 2021. The cumulative installed capacity also rose from 2.99 GW in 2013 to 16.1 GW in 2022. Looking at the share of offshore wind power in the EU's total, the power generation from offshore wind rose from 3.89% in 2013 to 12.35% in 2021, an increase of 8.46 percentage points. Similarly, the cumulative installed capacity increased from 2.82% in 2013 to 7.91% in 2022, figs. 1 and 2. Although onshore wind currently dominates the EU's wind power portfolio, both the power generation and installed capacity shares of offshore wind have rapidly increased. Especially in Europe, where population density is high, this trend is expected to continue.

Offshore wind power installed capacity and power generation by EU countries

Looking at the offshore wind power generation by country within the EU, Germany is currently the leading source. In 2021, Germany's offshore wind power generation amounted to 24375 GWh, accounting for approximately 51% of the EU's total. The Netherlands, Denmark, and Belgium followed with offshore wind power generations of 7952 GWh, 7593

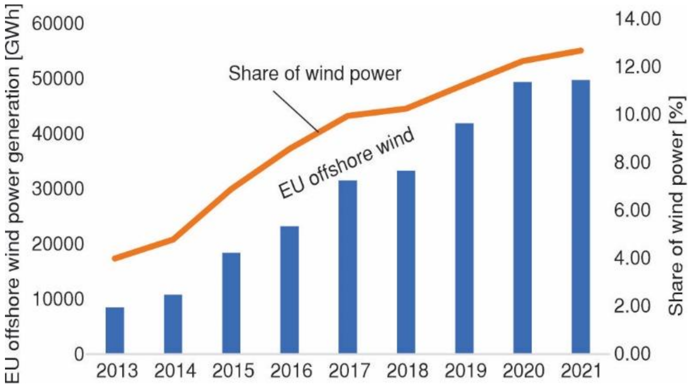

Figure 1. The EU offshore wind power generation and its share of wind power generation

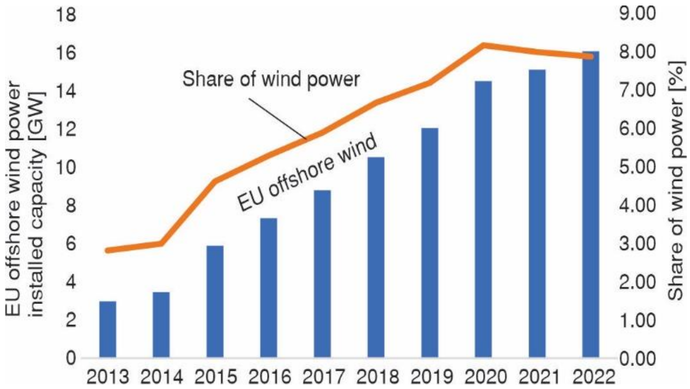

Figure 2. The EU offshore wind power installed capacity and its share in wind power generation

GWh, and 6926 GWh, respectively, accounting for 17%, 16%, and 14%, fig. 3(a). A similar pattern is observed in terms of cumulative installed capacity, with 52% of the EU's offshore wind power installed capacity coming from Germany. In 2021, Germany's cumulative offshore wind power installed capacity was 7.79 GW, approximately 52% of the EU's total. The Netherlands, Denmark, and Belgium had cumulative installed capacities of 2.46 GW, 2.36 GW, and 2.26 GW, respectively, accounting for 16%, 15%, and 15%, fig. 3(b).

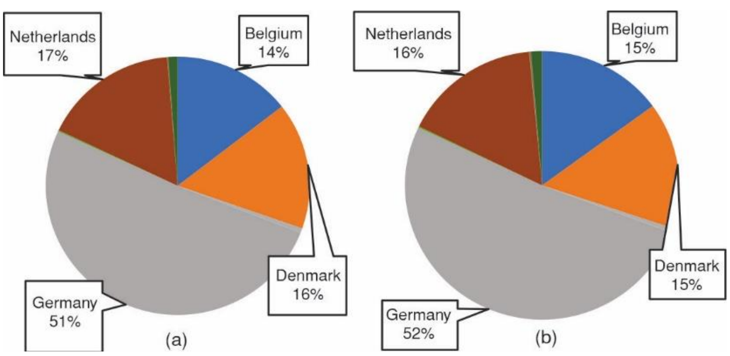

Figure 3. Offshore wind power generation; (a) and installed capacity and (b) in EU countries in 2021

Response of offshore wind power installed capacity and power generation to GHG emissions and environmental factors like population density in European countries

Combining the 2021 data on GHG emissions from the EU Statistical Office, population density and per capita arable land area from the World Bank, and offshore wind power installed capacity and power generation from the International Renewable Energy Agency for EU countries, it is observed that the installed capacity and annual power generation of offshore wind power in EU countries have a positive correlation with their GHG emissions. Specifically, the correlation coefficient between GHG and the offshore wind power generation and cumulative installed capacity for 2021 is 0.83 for both, with significance ($p < 0.05$). This indicates that within European countries, the higher the GHG emissions, the more urgent is the installation and use of RES like offshore wind power. There is also a positive correlation between offshore wind power generation and installed capacity with population density, with correlation coefficients of 0.24 and 0.25, respectively, although these did not reach a significant level ($p > 0.05$). However, there is a negative correlation with per capita arable land area, with correlation coefficients of -0.12 and -0.13, respectively. This conclusion is consistent with the findings of Pryor *et al*. [13] suggesting that within EU countries, some nations, due to higher population density, tend to build offshore wind power facilities that do not occupy land area. When comparing the correlation coefficients between the offshore wind power generation and installed capacity with three GHG (CO_2, CH_4, and N_2O), the correlation coefficients for power generation and installed capacity with CO_2, CH_4, and N_2O are 0.84, 0.80, and 0.79, respectively, all with significance, and the correlation with CO_2 is even higher than with GHG overall. Given that CO_2 is the dominant component in GHG, this suggests that the installed capacity and power generation of offshore wind power in the EU are more influenced by the pressure to reduce CO_2 emissions.

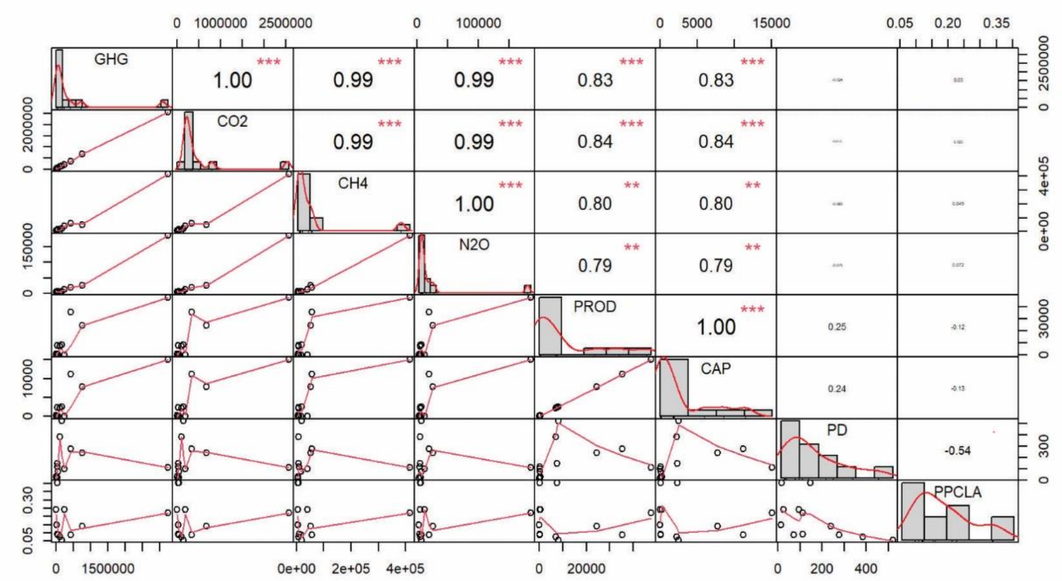

Figure 4. Correlation analysis of sea-wind power generation and installed capacity with GHG, population density, and arable land area per capital

Economic benefit analysis of offshore wind power in EU countries

The previous analysis has confirmed that the pressure from GHG emissions and the goal of energy transition are driving EU countries to install and generate electricity from offshore wind power, fig. 4. Moreover, with the comprehensive EU carbon emissions trading system, excessive GHG emissions can lead to significant economic losses. Offshore installations, being an efficient mode of electricity generation that does not occupy land, not only can achieve the country's energy transition but also obtain considerable economic benefits within the carbon trading system.

The linear fitting results of the EU countries' offshore wind power generation and installed capacity with GHG (CO_2 equivalent) are $R_2 = 0.77$, $p < 0.05$ for generation, and $R_2 = 0.57$, $p < 0.05$ for installed capacity. This indicates that in European countries, both generation and installed capacity are significantly related to GHG emissions. According to the linear fitting results, to reach the EU average level, for every 100 million tons of GHG produced, countries should achieve an annual power generation of 3148.11 GWh through offshore wind and increase their national cumulative installed capacity to 768045 MW. If the annual power generation exceeds 3148.11 GWh, it can correspondingly acquire economic value. If based on the EU's carbon pricing of 30 €/ton of CO_2 or the current carbon price, it could, beyond the national energy transition, levy a "carbon tax" on high-emission countries within the EU with its developed offshore wind power generation.

Among the EU countries discussed in this study, although Germany emits far more GHG than other countries, its early start in offshore wind power installation means that in 2021, Germany's cumulative offshore wind power installed capacity and power generation accounted for 52% and 51% of Europe's total, respectively. Hence, offshore wind power projects can serve to create economic benefits through energy transition for Germany. The Netherlands, Denmark, and Belgium, although not high in GHG emissions, can subsidize their economies through their offshore wind power installed capacity and generation. Meanwhile, countries like France, Italy, and Spain, which have not yet started on offshore wind power projects, would need to pay a corresponding *carbon tax* to countries like Germany and the Netherlands for offshore wind projects.

Discussion

Current situation of offshore wind power installation in the EU and comparison with its targets

The EU's offshore wind power generation and installed capacity have maintained a leading position globally for a long time, with cumulative installed capacity surpassed by China in 2014 and offshore wind power generation surpassed by China in 2017. However, the EU's offshore wind power generation still firmly holds the second position worldwide. In the EU, Germany contributes more than half of the offshore wind power installed capacity and generation. According to the EU's long-term framework, the goal is to reduce GHG emissions by 80-95% by 2050 compared to 1990 levels.

The electricity sector is key to achieving this target, as the EU's roadmap explicitly states that CO_2 emissions from the electricity sector will be entirely eliminated by 2050. Research by Karanikolas *et al.* [18] suggests that Germany's offshore wind power generation is expected to see a growth explosion in the next decade, predicting that Germany's offshore wind power installed capacity in 2020 will be about twice that of 2014. This study, referencing data from the International Energy Agency, calculates the result as 1.61 times, although Germany's offshore wind power generation did indeed grow by 2.25 times from 2014 to 2020. Karanikolas *et al*. [18] were more optimistic about Sweden's offshore wind power installed capacity, predicting a growth explosion from 2014, expecting it to increase by 1.5 times compared to 2013. However, this prediction did not materialize, with Sweden's offshore wind power installed capacity only growing by 21% in 2014 and by 1.38 times by 2020, not yet reaching the target.

Considering the EU's RePower EU plan, the net-zero emission targets of several EU countries, and the current development status of the EU's offshore wind power, to meet the above targets, the EU's offshore wind power is expected to undergo a rush in installations in the coming years to make up for past progress lag. Additionally, the EU is expected to accelerate its clean energy transition, increasing the share of green electricity in its energy structure.

Environmental benefits of offshore wind power in the EU

Based on the power generation and corresponding emission reductions of offshore wind in the EU, although offshore wind has contributed to the EU's emission reduction targets, there is still significant room for improvement. According to models by Akda and Yeroglu [19], a 204.6 MW offshore wind farm can reduce GHG emissions by 1527 million tons per year, which means 1 MW of offshore wind capacity can reduce emissions by 7463 tons. This differs from Snyder *et al.* [4] who estimated a reduction of 1800 tons of GHG per MW of offshore wind capacity. Research in Massachusetts at Cape Cod and Martha's Vineyard by American scholars predicted that 246 MW of wind power would reduce emissions by 415203 tons [20]. By these calculations, the EU's offshore wind capacity in 2022, amounting to 203539 MW, could reduce emissions by an average of 0.46 tons per MW of capacity, leading to a total reduction of 873 million tons of GHG in 2021, about 2.69% of the EU's emissions. Using the more conservative figure of 1800 tons of emission reduction per MW, the total reduction would be 366 million tons, approximately 1.13% of the EU's emissions.

Offshore wind not only reduces GHG emissions but also decreases the emission of toxic gases. Modeling by Akda *et al.* [19] showed that 204.6 MW of capacity could reduce toxic gas emissions by 7616 tons, equating to 37.22 tons per MW of capacity. By this estimate, the EU's 2021 offshore wind capacity could reduce around 7.015 million tons of toxic gases.

Economic benefits of offshore wind power in the EU

Currently, the EU hosts the most comprehensive carbon trading system globally, facilitating the direct conversion of environmental benefits from green power sources like offshore wind into economic benefits. With the EU's carbon pricing at approximately 25 € per ton of CO_2, and based on the calculations from section 4.2 (0.46 tons of GHG reduced per MW of offshore wind capacity), offshore wind projects in the EU in 2021 could have reduced CO_2 emissions by 873 million tons, translating into an economic benefit of approximately 21.825 billion €. As the EU's industrial energy use increases and the offshore wind capacity expands, these projects are expected to generate even greater economic benefits in the future. By 2030, even with mid-carbon cost carbon pricing, the economic benefits could reach 52.38 billion €, with high-carbon cost pricing at 120 € per ton of CO_2, this figure could double to 104.76 billion € [21].

The economic benefits of offshore wind are not limited to direct earnings from carbon trading. The substitution of energy generated by offshore wind also saves a significant amount of fossil fuels. Before the Russo-Ukrainian conflict, the EU heavily relied on natural gas from Russia for electricity generation. Following the conflict and subsequent sanctions against Russia, the EU turned to importing costly LNG from the USA, and some EU countries had to reactivate coal-fired power plants. Scholars estimate that avoiding 1 ton of CO_2 emissions costs about 30 $, and coal-fired power generates 0.839 tons of CO_2 per MWh, meaning clean energy generation can save about 25 $ per MWh. With the EU's offshore wind power generation at 83318 GWh in 2021, the projects could offset about 2083 billion $ in coal-fired electricity costs [4]. Another study indicated that the EU's offshore wind industry reduced fuel costs (including imports of carbon, oil, natural gas, biomass, and waste fuels) by 571 million € in 2010, with a total savings of 2.018 billion € from 2007 to 2010. Additionally, some countries provide government incentives for offshore wind projects, such as Turkey, where the government pays a carbon incentive of 5.2 € per ton of CO_2 emitted by renewable energy power plants, tab. 1 [19].

Table 1. Economic benefits of offshore wind power for energy conservation and emission reduction and government incentive revenues

The CO_2 price (unless specifically marked, all in € per ton)	Source of literature	Remarks
25	Scenarios to 2030 of energy use and CO_2 emissions in EU industry [21]	Current plan
60		Mid-carbon cost Scenario for 2030
120		High-carbon cost Scenario for 2030
52	Increasing carbon pricing in the EU: Evaluating the options	
5.2	An evaluation of an offshore energy installation for the Black Sea region of Turkey and the effects on a regional decrease in GHG emissions [19]	Government subsidies
25 $/tonne	Ecological and economic cost-benefit analysis of offshore wind energy [4]	Fossil fuels saved

Conclusions

Based on the data released by the International Renewable Energy Agency, the EU was the world's largest installer of offshore wind power before 2014 and remained second in global wind power generation until 2017. Even after its installed capacity and power generation were surpassed by China, by 2022, the EU's cumulative wind power installed capacity still accounted for 22.64% of the global total, and its wind power generation in 2021 accounted for 21.05%, only second to China. Offshore wind power's share within the EU's wind power has become increasingly important, with its generation share rising from 3.89% in 2013 to 12.35% in 2021, and the cumulative installed capacity increasing from 2.82% in 2013 to 7.91% in 2022.

The cumulative installed capacity and power generation from offshore wind in the EU show a positive correlation with GHG emissions, indicating that the more a country emits GHG, the greater the pressure it faces to reduce carbon through offshore wind power. The correlation coefficient between GHG and the offshore wind power generation and cumulative installed capacity for 2021 is 0.83 for both, showing significance.

Based on linear fitting results, to reach the EU average, for every 100 million tons of GHG produced, offshore wind power should achieve an annual power generation of 3148.11 GWh and increase the cumulative installed capacity of offshore wind power to 768045 MW. If the annual power generation exceeds 3148.11 GWh, it would correspond to acquiring additional economic value.

Integrating previous studies, 1 MW of offshore wind capacity reduces 0.46 thousand tons of GHG emissions. With the EU's GHG emissions at 3.2417 billion tons in 2021, offshore wind capacity contributes to approximately 2.69% of the EU's emission reduction. Combining this with the current EU carbon pricing of 25 € per ton of CO_2, EU offshore wind projects could generate an economic benefit of approximately 21.825 billion €.

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