The paradox of structural transformation: Decarbonization through energy supply limitation in Germany (2000–2025)

Paradoks transformacji strukturalnej: Dekarbonizacja poprzez ograniczenie podaży energii w Niemczech (2000–2025)

ZIEMOWIT MIŁOSZ MALECHA, PIOTR GRĄDZIK

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Analysis of the German energy transition between 2000 and 2025 reveals that the primary driver of CO_2 emission reductions was not the expansion of intermittent renewable energy sources (VRE), but a significant decline in total electricity production. While wind and solar generation increased by 215.4 TWh during this period, nearly 80% of this growth was offset by the simultaneous phase-out of 171.3 TWh of carbon-free nuclear power. This resulted in a net gain of only 44.1 TWh of low-emission energy, whereas fossil fuel generation fell by 190.3 TWh. The remaining deficit of 146.2 TWh shows high convergence with the overall 146 TWh decline in Germany's total energy supply. These findings indicate that over 77% of the observed decarbonization resulted from reduced energy production rather than technological substitution. The study suggests that without a systemic drop in energy demand, the current rate of VRE development would be insufficient to meet climate goals, especially when coupled with the decommissioning of dispatchable zero-emission sources.
Keywords: European green deal; decarbonization; energy supply decline; variable renewable energy sources (VRE); nuclear phase-out

Analiza niemieckiej transformacji energetycznej w latach 2000–2025 wykazuje, że głównym czynnikiem redukcji emisji CO_2 nie był rozwój niestabilnych odnawialnych źródeł energii (VRE), lecz znaczący spadek całkowitej produkcji energii elektrycznej. Chociaż generacja z wiatru i słońca wzrosła w tym okresie o 215,4 TWh, blisko 80% tego przyrostu zostało zniwelowane przez jednoczesne wygaszanie bezemisyjnych elektrowni jądrowych (-171,3 TWh). W rezultacie zysk netto nowej niskoemisyjnej energii wyniósł zaledwie 44,1 TWh, podczas gdy produkcja z paliw kopalnych spadła o 190,3 TWh. Powstały deficyt rzędu 146,2 TWh wykazuje niemal pełną zbieżność ze spadkiem całkowitej podaży energii w Niemczech, wynoszącym 146 TWh. Wyniki te wskazują, że ponad 77% sukcesu dekarbonizacyjnego wynikało z ograniczenia produkcji, a nie z samej substytucji technologicznej. Studium sugeruje, że bez systemowego spadku zapotrzebowania na energię, obecne tempo rozwoju VRE byłoby niewystarczające do osiągnięcia celów klimatycznych, szczególnie w obliczu rezygnacji ze sterowalnych źródeł bezemisyjnych.
Słowa kluczowe: Europejski Zielony Ład; dekarbonizacja; spadek podaży energii; niestabilne odnawialne źródła energii (VRE); wycofanie z energetyki jądrowej

Introduction

Variable renewable energy sources (VRE), including photovoltaic and wind power, have long been promoted as primary instruments for reducing CO_2 emissions. However, the actual extent of their contribution to emission mitigation and climate change remains a subject of ongoing debate [1]. Furthermore, a recent meta-analysis of global climate policies revealed that a mere 63 interventions (approximately 4%) out of 1,500 achieved a measurable effect [2]. The policies that did succeed in reducing CO_2 were primarily those associated with forced energy transitions: high carbon taxation (the ETS system), significant subsidies for VRE, and stringent regulations prohibiting the combustion of fossil fuels. Research indicates that these policies collectively managed to limit CO_2 emissions by only about 0.6–1.8 Gt. Meanwhile, global emissions have risen uninterruptedly since 1950 at a rate of 0.5–1.0 Gt per year, now approaching the 40 Gt threshold [3]. Thus, the cumulative effort of the "best" policies from the last 20 years has only been able to offset a single year of the natural growth in global emissions.

Furthermore, the influence of VRE on power system stability and load management creates major technical problems and additional costs [4, 5]. A fundamental issue lies in the current structure of the power system, which effectively consists of two systems working in parallel: a stable, dispatchable system (coal, gas, nuclear, and hydro) and an oversized VRE system. From an economic perspective, the total investment, operational, and integration costs associated with VRE, such as capacity markets, balancing, and the expansion of dedicated grids and storage, should only be compared with the value of

prof. dr hab. inż. Ziemowit Miłosz Malecha ORCID: 0000-0001-8560-760X, Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland, Coresponding author: e-mail: ziemowit.malecha@pwr.edu.pl; Piotr Grądzik, Independent expert in the field of energy systems security, e-mail: gradzikp@gmail.com

the fuel displaced from the dispatchable system [4].

Additional challenges lie in the gap between the theoretical generation potential of VRE and the amount of energy effectively delivered to the grid [5, 6]. The availability of this energy depends not only on meteorological variability but also on factors such as technological degradation [7, 8], the surface contamination of PV modules and turbine blades [9], and periodic shutdowns for safety or maintenance. Furthermore, mutual aerodynamic interference between adjacent wind turbines can significantly decrease overall generation efficiency [10]. In this context, it is crucial to note that VRE generally exhibit low capacity factors and therefore must often be backed up or replaced by conventional, emission-intensive power sources to ensure grid reliability [11].

Public and academic discourse often relies on the Levelized Cost of Electricity (LCOE) to argue for the economic superiority of VRE. However, as noted in the literature, interpreting LCOE as a full system cost is a significant methodological error. LCOE measures only the cost of generation, omitting the exponentially growing integration costs—such as power balancing, energy storage, and grid over-dimensioning—that arise when VRE penetration exceeds certain thresholds. At shares exceeding 20%, these integration costs can equal the costs of generation itself [9, 10]. Consequently, a transition strategy that prioritizes VRE without addressing the efficiency of the underlying dispatchable fleet may lead to "over-investment," where the marginal cost of new VRE exceeds the economic value of the fuel they displace.

Another unfavorable aspect of this approach is the reduction of the overall Energy Return on Investment (EROI) of the energy system [11, 12], which ultimately limits the availability of affordable energy and contributes to social and economic decline [13, 15].

In the present study, a case study analysis was carried out focusing on Germany — Europe's largest economy and one of the largest electricity producers. Germany serves as a prime example of an intensive transition toward VRE at the expense of phasing out dispatchable sources, such as nuclear power [3, 13]. The aim of this analysis is to demonstrate that VRE sources are not capable of reducing CO_2 emissions to the extent planned in the European Green Deal strategy. Instead, the significant reduction in emissions is primarily linked to the decline in total electricity production. This analysis should serve as a warning, particularly for countries that envision their energy transition path based on installing massive VRE capacities that significantly exceed their average electricity demand.

Metodology

This study utilizes official statistical data from the German energy system covering the period from 2000 to 2025. Specifically, the analysis incorporates data regarding CO_2 emissions [14], gross electricity generation [15], generation volumes by specific technology, electricity import and export balances [16, 17], and the installed capacity of various power generation technologies [18]. The data is based on gross electricity generation to ensure a comprehensive view of the sector's total output.

The unit emission intensity discussed in the study is defined herein as the specific carbon intensity of the fossil fuel generation fleet (Coal, Gas, Oil), rather than the average of the entire national mix. Specifically the unit emission intensity for coal, gas and oil power plants (UEICGO) is calculated based on gross electricity generation from these specific fossil sources in relation to the total CO_2 emissions generated by the electricity production sector.

Results and discussion

Changes in energy mix structure and CO_2 emissions

Figure 1 illustrates the dynamics of change in total electricity production (Total) and production from fossil fuels (coal, oil, and natural gas – hereinafter: CGO) in relation to the volume of CO_2 emissions generated by this sector. Analysis of the empirical data demonstrates a distinct quantitative and qualitative correlation between the reduction in electricity generation from fossil fuels and the drop in carbon dioxide emissions. Simultaneously, there is a strong convergence between these trends and the decline in total energy production (Total), which includes renewable sources (wind, solar, hydro, bioenergy) and nuclear power.

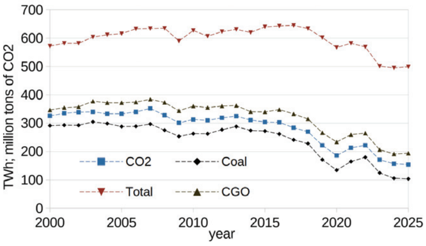

Fig. 1. Correlation between fossil fuel energy production (CGO), total production (Total), and CO_2 emissions in Germany from 2000 to 2025

Rys. 1. Korelacja między produkcją energii z paliw kopalnych (CGO), całkowitą produkcją (Total) i emisjami CO2 w Niemczech w latach 2000–2025

It is worth emphasizing that despite a significant reduction in total emissions, the unit emission intensity from coal, gas and oil power plants (UEICGO) remained at a relatively high level, averaging 0.9 kg CO_2/kWh until 2016, before gradually declining to approximately 0.8 kg CO_2/kWh by 2025. This persistence of high UEICGO values is notable despite the successive reduction of coal's share in the energy mix (which dropped from 291.4 TWh in 2000 to 103.7 TWh in 2025). Figure 2 presents these relationships within the broader context of structural transformation, highlighting the parallel process of phasing out nuclear power (a decrease of approximately 171 TWh between 2000 and 2025) and the dynamic growth of variable renewable energy sources (VRE – wind and solar), whose production increased by approximately 215 TWh during the same period. Simultaneously, the import of electricity increased dramatically starting from the year 2023 (see Fig. 3).

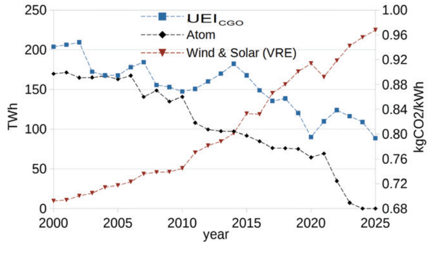

Fig. 2. Structural transformation of the German energy mix: a comparison of the dynamics of the nuclear phase-out (Atom) and the growth of weather-dependent sources (VRE – wind+solar) against the unit emission intensity from coal, gas and oil power plants (UEICGO)

Rys. 2. Strukturalna transformacja niemieckiego miksu energetycznego: porównanie dynamiki wycofywania energii jądrowej (Atom) i wzrostu udziału źródeł zależnych od pogody (VRE – wiatr + słońce) na tle jednostkowej intensywności emisji z elektrowni węglowych, gazowych i olejowych (UEICGO)

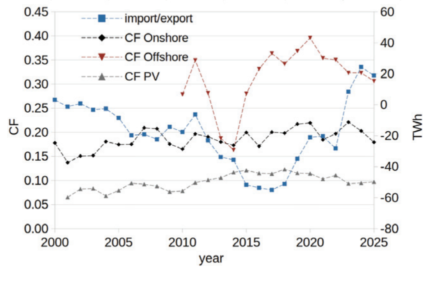

Fig. 3. Change of capacity factor (CF) for photovoltaic (PV), onshore, offshore sources, and import (positive values) and export (negative values) of energy in Germany

Rys. 3. Zmiana współczynnika wykorzystania mocy (CF) dla źródeł fotowoltaicznych (PV), lądowych i morskich oraz importu (wartości dodatnie) i eksportu (wartości ujemne) energii w Niemczech

The relatively high UEICGO, despite the increased share of gas in production, suggests that there was no significant improvement in the average thermal efficiency of fossil fuel-based generation units during the studied period. Furthermore, the balance indicates that the capacity increase in the VRE sector largely served to compensate for decommissioned nuclear units, meaning the real reduction in emissions was primarily conditioned by the decline in the total energy supply within the system.

Specific emission intensity analysis

Table 1 details the changes in the unit emission intensity of CGO plants (UEICGO), the growth of production from gas power plants, and the resulting unit emissions from coal and oil power plants (UEICO). Production from coal and oil (CO) can be interpreted primarily as production from coal power plants, as coal's share within the CO category remains well above 95%. The values were calculated by assuming a constant emission factor for gas of 0.55 kg CO_2/kWh.

While the combined intensity (UEICGO) has declined due to a shift towards natural gas, a more detailed analysis reveals that the emission intensity for coal and oil (UEICO) has stagnated at approximately 1.0 kg CO_2/kWh. This confirms that the German energy transition has not led to significant efficiency gains within the coal-fired fleet even though the German energy sector continues to depend heavily on them.

The paradox of structural transformation

Table 2 presents the detailed dynamics of changes in energy production for the years characterized by peak production from various sources: CGO sources (384.4 TWh in 2007), nuclear power plants (171.3 TWh in 2001), and the peak of total production (645 TWh in 2017).

Comparison of these data reveals a phenomenon that can be called the "paradox of structural transformation". Although the common narrative attributes emission reductions to the growth of weather-dependent renewable energy sources (VRE), the detailed energy balance points to a different mechanism.

Table 1. Change in unit emission intensity for coal, gas and oil power plants (UEICGO) and for coal and oil plants (UEICO)
Tabela 1. Zmiana intensywności emisji jednostkowej dla elektrowni węglowych, gazowych i olejowych (UEICO) oraz elektrowni węglowych i olejowych

Year	CGO [TWh]	Gas [TWh]	Gas [%]	UEICGO [kgCO_2/kWh]	UEICO [kgCO_2/kWh]
2000	346.5	49.2	14.20	0.94	1.01
2001	354.8	55.5	15.64	0.94	1.02
2002	357.6	56.3	15.74	0.95	1.02
2003	377.6	62.6	16.58	0.90	0.97
2004	372.2	62.7	16.85	0.89	0.96
2005	372.3	72.2	19.39	0.89	0.98
2006	374.5	74.7	19.95	0.91	1.00
2007	384.4	77.5	20.16	0.92	1.01
2008	373.2	88.5	23.71	0.88	0.98
2009	343.7	80.3	23.36	0.88	0.98
2010	360.3	88.8	24.65	0.87	0.97
2011	355.2	85.7	24.13	0.87	0.98
2012	360.5	75.9	21.05	0.88	0.97
2013	362.2	67	18.50	0.90	0.98
2014	340.5	60.6	17.80	0.91	0.99
2015	339.8	61.5	18.10	0.89	0.97
2016	348	80.6	23.16	0.87	0.97
2017	332.8	86	25.84	0.85	0.96
2018	314.9	81.6	25.91	0.86	0.96
2019	266.2	89.9	33.77	0.83	0.98
2020	233.9	94.7	40.49	0.80	0.96
2021	259.6	90.3	34.78	0.82	0.96
2022	264.7	79	29.85	0.84	0.96
2023	206.3	76.6	37.13	0.83	0.99
2024	191.6	81.6	42.59	0.82	1.02
2025	194.1	86.3	44.46	0.79	0.99

Table 2. Dynamics of energy production changes in Germany for individual sources
Tabela 2. Dynamika zmian produkcji energii w Niemczech dla poszczególnych źródeł

Category	Past production TWh (year)	Production in 2025 [TWh]	Change [TWh]
Fossil Fuels (CGO)	384.4 (2007)	194.1	-190.3
Wind and Solar (VRE)	9.5 (2000)	224.9	+215.4
Nuclear (Atom)	171.3 (2001)	0	-171.3
Total Production	645 (2017)	499	-146

During the period under review, the increase in production from wind and solar by 215.4 TWh was almost entirely offset by the simultaneous phasing out of emission-free nuclear capacities (-171.3 TWh). As a result, the actual net gain of new low-emission energy in the system was only 44.1 TWh. This means that as much as 80% of the decarbonization potential of VRE was consumed by the process of withdrawing nuclear power instead of directly replacing fossil fuel combustion.

Given that fossil fuel production fell by 190.3 TWh while the net gain from new emission-free sources was only 44 TWh, a deficit of 146.2 TWh appears. This value shows high convergence with the decline in total energy production, which amounted to 146 TWh in the discussed period. Therefore, it can be argued that over 77% (146 out of 190.3 TWh) of the reduction in fossil fuel combustion—and the resulting drop in CO_2 emissions—is due not to VRE growth, but to the limitation of the total energy supply in the German electricity system.

Capacity factor and system saturation

Figure 3 presents the average annual capacity factors (CF) for photovoltaics, onshore, and offshore wind from 2000 to 2025. These factors are lower than theoretically assumed, averaging 0.093 for PV, 0.186 for onshore, and 0.294 for offshore (2010–2025). Furthermore, these coefficients have been gradually declining since approximately 2020, illustrating the negative effects of significant system saturation with VRE sources and other factors such as technical failures, degradation, and significant overproduction. The decline in CF values for VRE correlates with an increase in energy imports, highlighting deep structural problems. Particularly critical are the low capacity factors for offshore wind, where CAPEX and OPEX are several times higher than for onshore, further exacerbated by VRE sources "competing" with each other for generation during the same meteorological periods.

The socio-economic cost of energy limitation

The observed decarbonization in Germany is inextricably linked to a decline in industrial activity. Between 2000 and 2025, electricity demand fell by 48 TWh in heavy industry and 23 TWh in the service sector [19]. This trend, often mislabeled as 'efficiency,' is actually a structural withdrawal of energy-intensive production [20]. Global corporations such as BASF have permanently reduced their German capacities, shifting new investments to China. This 'Capex leakage' proves that European climate policies are driving industrial capital to regions where energy remains affordable, often at the cost of global net-emission increases [21].

The German experience serves as a physical and economic warning for other nations, particularly Poland. The Polish 'KPEiK' scenarios (WEM/WAM) [22] propose a transition that may be physically unfeasible. For instance, building over 20 GW of new gas capacity in 13 years would require roughly 1/3 of the entire global annual production of gas turbines, where current manufacturer queues exceed five years. Furthermore, the demand for battery storage (19 GW) in these scenarios would require approximately 10% of the total global lithium extraction, creating extreme supply chain vulnerabilities [21].

Ignoring the necessity of dispatchable 'cushion' capacity leads to structural power deficits. In Poland, the current transition trajectory risks a structural deficit of 14--19 GW by 2040 during winter peaks. Without maintaining a stable base of conventional or nuclear sources, winter blackouts become a statistical inevitability, as weather-dependent RES cannot provide frequency regulation or mechanical inertia during periods of 'dunkelflaute' [21].

A more economically sound alternative for Poland would be 'Coal Repowering'—modernizing the coal fleet with ultra-supercritical units. This path could save the Polish economy approximately 1.8 trillion PLN by 2040. While the current transition path (WAM) leads to energy prices exceeding 800 PLN/MWh, a modernized dispatchable fleet could maintain a competitive price target of 300 PLN/MWh [21].

Summary

The conducted analysis proves that the reduction of CO_2 emissions in Germany by approximately 47% between 2000 and 2025 was not the result of a simple substitution of coal with variable renewable sources. It was primarily conditioned by a drastic drop in the total amount of energy produced. If energy supply had remained at the levels of the early 2000s, the current development of wind and solar energy would have proven insufficient for significant emission reductions, as it would have first had to compensate for the gap left by withdrawn nuclear power. The German energy transition was thus based on two interdependent pillars:

1. VRE expansion primarily served to replace emission-free nuclear energy.
2. The reduction of total production enabled the actual withdrawal of high--emission units from the energy mix.

These results indicate that without a systemic drop in energy production (resulting from structural changes in industry and foreign trade balances), climate goals would have been impossible to achieve at the current rate of VRE development and the simultaneous departure from nuclear power.

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