The Impact of Offshore Wind Farms on Increasing Electricity Production and Reducing CO_2 Emissions

Wpływ udziału morskich farm wiatrowych na zwiększenie produkcji energii elektrycznej oraz ograniczenie emisji CO_2

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This paper analyzes the actual impact of offshore wind farms on changes in the global capacity factor for wind energy. It also examines the real influence of unstable renewable energy sources (URES), namely photovoltaic and wind installations, on the reduction of CO_2 emissions. The study utilizes available data from the years 2000–2023 for Denmark, Germany, and Poland — countries characterized by significantly different shares of URES in their energy mixes. The analysis demonstrates that the reduction of CO_2 emissions is primarily correlated with a decrease in total electricity production. The effect of increasing installed URES capacity on emission reduction is secondary. It was also shown that the growing share of offshore wind farms in the wind energy sector does not translate into an increase in the global capacity factor (GCF). This may be related to lower-than-expected electricity generation from URES, as well as the necessity to curtail unstable sources due to the lack of demand (or technical ability) to accommodate additional electricity volumes within the grid.
Keywords: Unstable Renewable Energy Sources; Offshore Wind Farms, Global Capacity Factor; CO_2 Emission Reduction

W artykule przeanalizowano rzeczywisty wpływ morskich farm wiatrowych na zmiany globalnego współczynnika wykorzystania mocy (GCF) dla energetyki wiatrowej. Zbadano również faktyczny wpływ niestabilnych źródeł energii odnawialnej (URES), tj. instalacji fotowoltaicznych i wiatrowych, na redukcję emisji CO_2. Analizę oparto na dostępnych danych z lat 2000–2023 dla Danii, Niemiec i Polski — krajów o wyraźnie zróżnicowanym udziale URES w miksie energetycznym. Wyniki analizy wskazują, że redukcja emisji CO_2 jest przede wszystkim skorelowana ze spadkiem całkowitej produkcji energii elektrycznej. Wzrost zainstalowanej mocy URES ma drugorzędny wpływ na ograniczenie emisji. Wykazano również, że rosnący udział morskich farm wiatrowych w sektorze energii wiatrowej nie przekłada się na wzrost globalnego współczynnika wykorzystania mocy. Może to być związane z niższą niż oczekiwano produkcją energii z farm wiatrowych oraz koniecznością ograniczania pracy niestabilnych źródeł z powodu braku zapotrzebowania (lub możliwości technicznych) na przyjęcie dodatkowych ilości energii w sieci.
Słowa kluczowe: niestabilne odnawialne źródła energii; morskie farmy wiatrowe; globalny współczynnik wykorzystania mocy; redukcja emisji CO_2

Introduction

Although unstable renewable energy sources (URES), which include photovoltaic and wind farms, have for years been promoted as a key element in the fight against CO_2 emissions, it still remains unclear to what extent they actually contribute to emission reduction and how they realistically affect the stability and load of the entire power system. A significant issue lies in the discrepancy between the estimated amount of energy generated by URES and the volume that is effectively delivered to the grid. The availability of this energy is influenced not only by the variability of weather conditions, but also by factors such as technological degradation, surface contamination of modules and turbine blades, as well as periodic shutdowns for safety reasons [1], [2], [3], [4], [5]. A crucial factor is also the reduction in electricity production caused by the mutual, adverse aerodynamic interaction between individual wind turbines[6], [7], [8].

In this study, data from international statistical platforms such as *Our World in Data* [9] and *Statista* [10] were used to compare the global capacity factors (GCF) for wind farms (both onshore and offshore) across three selected energy systems, each characterized by a different share of URES and a varying contribution from offshore wind farms. Based on this analysis, original conclusions were drawn regarding the actual impact of offshore wind farms on increasing the global capacity factor.

Methodology

This study investigates the real-world impact of unstable renewable energy sources (URES), particularly offshore and onshore wind farms, on electricity production and CO_2 emissions reduction. The methodology involves a comparative analysis of historical energy data from three European countries: Germany, Denmark, and Poland. These countries were selected due to their diverse energy mixes, varying levels of URES integration, and different shares of offshore wind capacity.

The primary data sources used in the study were publicly available and verified datasets from *Our World in Data* [9] and *Statista* [10], which include detailed statistics on electricity generation, installed capacities by energy source, and CO_2 emissions.

The data served as the basis for comparative and trend analyses, focusing on electricity production from fossil fuels, URES, stable renewable energy sources (SRES), as well as the installed capacities of these sources, total electricity generation, and CO_2 emissions.

The comparative analysis of the influence of offshore wind farms on electricity production was based on the definition and evaluation of the Global Capacity Factor (GCF) defined as:

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$$GCF = \frac{AEP^{WF}}{P_R^{WF} \cdot 8760} \quad (1)$$

where AEP^{WF} denotes the annual energy production of all wind farms in the power system in a given year, P_R^{WF} represents the total installed capacity of all wind farms in the power system, and 8760 is the number of hours in a year.

The analysis based on Equation (1), together with data on the share of offshore installations in each of the analyzed countries, was used to identify correlations and discrepancies. The goal was to compare theoretical expectations that offshore wind farms should increase the global capacity factor of electricity generation from wind sources with the actual measured performance observed over the multi-year period from 2000 to 2023.

Results and Discussion

Figure 1 presents the annual global capacity factor GCF for the analyzed countries. It can be observed that the variability of GCF is correlated among the countries included in the analysis, indicating that wind conditions across Denmark, Germany, and Poland tend to coincide during the same periods. Additionally, it is worth noting that starting from 2015, the GCF values for Denmark and Poland have been very similar, while those for Germany have remained significantly lower. This observation is particularly important, as Poland operates only onshore wind farms, whereas both Denmark and Germany have a significant share of offshore wind farms, as shown in Figure 2.

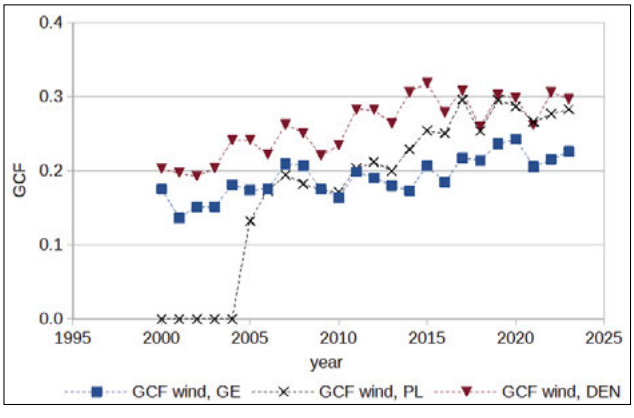
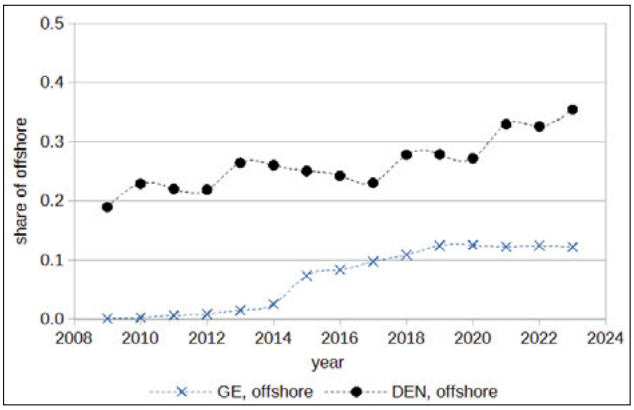


Figure 1.
Global capacity factor GCF for all onshore and offshore wind farms in Germany (GE), Poland (PL), and Denmark (DEN)
Rysunek 1. Globalny współczynnik wykorzystania mocy GCF dla wszystkich farm wiatrowych lądowych oraz morskich dla Niemiec (GE), Polski (PL) i Dani (DEN)

By analyzing the data from Figures 1 and 2, it can be observed that despite offshore wind farms accounting for approximately 35% of Denmark's wind power capacity, the global capacity factor GCF remains at a similar level to that of Poland, which has no offshore wind farms. In contrast, the GCF for Germany is over 20% lower than that of Poland, even though offshore wind farms contribute more than 12% to Germany's total installed wind capacity. It is worth noting that, according to theoretical estimates, offshore wind farms should achieve capacity factors in the range of 45–50% [6], [7], [11], thereby significantly increasing the global capacity factor for URES.

Figure 2.
Share of offshore wind farms in the total installed wind power capacity for Germany (GE) and Denmark (DEN)
Rysunek 2. Udział morskich farm wiatrowych w porównaniu do całej mocy zainstalowanej w energetyczne wiatrowej dla Niemiec (GE) oraz Dani (DEN)



These results indicate a lack of actual impact from offshore wind farms on increasing electricity production from wind power, despite their theoretically higher capacity factors. Considering that offshore wind farms are approximately four times more expensive in both investment and operational terms compared to onshore farms, this raises serious questions about the overall rationale for their development [12], [13], [14].

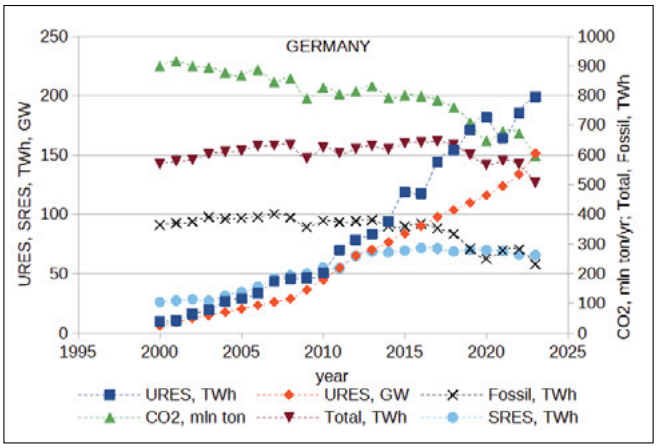
The lack of the expected increase in the capacity factor GCF of installed URES generation capacity, despite the significant growth in the share of offshore wind farms, may be attributed to the highly challenging operational conditions in offshore environments. Another potential reason is related to safety issues and the necessity of disconnecting these installations from the grid during periods of substantial electricity overproduction, which is clearly correlated with a significant surplus of installed URES capacity relative to actual energy demand. This issue is particularly evident when considering the number of hours with negative electricity prices in Germany, which amounted to 301 hours in 2023 and increased to 457 hours in 2024 [15].

Equally important is the considerable level of electricity imports in Germany, which reached 54.3 TWh in 2023 and increased to 67 TWh in 2024, corresponding to 12.1% and 15.5% of the country's total electricity production, respectively. It should be noted that the majority of the imported electricity — over 73% — came from stable sources (primarily nuclear and hydroelectric power plants) [15]. Equally important is the considerable level of electricity imports in Germany, which reached 54.3 TWh in 2023 and increased to 67 TWh in 2024, corresponding to 12.1% and 15.5% of the country's total electricity production, respectively. It should be noted that the majority of the imported electricity — over 73% — came from stable sources (primarily nuclear and hydroelectric power plants).

Figures 3, 4, and 5 present data sets showing total electricity production, production and installed capacity of URES, production from stable renewable energy sources SRES, fossil fuel-based production, and CO_2 emissions from 2000 to 2023 for Germany, Poland, and Denmark.

In Figure 3, it can be observed that the decrease in CO_2 emissions in Germany, despite the rapid increase in the share of URES, is clearly correlated with a decline in total electricity production rather than an increase in URES production and installed capacity. This suggests that the saturation of the energy system with

Figure 3.
Comparison of production and installed capacity of different power generation sources and CO_2 emissions from 2000 to 2023 for Germany
Rysunek 3. Porównanie produkcji i mocy zainstalowanych różnych źródeł wytwórczych oraz emisji CO_2 w latach 2000 do 2023 dla Niemiec



URES to a level of 39.4% annual production (with 27.2% from wind power, as of 2023) may indicate the crossing of the optimal share of URES in the system, beyond which further effective reductions in CO_2 emissions are no longer feasible. This aligns with estimates made in [16].

Figure 4 presents a similar data set to Figure 3, but for Poland, whose energy mix is still predominantly based on fossil fuels. It can be observed that the correlation between the decrease in CO_2 emissions and the decrease in total electricity production is not as pronounced as in Germany. This is due to the significantly lower share of URES, whose presence in the Polish energy system still has a real impact on

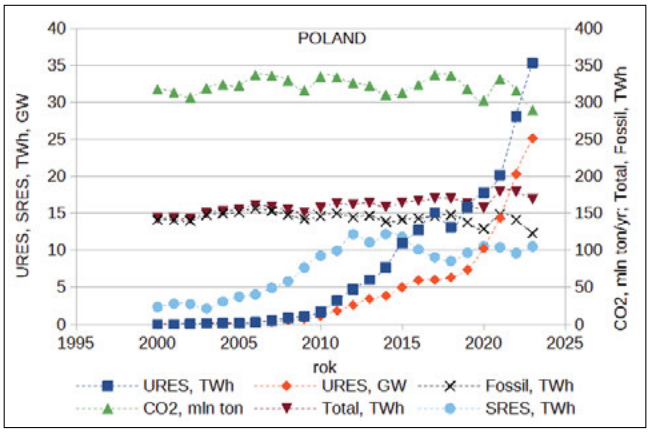


Figure 4. Comparison of production and installed capacity of different power generation sources and CO_2 emissions from 2000 to 2023 for Poland
Rysunek 4. Porównanie produkcji i mocy zainstalowanych różnych źródeł wytwórczych oraz emisji CO_2 w latach 2000 do 2023 dla Polski

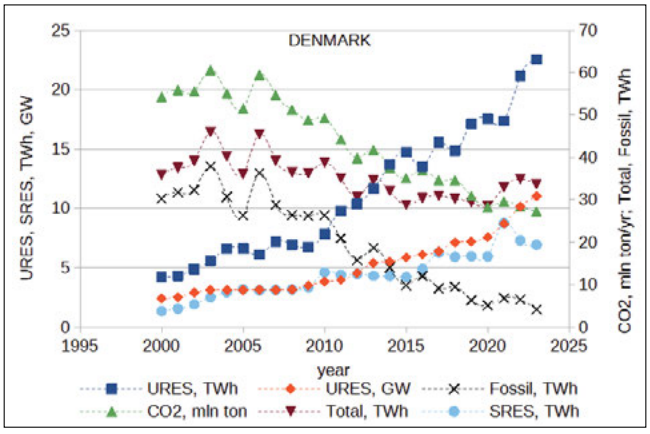


Figure 5. Comparison of production and installed capacity of different power generation sources and CO_2 emissions from 2000 to 2023 for Denmark
Rysunek 5. Porównanie produkcji i mocy zainstalowanych różnych źródeł wytwórczych oraz emisji CO_2 w latach 2000 do 2023 dla Dani

reducing electricity production from fossil fuels, which leads to a decrease in CO_2 emissions. Nevertheless, it is worth emphasizing that despite the significant increase in the share of URES in 2023, a decrease in total electricity production was also recorded, which is clearly correlated with a reduction in CO_2 emissions. This may indicate a gradual approach to the saturation level of URES in the system, beyond which further increases in their share will no longer lead to a noticeable reduction in emissions.

Figure 5 presents data for Denmark, whose energy mix is characterized by the highest share of URES. It can be observed that starting from 2015, the significant increase in the share of URES, along with a substantial decrease in the share of fossil fuel-based sources, has had a very limited impact on further CO_2 emissions reduction. It is worth noting that in 2015–2016, the share of electricity production from URES was around 45%, which is comparable to the level achieved in Germany in 2023. As shown in Figure 3, even in the case of Germany, further growth in URES beyond this level results in a minimal effect in terms of CO_2 emissions reduction.

Summary

This paper, based on available data for Denmark, Germany, and Poland, indicates that the increase in the share of URES in the energy mix is significant for reducing CO_2 emissions only for relatively small shares of URES in the energy mix, not exceeding approximately 30% of annual energy production. Further increases in the share of URES do not contribute to a decrease in CO_2 emissions, and additionally destabilize the system, leading to an increase in the time when URES are shut down or negative electricity prices occur. Furthermore, it has been shown that the capacity factor of offshore wind farms is not significantly higher than that of onshore wind farms. This may be due to the aerodynamic wake of offshore wind turbines extending over distances ranging from several dozen to even several hundred kilometers [17].

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