IMPACT OF IMPROVING COAL POWER PLANT EFFICIENCY ON CO_2 EMISSION REDUCTION: A CASE STUDY OF THE POLISH POWER SYSTEM

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Abstract - The aim of this study was to analyse the impact of increasing the efficiency of coal-fired power units on CO_2 emission reduction in Poland during the period 2010–2024, and to determine the actual contribution of new coal units and intermittent renewable energy sources (IRES) to the observed emission decline. The case study was based on data concerning electricity production and the commissioning of high-efficiency supercritical units. Quantitative analysis demonstrates that modernizing all coal-fired power plants to an efficiency level of 45% could reduce CO_2 emissions by approximately 33 Mt per year—around 6 Mt more than in a scenario prioritizing the development of IRES. It was also estimated that new high-efficiency coal units accounted for a reduction of 12.4 Mt CO_2, while IRES contributed 22.6 Mt CO_2. The results indicate that in energy systems with a high share of coal, greater emission reduction effects can be achieved by improving the efficiency of conventional units—while maintaining grid stability—before further large-scale integration of renewable energy.

Keywords: Coal Power Efficiency; CO2 Emissions Reduction; Supercritical Units.

1. INTRODUCTION

Intermittent renewable energy sources (IRES), including photovoltaic and wind power, have long been promoted as key instruments in reducing CO_2 emissions. However, the actual extent of their contribution to emission reduction and climate change mitigation [1], as well as their influence on power system stability and load management, remains uncertain. A major challenge lies in the gap between the theoretical generation potential of IRES and the amount of energy effectively delivered to the grid [2], [3]. The availability of this energy depends not only on the variability of meteorological conditions, but also on factors such as technological degradation [4], [5], surface contamination of PV modules and turbine blades [6], and periodic shutdowns for safety or maintenance reasons. Furthermore, mutual aerodynamic interference between adjacent wind turbines can significantly decrease overall generation efficiency [7]. An important aspect in this context is that IRES generally exhibit low capacity factors and therefore often need to be backed up or replaced by conventional, emission-intensive power sources to ensure grid reliability [8].

Furthermore, the public and academic discourse often relies on the Levelized Cost of Electricity (LCOE) to argue for the economic superiority of IRES. 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 IRES 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 IRES without addressing the efficiency of the underlying dispatchable fleet may lead to 'over-investment' where the marginal cost of new IRES 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], [14], [15].

In the present study, a case study analysis was carried out using the example of Poland—a relatively large European country whose power system, up to around 2010, consisted almost entirely of coal-fired power plants with efficiencies not exceeding 33% [16], [17]. Based on data from international statistical platforms such as Our World in Data [18] and Statista [19], an estimation was made to assess the relative share of rapidly developing IRES compared to modern, high-efficiency supercritical coal units commissioned during the same period. This assessment was used to demonstrate that in an alternative scenario, where all low-efficiency coal units were first replaced with high-efficiency ones, the resulting CO_2 emission reductions would have been greater than in the current strategy focused primarily on the rapid expansion of IRES. This comparative approach provides insights into the potential trade-offs between efficiency-driven and renewable-driven transition pathways.

2. METHODOLOGY

The primary data sources used in the study were publicly available and verified datasets from Our World in Data [18] and Statista [19], which include detailed data on electricity generation, installed capacities by energy source, and CO_2 emissions.

Until 2008, all coal-fired power plants in Poland operated with an average efficiency of approximately 31.5% [16, 17]. The first high-efficiency units were commissioned in 2008 and 2009, with installed capacities of 474 MW and 460 MW, respectively, and efficiencies of around 42% [17]. In 2011, another supercritical unit with an efficiency of 42% and a capacity of 858 MW was put into operation. By 2025, a total of 6,083 MW of high-efficiency supercritical coal-fired units had been commissioned. The commissioning dates and installed capacities of individual units are summarized in Table 1.

Table 1. Polish supercritical coal-fired power units and date of commissioning [17]

Unit	Capacity, MW	Efficiency, %	Date	Fuel
Pątnów 2 B9	474	41	2008	Lignite
Łagisza B10	460	42.8	2009	coal
Bełchatów B14	858	42	2011	lignite
Kozienice 2 B11	1075	45.6	2017	coal
Opole B5	905	45.6	2019	coal
Opole B6	905	45	2019	coal
Jaworzno 2 B7	910	45.9	2021	coal
Turów B11	496	43	2021	lignite

Figure 1 presents the electricity generation mix, divided into renewable energy sources (Solar + Wind), coal-fired power plants (Coal), and fossil-fuel-based power plants (Coal + Gas + Oil). It can be observed that in 2010 the share of renewables was minimal, and from that point onward, it experienced a continuous and significant increase. Despite a substantial installed capacity of IRES in 2024, 21 GW of solar and 10 GW of wind, the annual electricity generation from these sources reaches only about 40 TWh. This corresponds to a capacity factor about 11%, highlighting the intermittency and low utilization of renewable power in the current system.

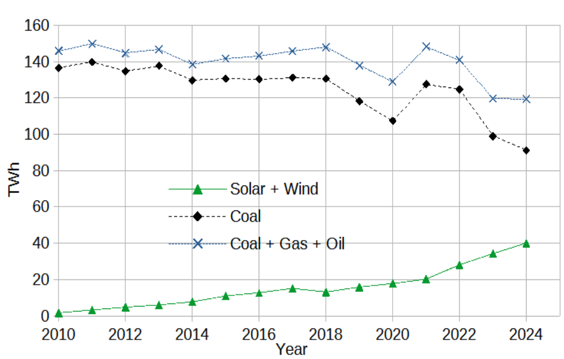

Fig. 1. Electricity generation by source in Poland.

In 2010, the total electricity generation in Poland amounted to 157 TWh, of which the vast majority, 146 TWh, came from fossil fuels: 137 TWh from coal, 5 TWh from gas, and 5 TWh from oil. Figure 2 shows the unit CO_2 intensity (UEm) of the entire power system, as well as the total electricity generation from all sources (AEP_all). Based on these data, CO_2 emissions resulting solely from electricity production (ECO2) were calculated for the period 1985–2024.

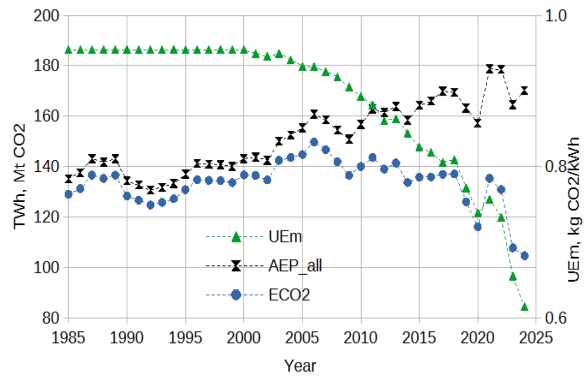

Fig. 2. Unit CO2 emissions (UEm), total electricity production (AEP_all) and corresponding CO2 emissions from electricity generation (ECO2) in Poland for the period 2010 to 2024.

In Figure 2, it can be observed that the unit CO_2 intensity (UEm) of the electricity system began to decline around the year 2000, with a noticeable increase in the rate of decrease from 2008, when the first supercritical units were commissioned (see Table 1). It should be noted that during the same period there was a significant increase in electricity generation accompanied by a clear reduction in CO_2 emissions. At that time, the share of IRES remained marginal. This indicates that the observed emission reductions were closely correlated with the replacement of old coal units with new high-efficiency ones.

The confirmation of emission reduction achieved by replacing old coal-fired power plants with high-efficiency units is particularly evident in Figure 3.

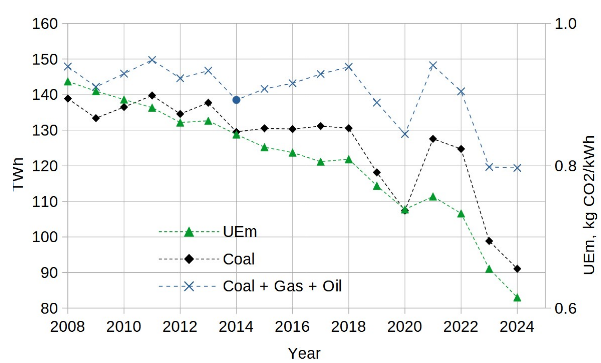

Fig. 3. Correlation between unit emissions (UEm) and electricity production from fossil fuels.

It can be observed that between 2014 and 2018, electricity generation from coal remained stable or even slightly increased. Furthermore, the total production from fossil fuels (Coal + Gas + Oil) clearly rose, yet emissions concurrently decreased. This trend is also visible when comparing the years 2011 and 2013, as well as 2021 and 2022. A faster drop in emissions, for example, from 2023 to 2024, is correlated with a reduction in coal-based electricity generation. This suggests that a part of this decline can be attributed to the installation of very large volume of IRES.

Figure 4 illustrates the change in CO_2 emissions from 2010, which marks both the beginning of significant IRES development and the commissioning of additional high-efficiency coal units. The figure also shows a linear regression, indicating an average annual reduction in CO_2 emissions of approximately 2.14 Mt per year. The absolute decrease in emissions between 2010 and 2024 amounts to 35 Mt CO_2.

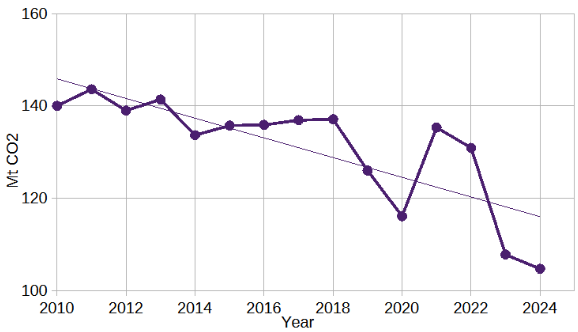

Fig. 4. CO2 emission decline in Poland for the period 2010 -- 2024

2.1. Contribution of New Coal-Fired Units to CO_2 Emission Reduction in 2010–2024

According to the data presented in Figure 1, the increase in electricity generation from zero-emission IRES amounted to 40 TWh, representing 23.5% of total electricity production in 2024. To estimate the impact of new high-efficiency coal units on CO_2 emission reductions and to determine the actual contribution of IRES to the observed decrease in emissions during 2010–2024, the following assumptions were made:

The new units commissioned in the years listed in Table 1 replace an equivalent capacity of older coal units with an efficiency of 31.5%.

The new units operate with an annual capacity utilization of 8,000 hours.

As a first step, it is necessary to determine the unit emissions for coal units with an efficiency of 31.5% (η_1 = 0.315). This calculation is based on the CO_2 emissions in 2010 (Em_{31}^{2010}) and the annual electricity generation from coal-fired power plants in 2010 (AEP_{Coal}^{2010}):

$$UEm_{31}=Em_{31}^{2010} / AEP_{Coal}^{2010} = 1.022 \text{ [MtCO2/TWh]} \quad (1)$$

It should be noted that the unit emissions obtained from equation (1) are slightly higher than the actual values, as they also include emissions from gas and oil-fired sources; however, their contribution to total emissions was negligible.

In the next step, it is necessary to calculate how the unit emissions change when the efficiency increases from η_1 to η_2. For example, for an increase in efficiency to 45% (η_2 = 0.45):

$$UEm_{45}=UEm_{31}\, \eta_1/\eta_2 = 0.715 \text{ [MtCO2/TWh]} \quad (2)$$

Next, using equation (2), it is possible to calculate how the CO_2 emissions of a coal-fired power plant with higher efficiency (η_2) change for a given electricity generation (E_E):

$$Em_{CO2}=E_E\, UEm_{45} \quad (3)$$

3. RESULTS

Using equations (1)–(3), the emission reduction (REm) attributable to each new high-efficiency coal-fired unit was calculated. The results are summarized in Table 2. They show that the total emission reduction, calculated as the sum of reductions for all new units, amounted to 12.4 Mt CO_2. Comparing this value with the actual decrease in emissions between 2010 and 2024, which was 35 Mt CO_2, indicates that the contribution of IRES amounted to 22.6 Mt CO_2.

Table 2. Emission reduction (REm) attributable to each new high-efficiency coal-fired

Year	Unit	Capacity MW	Efficiency %	AEP TWh	UEm	REm Mt CO2
2011	Bełchatów B14	858	0.420	6.86	0.77	1.75
2017	Kozienice 2 B11	1075	0.456	8.60	0.71	2.72
2019	Opole B5	905	0.456	7.24	0.71	2.29
2019	Opole B6	905	0.450	7.24	0.72	2.22
2021	Jaworzno 2 B7	910	0.459	7.28	0.70	2.33
2021	Turów B11	496	0.430	3.97	0.75	1.08

3.1. CO_2 Emission Reduction Resulting from Increasing the Efficiency of All Coal-Fired Power Plants

Considering the efficiencies of modern coal-fired power plants presented in Table 1, a value of 45% can be assumed as a target efficiency. This assumption is justified by the actual operational parameters of the newest supercritical units in the Polish system, as listed in Table 1. Specifically, units such as Kozienice B11 (45.6%), Opole B5 (45.6%), and Jaworzno B7 (45.9%) demonstrate that an average fleet efficiency of 45% is technologically achievable and already operational within the current infrastructure.

To estimate the scale of emission reduction in an alternative scenario, in which all existing coal-fired power plants in 2010 were replaced with units operating at 45% efficiency, the following assumptions were made:

1. According to actual data, coal-fired electricity generation in 2010 amounted to 137 TWh,

corresponding to CO_2 emissions of 140 Mt (see Figure 3).

2. All coal units in 2010 had an average efficiency of 31.5%. This figure represents the average net efficiency of the aging Polish coal fleet prior to the large-scale commissioning of supercritical units around 2008. This baseline is critical for calculating the emission intensity of the older generation of 200 MW and 360 MW units that are being replaced.
3. The total electricity generation (AEP) in 2010 was 157 TWh, of which approximately 20 TWh came from non-coal sources.
4. In the analyzed scenario, it was assumed that the efficiency of all coal-fired power plants would increase to 45%, with an increase in their annual electricity generation to 150 TWh. Taking into account unchanged production from other sources (20 TWh), the total electricity generation would reach 170 TWh—equivalent to the level observed in 2024.

Taking into account the above assumptions and using equations (1)–(3), it can be shown that for electricity generation at the level of 150 TWh, produced by coal-fired power plants with an efficiency of 45%, total CO_2 emissions would amount to 107.3 Mt. Comparing this value with the emissions in 2010 indicates that the expected reduction would be approximately 33 Mt CO_2.

This means that in the analyzed scenario, the emission reduction would be 10.4 Mt CO_2 higher than that attributable to IRES under the actual conditions observed in 2024. It is worth noting that in 2024 the total installed capacity of IRES in Poland was approximately 31 GW, including 21 GW from photovoltaics and 10 GW from wind power.

3.2. Sensitivity Analysis

To evaluate the robustness of the "Alternate Transformation" scenario, a sensitivity analysis was performed on two critical parameters: the volume of electricity production and the average net efficiency of the coal fleet.

The first analysis examines how the emission reduction potential changes if the coal-based generation varies relative to the 150 TWh baseline, assuming a constant target efficiency of 45%. As shown in Table 3, the potential for emission reduction is directly proportional to the volume of energy produced by the high-efficiency units.

Table 3. Sensitivity of emission reduction to coal-based electricity production.

Production Level (Relative to Baseline)	Electricity Generation [TWh]	Emission Reduction [Mt CO_2]
100% (Baseline)	150.0	32.7
90%	135.0	29.4
80%	120.0	26.1
70%	105.0	22.9
60%	90.0	19.6
50%	75.0	16.3

The results in Table 3 indicate that a 10% decrease in production from these units (e.g., if displaced by IRES) reduces the direct environmental contribution of the modernized fleet by approximately 3.3 Mt CO_2.

The second analysis assesses the impact of the achieved net efficiency on total emissions, assuming the production volume remains constant at 150 TWh. The sensitivity of these results to technological performance is summarized in Table 4.

Table 4. Sensitivity of emission reduction to average fleet efficiency.

Efficiency [%]	Unit Emissions [Mt/TWh]	Total Emissions [Mt CO_2]	Reduction vs. 2010 [Mt]
45.0% (Target)	0.7153	107.3	32.7
42.5%	0.7574	113.6	26.4
40.0%	0.8047	120.7	19.3
37.5%	0.8584	128.8	11.2
35.0%	0.9197	138.0	2.0

As detailed in Table 4, achieving the 45% efficiency target is critical. A drop in average efficiency to 40% (typical for older supercritical units) results in a 40% decrease in emission reduction potential, falling from 32.7 Mt to 19.3 Mt CO_2.

The sensitivity analysis presented in Tables 3 and 4 demonstrates that the success of the "Alternate Transformation" depends on maximizing the utilization of the most efficient units. While reducing coal production through IRES integration lowers absolute emissions, the specific ecological efficiency of the coal fleet itself is highly sensitive to technological standards. To achieve the projected 33 Mt reduction, the system must prioritize maintaining an average fleet efficiency near 45%.

3.3. Discussion

The above results show that more pragmatic strategy involves maintaining a stable fossil-fuel base while systematically increasing its efficiency and lowering its carbon intensity. This “smart strategy” is reflected in the comparison between the European Union and the United States. While both regions have achieved similar emission declines over the past two decades, the U.S. prioritized a shift toward natural gas, a more stable and cleaner fossil source, paired with high-efficiency standards. This has resulted in electricity prices that are significantly lower (often cited as over 2x lower) than those in the EU [18, 19].

Economically, the integration of IRES into a complex grid primarily yields savings in displaced fuel costs. However, these savings are often substantially lower than the massive capital investments required for IRES volumes and the necessary over-dimensioning of distribution networks [20].

The limitations of a transition focused solely on IRES expansion are clearly illustrated by the German *Energiewende*. Data from 2007 to 2023 reveals a transformation paradox: while IRES production (wind and solar) increased by 157.73 TWh, this growth was almost entirely offset by the decommissioning of 133.31 TWh of zero-emission nuclear power. As a result, the net gain of new low-emission energy in the system was only 24.42 TWh, meaning 85% of the decarbonization potential of OZE was consumed by the nuclear phase-out rather than replacing fossil fuels [18, 19].

Crucially, the observed 46% reduction in German CO_2 emissions during this period was not primarily driven by IRES substitution, but by a drastic drop in total electricity production, which fell by 127.41 TWh (from 631.10 TWh in 2007 to 503.69 TWh in 2023). It suggests that over 71% of the reduction in fossil fuel combustion was attributable to this drop in total supply rather than the expansion of renewables. This demonstrates that without a systemic decline in energy demand, driven by industrial shifts or trade balances, current IRES development rates are insufficient to meet climate goals if stable, zero-emission sources are simultaneously removed.

4. CONCLUSIONS

Based on the above analysis, it can be concluded that in an energy system dominated by low-efficiency coal-fired power plants, priority should be given first to improving their efficiency, and only afterward to the expansion of weather-dependent renewable energy sources (IRES). Increasing the efficiency of coal units to 45% could reduce total CO_2 emissions by up to approximately 30%. Importantly, the scale of this reduction would be greater than in a scenario where the development of IRES is prioritized.

Maintaining modern coal-fired power plants in the system would also help preserve the stability of the electricity grid without the need for costly investments in transmission infrastructure and energy storage, which are necessary when renewable sources have a large share. Further reductions in CO_2 emissions could be achieved in a subsequent stage through the gradual integration of IRES. The cooperation of such renewable sources with modern coal units would be more effective due to the greater operational flexibility of these units.

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