energies

MDPI

Article

Energy Transition Trends in Poland in 2005–2024

Anna Marciniuk-Kluska [1] and Mariusz Kluska [2,*]

[1] Faculty of Social Sciences, University of Siedlce, 39 Zytnia Str., 08-110 Siedlce, Poland; anna.marciniuk-kluska@uws.edu.pl
[2] Faculty of Natural Sciences, University of Siedlce, 54 3-Maja Str., 08-110 Siedlce, Poland
* Correspondence: mariusz.kluska@uws.edu.pl; Tel.: +48-256-431-083

Abstract

This study describes changes in Poland's electricity system during 2005–2024 using PSE gross electricity balances, KOBiZE fuel inputs for public electricity and heat (IPCC 1.A.1.a), KOBiZE electricity-attributed combustion CO_2, and Eurostat SHARES renewable electricity. Published inputs and reporting boundaries are identified separately. Between 2005 and 2024, public electricity-and-heat fuel input declined by 26.0%, while the renewable-electricity share in gross final electricity consumption rose from 2.5% to 30.4%. Directly published electricity-related CO_2 decreased from 120.436 Mt in 2014 to 88.716 Mt in 2024 (−26.3%); electricity-attributed CO_2 declined while PSE gross generation increased in both 2014–2019 and 2019–2024. Fixed-2019 segmented regressions with Newey–West inference, rank trends and period-specific comparisons are interpreted descriptively. CO_2 for 2005–2013 and 2017 is calculated, not independently observed. Because public electricity-and-heat fuel and electricity-attributable emissions have different reporting boundaries, plant efficiency and fuel-specific causal effects cannot be established from these aggregates.

Keywords: Poland; electricity transition; public electricity and heat; KOBiZE; CO_2 emission intensity; cogeneration; renewable electricity; time-series analysis

1. Introduction

Poland entered the study period with an electricity system dominated by coal. The IEA's country assessment documents the significance of coal dependence for energy security and decarbonisation [1]; Nikas et al. examine prospective transition pathways and associated risks [2]. According to Eurostat SHARES, renewable electricity accounted for 2.5% of Poland's gross final electricity consumption in 2005 [3]. We focus on the sectoral indicators observed between 2005 and 2024, using the national energy and emissions inventories as context for broader comparisons.

Between 2005 and 2024, Poland faced the simultaneous challenges of energy security, infrastructure renewal and emissions reduction. Policy benchmarks have different jurisdictions, accounting boundaries and base years. Poland's binding 2020 renewable-energy target was 15% of renewable energy in gross final energy consumption across electricity, heating/cooling and transport—not 15% of electricity generation. For 2030, Directive (EU) 2023/2413 establishes an EU-wide binding renewable-energy share of at least 42.5% of gross final energy consumption and a collective ambition to reach 45%; it does not prescribe those percentages as an identical national obligation for Poland [4]. Poland's nationally adopted June 2026 updated National Energy and Climate Plan (NECP; KPEiK) specifies a national planning contribution of 30–32% in gross final energy consumption for 2030 and separate electricity-sector scenario outcomes [5,6]. Likewise, the EU-wide objective

Check for updates

Academic Editor: Mihaela Simionescu

Received: 14 September 2026
Revised: 22 October 2026
Accepted: 22 October 2026
Published: 24 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

of at least a 55% reduction in net greenhouse-gas emissions by 2030 is measured against 1990 for the Union as a whole; it is not a numerical electricity-sector emissions target for Poland. Under the Effort Sharing Regulation, Poland has a distinct 2030 reduction target of 17.7% relative to 2005 for the covered non-ETS sectors, which excludes electricity generation covered by the ETS [7,8]. The national energy strategy PEP2040, EU ETS, renewable-energy support legislation and other policies constitute relevant historical and planning context, but their adoption alone is not proof that the Polish electricity system achieved a specified decarbonisation result [9–13]. Comparisons across EU Member States also suggest that energy and environmental taxes are not uniformly associated with faster renewable deployment [14]; this study does not transfer those panel estimates to Poland. The original PEP2040 strategy and its forecast annex [15,16], together with the earlier 2019 NECP [17], are separate historical planning documents and must not be confused with the updated 2026 NECP. The European Green Deal communication [18] and the EEA's European trends-and-projections assessment [19] provide wider policy context rather than an electricity-only statistical series for Poland.

This article analyses four complementary domains during 2005–2024: (1) gross domestic electricity production and consumption (PSE); (2) combustible-fuel energy input in public electricity and heat production (KOBiZE, IPCC 1.A.1.a); (3) combustion CO_2 attributable to electricity generation (KOBiZE electricity emission-factor reports); and (4) the Eurostat SHARES renewable-electricity share in gross final electricity consumption. An additional indicative electricity-output CO_2 intensity is calculated using an explicitly identified numerator and denominator. The study uses nonparametric trend tests, fixed-2019 segmented models and Spearman associations as exploratory, non-causal evidence. The four primary indicators are presented in numerical order: Table 1 reports PSE electricity production and consumption; Table 2 reports public electricity-and-heat fuel input; Table 3 reports electricity-attributable CO_2; and Table 4 reports the renewable-electricity SHARES indicator.

Section 2 situates the findings in previous empirical studies. Section 3 specifies the original sources, reporting boundaries, calculations and statistical procedures. Sections 4–7 present annual electricity, fuel, CO_2 and renewable results; Section 8 evaluates statistical trends and associations. Sections 9 and 10 discuss limitations and conclusions, with numerical statistical results provided in Appendix A.

2. State of Research and Main Conclusions of Previous Analyses

Poland-specific electricity-transition research addresses different, partly overlapping questions. Brauers and Oei [20] analyse the political economy of coal dependence, while Skoczkowski et al. [21] model the possible implications of climate policy and EU ETS pricing for conventional generating capacity. Nikas et al. [2] integrate electricity-system and macroeconomic models with stakeholder-perceived transition risks; their prospective scenario analysis is not a retrospective, consistently bounded 2005–2024 cross-indicator accounting test. Jorge-Vazquez et al. [22] compare Poland and Spain under evolving EU policy but do not establish the observation-level fuel/CHP/emissions harmonisation required here. These contributions show that generation technologies, institutions and policy instruments have been investigated substantively; the present paper should not claim that empirical research on Poland is absent. Cholewa et al. [23] also examine obstacles to renewable-energy-system transition in Poland and Azerbaijan; their comparative scope differs from the accounting exercise undertaken here.

Two further studies establish more precise comparators for the proposed contribution. Gołaś [24] uses decomposition and decoupling analysis for energy-related CO_2 and economic growth over 2004–2020; its national GDP-and-energy boundary differs from the

present electricity-balance perimeter. Gajdzik et al. [25] nalyse investment, innovation and renewable electricity during 2010–2023 by regression and clustering, identifying a rapid post-2020 development stage; their explanatory variables and observation period differ from the five annual indicators assessed here. Official KOBiZE and GUS publications [26–28] provide fuel and emissions accounting at specific inventory boundaries, not an automatically matched electricity-only series. Together, these studies motivate a transparent comparison of time periods and associations while revealing why the credibility of any new integrated indicator depends on primary-source reconciliation.

Previous analyses answer related, but different, questions: scenario studies [2,21] evaluate possible system pathways; cross-country comparisons [22] emphasise policy and national heterogeneity; Gołaś [24] studies economy-wide CO_2–GDP decoupling; and Gajdzik et al. [25] analyse investment and renewable deployment rather than the present four source-defined annual indicators. These sources neither provide nor claim a reconciled annual electricity-only fuel–emissions ledger with heat-only exclusions and unit-level CHP allocations. The present contribution is consequently an explicit comparison of published national indicators, their provenance and their accounting limits, rather than a new harmonised plant-level energy balance.

The source boundaries have a material analytical consequence. PSE reports operational gross electricity output; KOBiZE NID 2026 publishes combined public electricity-and-heat fuel consumption under IPCC 1.A.1.a; and KOBiZE electricity-emission-factor reports allocate combustion CO_2 to electricity. The inventory and electricity-emissions series must therefore be interpreted separately. For 2005–2013 and 2017, the Table 3 figures are derived using stated calculations; the other ten Table 3 masses come from directly published annual KOBiZE reports [26,29,30]. Existing CHP emission-allocation research provides an important methodological comparator. Schwenk-Nebbe, Victoria and Andresen [31,32] applied a heat-reference-efficiency assumption to reconstruct a historical public-electricity CO_2 proxy through 2018. In the present analysis, the precise reporting perimeters are identified rather than assigning combined electricity-and-heat fuel directly to electricity. Electricity output and heat are not interchangeable, and a physically meaningful fuel-based emission factor would require matched fuel and emissions accounts [33].

Research gap and contribution. The paper assembles and contrasts PSE annual gross-generation and consumption observations, KOBiZE category 1.A.1.a public electricity-and-heat fuel input, KOBiZE electricity-attributable CO_2 masses and Eurostat electricity SHARES. The novel element is an explicit audit of reporting perimeters, a separation of directly published from calculated emissions, and descriptive comparisons across fixed periods. Combining these series on a calendar-year axis does not establish identical source populations or recover heat-only and CHP allocation records; such matched allocations would be required for a physical electricity-only fuel or efficiency account. The companion workbook now identifies observation class and source at the year level and makes its remaining provenance limitations explicit.

The quantitative analysis differentiates direct publications from historical calculations and refrains from equating fuel input to public electricity-and-heat production with electricity-only carbon emissions. It is designed to describe associations and changes in trend rather than to identify causality from policy adoption.

The research questions are: (RQ1) How did PSE electricity production/consumption, KOBiZE public electricity-and-heat fuel input, electricity-attributed CO_2 and Eurostat SHARES change during 2005–2024? (RQ2) How do the pre-2019 and post-2019 descriptive changes compare? (RQ3) What rank associations and source-bounded CO_2–gross-generation decoupling patterns are visible, including in first differences? (RQ4) Which

prominent observed years coincide with wider market or policy developments, without statistically claiming an identified change point or causal effect?

A related publication by the present authors surveyed the transformation of Poland's energy market in the EU context [34]. The present article differs in scope and method: it concentrates on the electricity sector, compiles annual indicators for 2005–2024, quantifies their trajectories and assesses accounting comparability across generation, fuel inputs, emissions and renewable shares. The previous publication is cited here to identify the relationship between the two studies, rather than as independent validation of our numerical results.

3. Methodology

The annual dataset covers 2005–2024. The PSE national electricity balance, KOBiZE category 1.A.1.a energy input, KOBiZE electricity-attributable combustion CO_2 and Eurostat nrg_ind_ren (electricity SHARES) are kept as separately defined indicators. The same calendar-year and unit convention is used throughout, but reporting boundaries are not silently conflated. Historic CO_2 values calculated for 2005–2013 and 2017 are distinguishable from directly published masses in Table 3 and the workbook.

Source register and reporting editions. Gross production and consumption: PSE, Raport 2024 KSE, Section 6.3, Table 6.2 [29]. Fuel input: KOBiZE, National Inventory Document 2026, Table 3.2.6.1, TOTAL, IPCC 1.A.1.a Public electricity and heat production, annual PJ values [26]. Electricity-attributable CO_2: KOBiZE annual Wskaźniki emisyjności dla energii elektrycznej reports (2014–2024 reporting years) [30]. Renewables: Eurostat nrg_ind_ren, Poland, renewable energy in gross final electricity consumption (%), SHARES methodology [3].

Electricity-related CO_2 reconstruction. Ten annual CO_2 masses (2014–2016 and 2018–2024) are directly reported by KOBiZE. The 2017 figure equals 149,400,430 MWh multiplied by the published rounded combustion-emission factor of 814 kg CO_2/MWh and divided by 10^9, yielding 121.612 Mt CO_2. Values for 2005–2013 are calculated as $\hat{C}(t) = F_1.A.1.a(t) \times k$, where F(t) is the published KOBiZE fuel total in PJ and k is the median of the four published CO_2/F ratios for 2014–2016 and 2018. This parameter is an empirical historical reconstruction coefficient across two non-identical statistical populations; it is not a physical fuel-carbon emission factor. The model input series, coefficient and annual formulae are disclosed in the accompanying workbook.

Statistical design. OLS trend slopes, two-sided Mann–Kendall tests, Sen slopes, Durbin–Watson and Ljung–Box residual diagnostics are tabulated in Appendix A. A continuous segmented OLS model, $y(t) = \alpha + \beta(t - 2005) + \delta \cdot \max(0, t - 2019) + \varepsilon(t)$, uses a prespecified 2019 knot, with two-lag Newey–West heteroskedasticity/autocorrelation-consistent inference for δ; it does not estimate the date of a structural break. Separate endpoint comparisons (2005–2019, 2019–2024 and, where directly observed for CO_2, 2014–2019 and 2019–2024) complement this model. Only the ten directly published CO_2 masses, rather than the early reconstructions or the rounded-factor 2017 value, enter emissions inference.

RQ2. Within the prespecified continuous segmented model, β denotes the fitted slope before the 2019 knot, $\beta + \delta$ the fitted slope after it, and δ the fitted difference; the knot is not a statistically selected turning point. Appendix A Table A1 reports the full-period trend summaries, and Appendix A Table A2 reports HAC *p*-values. For clarity, Section "Descriptive Electricity, Emissions and Renewable Associations" also reports endpoint differences in fixed calendar intervals; these are descriptive and are not interchangeable with fitted slope changes. The short post-2019 segment limits power and precision.

RQ3: Spearman rank correlations are calculated separately for levels and first annual differences. For CO_2, only directly published KOBiZE observations enter the level correlations, and only adjacent years for which both masses were directly published contribute to

differenced correlations. Reconstructed historical entries and the rounded-factor value for 2017 are excluded from inferential CO_2 calculations. An association in trending levels is not proof of contemporaneous substitution, let alone policy causality.

Exploratory inference and data limitations. The source series are not a balanced, matched electricity-only physical account. The emissions test sample excludes the 2005–2013 reconstructions and the 2017 rounded-factor estimate; first differences additionally require adjacent directly reported years. Conventional OLS precision can be optimistic under residual serial dependence, so OLS slopes and R^2 are descriptive, residual diagnostics are reported, and significance attached to the segmented slope difference uses two-lag Newey–West covariance. No turning point is identified by breakpoint-search inference and no policy effect is estimated.

3.1. Data Provenance, Reporting Boundaries and Source Harmonisation

Official national series were selected according to geographic scope (Poland), reporting year, target statistic and measuring unit. Rather than force different reporting populations into a false common inventory, electricity production/consumption, public electricity-and-heat fuel input, electricity-attributable CO_2 and the Eurostat SHARES indicator are defined independently and linked only through carefully interpreted descriptive analyses [3,26,29,30].

Electricity balance. PSE, Raport 2024 KSE, Section 6.3, Table 6.2 supplies annual gross domestic electricity production and gross domestic consumption in GWh (2005–2024), converted to TWh by division by 1000. Their difference is net imports when positive. The gross production total includes electricity from combustible and non-combustible technologies, while electricity trade is not domestic generation [29].

Combustible energy input. Table 2 transcribes the published TOTAL annual PJ entries from NID 2026 Table 3.2.6.1 for category 1.A.1.a, Public electricity and heat production [26]. This perimeter includes electricity-only generation, CHP and public heat production; it is not electricity-only fuel consumption. A companion Mtoe value is computed as PJ/41.868 using the exact energy-equivalence definition. Every reported input is sourced to the same NID edition.

CHP and heat boundaries. Under the Eurostat/IEA electricity-and-heat questionnaire, CHP fuel may be allocated to electricity and heat in proportion to matched annual useful outputs where a more accurate national method is unavailable [33]. The present Table 2 is not so allocated: it is an official all-public-electricity-and-heat fuel total. A fuel-based t CO_2/TJ coefficient must not be calculated by dividing Table 3 electricity-only CO_2 by this broader Table 2 input.

Source-specific traceability versus complete harmonisation. The annual values can be followed to named PSE, KOBiZE and Eurostat publications and the workbook source register. However, neither raw individual-plant emissions and heat-only inputs nor the components used by Eurostat to normalise renewable electricity are available in the provided material. Year-level report references therefore support verification of quoted published figures, not a claim that electricity-only fuel inputs and emissions have been reconciled installation by installation. Additional national statistical context is available in the ARE electricity-statistics publications [35] and URE's 2024 electricity-market overview [36]. URE's separate report on electricity supplied to distribution networks from renewable microinstallations [37] does not, by itself, establish total prosumer self-consumption; none of these sources replaces the PSE gross operational series in Table 1.

Electricity-related CO_2. Table 3 is based on KOBiZE annual reports that attribute combustion CO_2 to electricity generation [30]. Exact published totals for 2014–2016 and 2018–2024 are retained in Mt CO_2 (reported kg divided by 10^9), whereas the 2017 total

is obtained from published MWh and the rounded 814 kg/MWh coefficient, and earlier 2005–2013 totals follow the reproducible historical model described above. Their classifications and primary-report URLs are preserved in the workbook.

Common electricity-output emission indicator. Let $C_e(t)$ be the electricity-attributable CO_2 mass [Mt] in Table 3 and Ggross(t) the PSE gross domestic electricity production [TWh] in Table 1. We calculate $I(t) = 1000 \times C_e(t)/Ggross(t)$ [g CO_2/kWh]. This is an indicative national gross-electricity-output ratio, not the specific KOBiZE combustion-generation emission factor, and not a carbon-emission coefficient per unit of combustible input; it must be interpreted with its PSE/KOBiZE population differences disclosed.

Renewable electricity. Table 4 presents the official Eurostat SHARES renewable-electricity share in gross final electricity consumption, dataset nrg_ind_ren, PL, annual, unit PC [3]. The denominator differs from PSE gross production, and this indicator must not be renamed as the proportion of renewable electricity in domestic gross generation. Country and year filters and the stable statistical definition are recorded in the workbook.

Table 1. Domestic electricity production and consumption in 2005–2024 (TWh).

Year	Gross Production [TWh]	Gross Consumption [TWh]
2005	156.024	144.838
2006	160.848	149.847
2007	159.528	154.170
2008	155.567	154.980
2009	150.923	148.718
2010	156.342	154.987
2011	163.153	157.909
2012	159.853	157.013
2013	162.501	157.980
2014	156.567	158.734
2015	161.772	161.438
2016	162.626	164.625
2017	165.852	168.139
2018	165.214	170.932
2019	158.767	169.391
2020	152.308	165.532
2021	173.583	174.402
2022	175.157	173.479
2023	163.629	167.518
2024	166.990	168.956

Source: PSE, Raport 2024 KSE, Section 6.3, Table 6.2 (1990–2024), verified against Table 6.1 for 2022–2024. Original GWh figures converted to TWh (three decimals); net imports = gross domestic consumption − domestic generation. https://teams.public.onecdn.static.microsoft/evergreen-assets/safelinks/2/atp-safelinks.html (accessed 12 October 2026). Source identification: PSE, "Raport 2024 KSE", reporting year 2024 (PSE annual online report), Section 6.3, Table 6.2, annual "Krajowa produkcja i zużycie energii elektrycznej w latach 1990–2024 [GWh]"; Section 6.2, Table 6.1, 2022–2024 gross generation, cross-border balance and domestic demand. The data in Table 1 are the gross operational series, converted GWh ÷ 1000 to TWh, and the import balance is calculated as consumption minus generation [29].

Autoproducers, electricity trade and public heat generation are handled according to their source publication definitions. The PSE gross balance is not treated as an electricity-only fuel inventory; the KOBiZE 1.A.1.a fuel data include heat production, while electricity-attributable CO_2 follows the agency annual allocation. These boundaries are fully disclosed and are not used to imply installation-specific generation efficiency.

Cogeneration methodology. With unit-level fuel F and outputs E (electricity) and H (useful heat) on a common energy basis, the optional electricity share is $\alpha = E/(E + H)$ [33]. Such an allocation is not implemented in the national Table 2 published TOTAL series;

therefore, no falsely harmonised CO_2-per-fuel emission factor or physical CHP efficiency is inferred from the current aggregated tables.

Provenance and reproducibility. The workbook supplies the calendar-year source register, reporting definitions and source links, source-data classification and arithmetic used for calculated indicators. This supports reproducibility of reported published entries and arithmetic, but it is not a substitute for the institutions' primary extraction files or for missing unit-level heat/CHP allocation records. In particular, no heat-only fuel exclusion or CHP electricity/heat allocation coefficient was estimated for KOBiZE 1.A.1.a, and no separate year-specific RES generation numerator, prosumer self-consumption adjustment or weather-normalisation component has been reverse-engineered from Eurostat SHARES. Accordingly, Tables 2–4 remain deliberately separate official or expressly modelled indicators, not a harmonised electricity-only production account. The companion workbook has a year-level provenance audit and a fixed-period/decoupling calculation sheet.

Reporting period. Every primary series is indexed to the calendar year measured (2005–2024), which may differ from its publication date. The KOBiZE NID edition is 2026, the PSE balance edition is 2024, and the Eurostat values follow the named SHARES annual database [3,26,29].

Reporting definitions. PSE gross domestic electricity production measures domestic generation. KOBiZE 1.A.1.a fuel input includes public electricity-only, CHP and heat production; its figures are not electricity-only input. Electricity-attributable CO_2 is taken from a different annual KOBiZE publication. Eurostat SHARES refers to renewable electricity in gross final electricity consumption, which uses a different denominator and statistical adjustment conventions from PSE generation. The authors therefore do not multiply SHARES percentages by PSE gross generation to claim actual renewable TWh or divide KOBiZE electricity-attributed CO_2 by mixed public electricity-and-heat fuel to obtain a physical emission factor.

3.2. Indicator Definitions, Physical Units and Emission-Intensity Accounting

For fuels, 1 Mtoe = 41.868 PJ and 1 TWh = 3.600 PJ; Mt CO_2 denotes mass of carbon dioxide and must not be confused with energy units. Combustible-energy input is measured in net-calorific energy, whereas hydro, wind and photovoltaics have different physical-energy content accounting. This distinction is necessary when interpreting Table 2 alongside gross generation [26,38–41]. The IEA World Energy Balances [42] and the GUS 2022–2023 energy-balance tables [43] offer complementary source definitions and historical energy-balance context. The IPCC's energy-systems assessment [44] provides mitigation context, rather than matched electricity-and-heat fuel inputs for the present calculations.

Let Ggross(t) [TWh] denote PSE gross domestic electricity production, Cgross(t) [TWh] gross domestic consumption, Fpublic(t) [PJ] published public electricity-and-heat fuel use under IPCC 1.A.1.a, and C_e(t) [Mt CO_2] electricity-attributable combustion emissions. Trade is Cgross − Ggross; neither fuel nor CO_2 is mechanically scaled by net electricity imports.

The fuel series is reported in PJ with Mtoe conversion as Fpublic(t)/41.868. The electricity-output intensity is I(t) = 1000 C_e(t)/Ggross(t) g CO_2/kWh. A matched fossil-fuel emission factor would instead require CO_2 and fuel inputs sharing electricity/heat scope and fossil/biogenic treatment; this requirement is not satisfied by directly dividing Tables 2 and 3.

Analytical role of derived quantities. The retained I(t) = 1000 C_e(t)/Ggross(t) [g CO_2/kWh] is an indicative electricity-attributed emissions/output descriptor with explicitly different KOBiZE and PSE coverage; it is not the official KOBiZE combustion-generation emission factor or a thermal-efficiency measure. The earlier fuel-only output/input index A(t) is not used. For audit purposes, the workbook additionally reports public electricity-and-heat

fuel input per unit of all PSE domestic generation, Fpublic(t)/Ggross(t) [PJ/TWh]. This is only a cross-series normalisation indicating movement in the aggregate public-fuel total relative to all domestic generation, not a plant heat rate, a measure of efficiency, or an electricity-only fuel requirement. The underlying fuel and generation series carry the primary information.

3.3. Statistical Interpretation and Chart Presentation

Figure 1 illustrates domestic gross electricity production and consumption. Figures 2–4 reproduce the KOBiZE electricity-related combustion CO_2 values, the Eurostat SHARES renewable-electricity share and public electricity-and-heat fuel input, respectively. The 2005–2013 and 2017 CO_2 points are identified in Table 3 and derived using the stated methods; statistical inference for CO_2 uses only the ten directly reported annual emission totals. Curve shapes do not identify individual policy effects, and no chart is extrapolated beyond 2024.

3.4. Policy-Benchmark Definitions and Treatment of 2030 Scenarios

The present renewable indicator is Eurostat SHARES renewable energy in gross final electricity consumption, not the share of gross domestic electricity generation. It must also be distinguished from renewable energy in gross final energy consumption across all sectors and from EU-wide legally binding renewable targets. Consequently, Table 4 is interpreted within its original Eurostat electricity denominator [3,4,45].

Comparisons with legally binding 2030 goals distinguish an EU-wide gross-final-energy share, Poland's all-energy planning contribution, and renewable electricity in gross final consumption. The present Eurostat electricity series does not by itself demonstrate achievement of any economy-wide national or EU target; forward scenarios are external conditional projections [3–6].

Prospective electricity demand and resource adequacy are separate analytical tasks. Annual gross consumption Cgross [TWh/year] is an energy volume, whereas peak load Pmax [GW], firm/derated available capacity, reserves, ramping capability, storage duration, interconnection availability and reliability criteria (including loss-of-load expectations) determine adequacy in stressed hours. Annual energy provides only a temporal average: Paverage [GW] = annual consumption [TWh] × 1000/8760, which cannot substitute for peak-load modelling. PSE's Network Development Plan 2025–2034, Section 4.4, employs distinct free-transition and dynamic-transition demand cases, climate-year sensitivities and separate hourly peak/load analyses [46]. Consequently, neither a 2030 electricity-consumption point forecast of 170–175 TWh nor continued system stability is derived or asserted from the historical indicator series. More generally, electricity-security and interconnection requirements are assessed separately from energy volumes in international power-sector outlooks [47,48]. Poland-specific renewable-energy prospects in IRENA's REmap 2030 study [49] and the broader IEA Renewables 2024 outlook [50] are prospective reference material, not measured entries in the present annual dataset.

4. Electricity Production and Consumption (2005–2024)

During the period under review, the Polish power sector transitioned from a phase of moderate demand growth in 2005–2015, through stagnation and crises-related shocks (the 2008–2009 global financial crisis and the 2020 COVID-19 pandemic), to a period of generation-mix change and marked demand fluctuations (including a 2021 consumption peak) [51–56]. Table 1 presents the total domestic electricity production and gross domestic consumption (including end-user consumption, network losses and power plant operation) in the years 2005–2024. Ember's European Electricity Review 2025 [57] offers broader

comparative electricity-sector context; its estimates are not substituted for the PSE gross domestic production and consumption series.

Arithmetic reconciliation of the 2024 gross electricity balance: 168.956 − 166.990 = +1.966 TWh (net imports). A 1 GWh published-versus-subtracted difference may occur for the 2022 trade balance (PSE Table 6.1 reports net exports of 1679 GWh, while the rounded production–consumption entries in Table 1 imply 1678 GWh); it should not be confused with a multiterawatt-hour discrepancy [29].

Table 1 reports the PSE gross electricity series on a single accounting basis. In 2005, Poland generated 156.024 TWh and consumed 144.838 TWh, yielding net exports of 11.186 TWh. In 2006, the corresponding net export balance was 11.001 TWh. Electricity consumption increased to 154.980 TWh in 2008 and decreased to 148.718 TWh in 2009 (−4.0% year on year) during the global financial crisis. By 2015, production (161.772 TWh) and gross consumption (161.438 TWh) had become nearly equal, corresponding to net exports of just 0.334 TWh. The balance changed sign in 2014, 2015 and 2016; Poland then recorded net imports in each year from 2016 through 2021. In 2018, demand reached 170.932 TWh and generation 165.214 TWh, producing a net import balance of 5.718 TWh (3.3% of gross consumption). Such descriptive balances do not determine the separate impacts of prices, demand, policy or cross-border trading conditions.

Between 2019 and 2021, gross consumption first declined and then rebounded: 169.391 TWh in 2019, 165.532 TWh in 2020 (−2.3% year on year) and 174.402 TWh in 2021 (+5.4% year on year). In 2019 and 2020, net imports were 10.624 TWh and 13.224 TWh, respectively, with the latter the maximum in the PSE 2005–2024 series. In 2021, domestic production increased from 152.308 to 173.583 TWh (+21.275 TWh, +14.0% relative to 2020), and the import balance fell to 0.819 TWh. Poland became a net exporter in 2022, with production of 175.157 TWh, consumption of 173.479 TWh and net exports of 1.678 TWh. The balance reversed again in 2023: consumption of 167.518 TWh exceeded production of 163.629 TWh by 3.889 TWh. These changes coincided with the pandemic, the energy-price shock, fuel-market developments and increasing renewable generation, but this aggregate series does not quantify the causal share of any one driver.

In 2024, Polish domestic production amounted to 166.990 TWh and gross domestic consumption to 168.956 TWh according to PSE Tables 6.1–6.2. The resulting net import balance was 1.966 TWh, equal to approximately 1.16% of gross consumption and about half the 2023 value of 3.889 TWh. Consumption increased by 0.9% between 2023 and 2024, whereas production increased by 2.1%; their different growth rates explain the narrowing import gap. The reported annual net balance is a cross-border accounting quantity, not a separate estimate of domestic electricity production.

Over 2005–2024, gross domestic electricity consumption increased from 144.838 to 168.956 TWh, i.e., by 24.118 TWh or 16.7%. Domestic gross generation also increased, from 156.024 to 166.990 TWh (+7.0%), indicating a modest increase in domestic generation over the study period. Gross consumption reached its highest value of 174.402 TWh in 2021 and then fell to 168.956 TWh in 2024, while the net balance fluctuated between exports and imports. Between 2013 and 2023, consumption increased from 157.980 to 167.518 TWh (+6.0%). The slower expansion of electricity demand relative to economic activity may be consistent with structural changes and energy-efficiency measures, but the data do not establish their individual contributions. Annual fluctuations and evolving electrification needs make projections of electricity demand to 2030 beyond the scope of the present historical analysis.

Demand and capacity adequacy. The gross annual consumption of 168.956 TWh in 2024 corresponds arithmetically to an annual-average load of about 19.29 GW (168.956 × 1000/8760); this is not the winter or summer peak requirement. Even if gross

consumption were hypothetically 170–175 TWh in 2030, its annual-average equivalent would be only 19.41–19.98 GW, not the necessary firm capacity. These 170–175 TWh figures are an illustrative conditional range, not a forecast produced by this study or an identified value from the 2026 NECP. Electrification, industrial demand, heat pumps, electric vehicles, data centres, weather and demand response may shift annual energy and peak load in different directions. PSE explicitly evaluates climate-dependent demand scenarios and peak-power requirements separately [46]; no inference on capacity reduction, reliability or system stability is made from a nearly flat annual TWh profile.

Figure 1 reproduces the verified PSE annual production and consumption series in Table 1. The vertical difference between the two curves is net imports when consumption is higher, and net exports when generation is higher. Rather than a permanent switch from export to import in 2015, the trade balance changed sign more than once; the largest net imports occurred in 2020 (13.224 TWh), followed by a reduction in 2021, net exports in 2022 and renewed net imports in 2023–2024. The 2024 gap was 1.966 TWh. The updated chart therefore documents changing domestic supply-demand balances without implying a monotonic trend or attributing these changes to one technology or policy.

The 2024 PSE balance records gross domestic electricity consumption of 168.956 TWh and gross domestic generation of 166.990 TWh [29]. International country rankings, grid-loss comparisons and the magnitude of savings attributable to network modernisation require separate, consistently defined source series. We do not infer those quantities from the annual gross electricity balance.

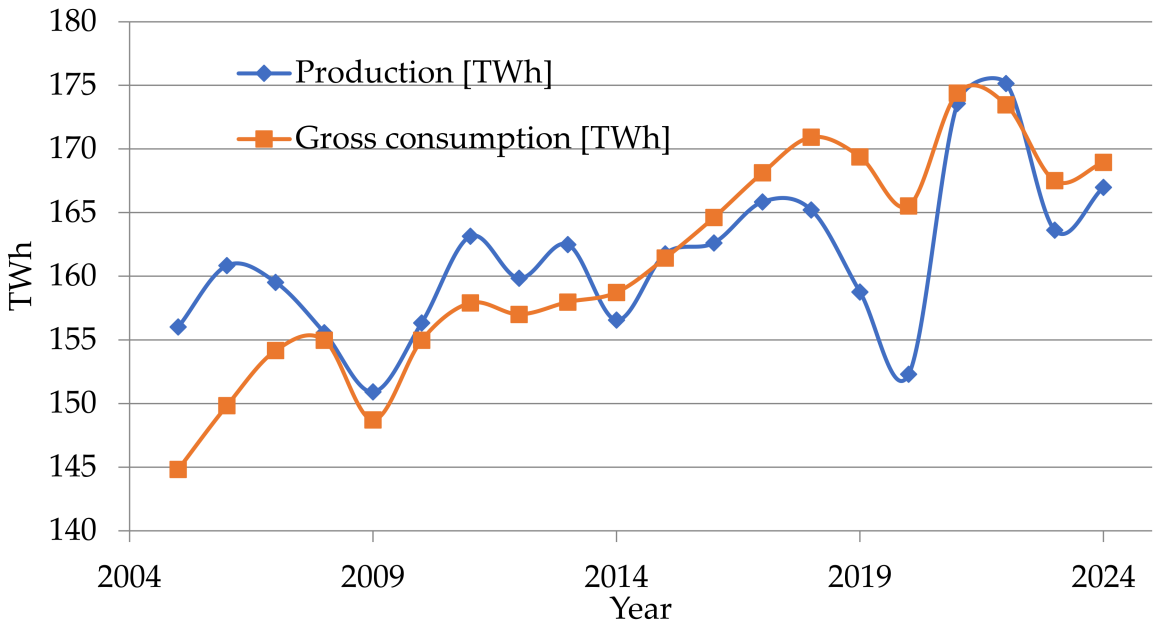


Figure 1. Trend in domestic electricity production and consumption in 2005–2024. Source: Own study based on data from Table 1.

5. Combustible Energy Input in Public Electricity and Heat Production

Table 2 provides the complete annual fuel-energy consumption within IPCC category 1.A.1.a, Public electricity and heat production. Values come directly from KOBiZE National Inventory Document 2026 Table 3.2.6.1, row TOTAL [26]. This category includes public thermal electricity-only plants, combined heat and power plants and heat-only production. It must not be mislabelled as fuel consumed exclusively for electricity generation.

Table 2. Fuel input in public electricity and heat production (IPCC 1.A.1.a), Poland, 2005–2024 (PJ).

Year	Public Electricity and Heat Fuel Input [PJ]
2005	1769.038
2006	1827.800
2007	1781.611
2008	1734.266
2009	1691.497
2010	1759.473
2011	1770.070
2012	1746.424
2013	1736.220
2014	1645.036
2015	1663.603
2016	1655.498
2017	1659.104
2018	1651.403
2019	1543.925
2020	1457.972
2021	1665.130
2022	1573.766
2023	1341.625
2024	1309.951

Source: KOBiZE, Poland's National Inventory Document 2026, Section 3.2.6.2.1, Table 3.2.6.1, TOTAL, category 1.A.1.a [26]. An independent energy-equivalent representation in Mtoe is available in the accompanying workbook (1 Mtoe = 41.868 PJ).

The officially documented combined electricity-and-heat fuel input declined from 1769.038 PJ (42.253 Mtoe) in 2005 to 1309.951 PJ (31.288 Mtoe) in 2024, a reduction of 26.0%. This result refers to the public electricity-and-heat inventory boundary and is not an electricity-only reduction or a direct measure of generating efficiency.

Changes in fuel consumption can reflect altered electricity and heat demand, fuel mix, CHP use, generating efficiency and output from non-combustible sources. The total alone cannot disentangle these contributions or attribute changes to any individual renewable-energy support measure.

The annual fuel data are consistently drawn from one official KOBiZE inventory series. They are not replaced by an eclectic mixture of other institutional totals, whose fuel coverage and generating populations may differ.

Because the public heat and electricity categories are jointly included in Table 2, no CO_2-per-fuel coefficient is inferred from the separately electricity-attributed CO_2 series in Table 3. This keeps the physical definition of the input consistent throughout the analysis [26,30,33].

6. Carbon Dioxide Emissions Attributable to Electricity Production

Table 3 reports KOBiZE combustion CO_2 attributed to electricity rather than the wider IPCC public electricity-and-heat category. Ten annual masses (2014–2016 and 2018–2024) are directly available in KOBiZE electricity-emission-factor reports [30]. Values for 2005–2013 are modelled from the disclosed empirical coefficient and the KOBiZE fuel series; 2017 is calculated using an annual output quantity and a rounded KOBiZE factor. Those ten calculated years are identified separately from source-observed masses, and statistical tests of emissions use only the ten directly reported years.

Table 3. Electricity-attributable combustion CO_2 in Poland (Mt CO_2) and indicative gross-electricity intensity (g CO_2/kWh), 2005–2024. * Historical reconstruction (2005–2013); † calculated from the rounded 2017 KOBiZE factor; unmarked emissions are directly published KOBiZE masses.

Year	Electricity CO_2 [Mt]	CO_2 Intensity [g/kWh]
2005	128.164 *	821.4 *
2006	132.421 *	823.3 *
2007	129.075 *	809.1 *
2008	125.645 *	807.7 *
2009	122.546 *	812.0 *
2010	127.471 *	815.3 *
2011	128.239 *	786.0 *
2012	126.526 *	791.5 *
2013	125.786 *	774.1 *
2014	120.436	769.2
2015	120.265	743.4
2016	119.213	733.0
2017	121.612 †	733.3 †
2018	119.900	725.7
2019	107.360	676.2
2020	99.611	654.0
2021	116.561	671.5
2022	113.799	649.7
2023	91.799	561.0
2024	88.716	531.3

Sources: KOBiZE annual Wskaźniki emisyjności dla energii elektrycznej (annual reports 2014–2024) [30]; PSE gross generation [29]. Methods: $\hat{C}$(2005–2013) = Fpublic × median(C_i/F_i) for published i = 2014–2016 and 2018; $\hat{C}$(2017) = 149,400,430 MWh × 814 kg CO_2/MWh÷10^9; I(t) = 1000 × C_e(t)/Ggross(t). The workbook specifies annual report URLs and complete formulae.

Interannual source-based check. The KOBiZE electricity-attributed masses are 120.265 and 119.213 Mt in 2015–2016 (−0.9%), and 113.799 and 91.799 Mt in 2022–2023 (−19.3%). PSE gross generation fell from 175.157 to 163.629 TWh between 2022 and 2023 (−6.6%) [29,30]. The larger percentage emissions decline is not taken as evidence of a particular fuel switch or CHP-allocation effect: those explanations require matched combustion fuel mix, heat outputs, biogenic treatment and allocation records that are not supplied by these two aggregate series. The directly sourced 2014–2024 endpoint change is −26.3%; no earlier unreconciled CO_2 totals enter the results.

Directly published electricity-related combustion CO_2 decreased from 120.436 Mt in 2014 to 88.716 Mt in 2024 (−26.3%). Over the same source-year endpoints, indicative emissions relative to PSE gross national production declined from 769.2 to 531.3 g CO_2/kWh. The full 2005–2024 descriptive table remains complete, but early calculated observations are not used as independent measurements in emissions hypothesis testing.

The long-run CO_2 trajectory is influenced by generating technology, electricity demand, fuel use and electricity imports. The annual descriptive values cannot quantify the separate effects of EU ETS prices, renewable generation or heat production. The aggregate reporting boundaries also do not provide an electricity-only combustible-energy denominator for a physically interpretable t CO_2/TJ factor.

Year-to-year CO_2 movements during the pandemic and energy-price shock should therefore be interpreted as associations. Statistical tests are restricted to directly published masses and are detailed in Appendix A.

Figure 2 summarises the electricity-related CO_2 trajectory in Table 3. Comparisons with EU ETS installation totals or with the broader IPCC category 1.A.1.a would require

matching the installation population and electricity/heat allocation. The plotted line is not used as a causal estimate or forecast.

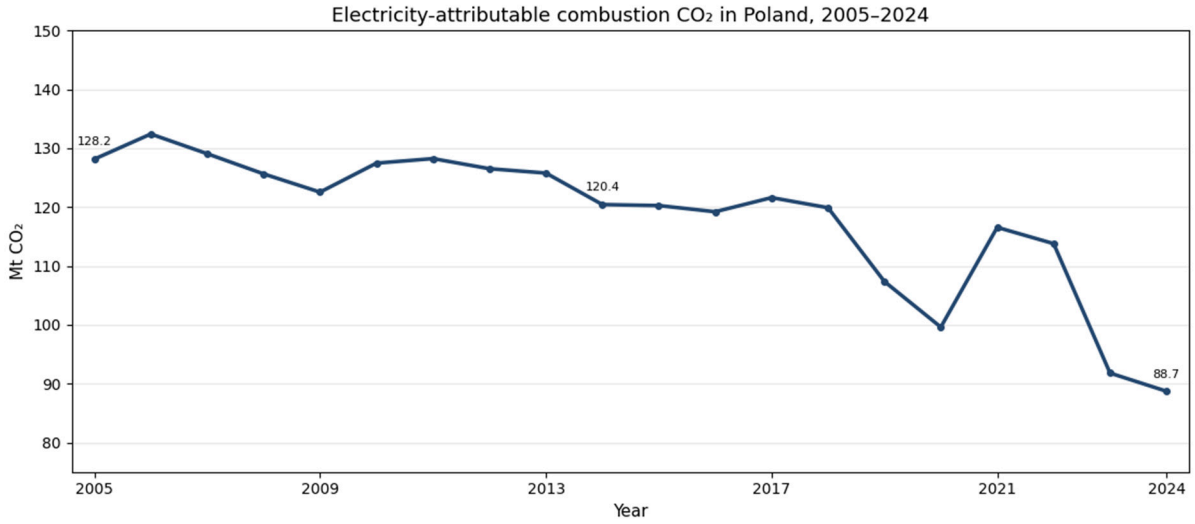


Figure 2. Annual electricity-attributable combustion CO_2 (Mt CO_2), 2005–2024. The early historical reconstruction and rounded-factor 2017 calculation are specified in Table 3; direct KOBiZE masses are used for inferential testing [30]. Source: KOBiZE electricity-emission-factor reports [30]; calculations in Table 3 and the Supplementary Workbook.

The share of lower-carbon generating technologies and changing dispatch conditions are plausible contextual explanations for reduced electricity-related emissions, but no causal decomposition is estimated. The reporting definition of Table 3 is distinct from a complete national greenhouse-gas inventory, which includes other energy sectors and gases [16,58].

Climate benchmarks and measured electricity-related CO_2 have different reference years and sectoral boundaries. The EU-wide 2030 net greenhouse-gas target and Poland's non-ETS obligation cannot be assessed directly from the electricity-emissions mass in Table 3. The source-defined 2014–2024 CO_2 decline is a descriptive historical observation, not a compliance test for the EU-wide target [7,8].

7. Renewable Energy in Gross Final Electricity Consumption

Renewable-electricity accounting. Table 4 uses Eurostat SHARES, i.e., the share of energy from renewable sources in gross final electricity consumption, rather than the share of gross domestic electricity generation reported by PSE. Its 2024 value is 30.4% [3]. A SHARES percentage must not be multiplied by the PSE gross generation total to estimate a supposedly verified RES output in TWh: the two denominators and their treatment of cross-border electricity, prosumer production and normalised wind/hydropower differ. A physical RES-generation balance would require a matched technology-level numerator, self-consumption treatment and the identical annual generation denominator, which are not reconstructed here.

Table 4. Share of renewable electricity in gross final electricity consumption (%), Poland, 2005–2024 (Eurostat SHARES).

Year	RES Share of Gross Final Electricity Consumption [%]
2005	2.5
2006	2.9
2007	3.3

Table 4. *Cont.*

Year	RES Share of Gross Final Electricity Consumption [%]
2008	4.2
2009	5.7
2010	6.5
2011	8.1
2012	10.6
2013	10.7
2014	12.4
2015	13.4
2016	13.3
2017	13.1
2018	13.0
2019	14.4
2020	16.2
2021	17.2
2022	21.0
2023	25.8
2024	30.4

Source: Eurostat nrg_ind_ren, geo = PL, renewable electricity in gross final electricity consumption, percentage unit, annual [3]. The indicator is not the renewable fraction of PSE domestic gross generation. Dataset compatibility. The current 2024 Eurostat SHARES electricity percentage (30.4%) and the PSE gross electricity generation total (166.990 TWh) do not form a matched numerator–denominator pair. No 49.1 TWh or 49.8 TWh renewable-production reconciliation is inferred from their product. Technology-resolved renewable generation, imports/exports, prosumer self-consumption and wind/hydro normalisation would have to be brought onto one statistical boundary before such a comparison could be made.

The official Eurostat share of renewable electricity rose from 2.5% in 2005 to 30.4% in 2024, an increase of 27.9 percentage points. The historical trajectory includes stages of wind deployment and later rapid expansion of solar photovoltaics, but the share alone cannot quantify a causal policy effect [3,59].

For RQ2, the Eurostat SHARES increase was +11.9 percentage points in 2005–2019 (2.5% to 14.4%) and +16.0 percentage points in 2019–2024 (14.4% to 30.4%). These non-overlapping endpoint changes cover intervals of unequal length and do not constitute a causal acceleration estimate. The fixed-2019 segmented SHARES slope rises from 0.867 to 2.674 percentage points per year (δ = +1.806; two-lag HAC p = 0.000065; Appendix A Table A2). Statistical evidence refers to a prespecified change in fitted slopes, not a data-identified policy turning point.

Wind, photovoltaic, hydro, biomass and other renewable technologies contribute to the broader transformation of electricity supply; their statistical treatment in Eurostat SHARES is normalised and may differ from raw gross generation. Pumped-storage output is not new renewable generation. Detailed technology shares would require separate harmonised source tables [3,60]. IRENA's Renewable Energy Statistics 2025 [61], Renewable Capacity Statistics 2025 [62] and Offshore Wind Outlook 2019 [63] cover related generation, capacity and technology perspectives, but those distinct metrics cannot be substituted for the Eurostat SHARES electricity-consumption denominator.

A rising renewable-electricity share may coincide with lower combustion emissions, but the actual displacement depends on hourly dispatch, trade, fuel mix, demand, balancing and network constraints. The present annual correlations do not identify displacement effects or future system adequacy. Renewable electricity cost estimates are discussed in IRENA's Renewable Power Generation Costs in 2023 [64], but technology cost trends are not included as explanatory variables in this study.

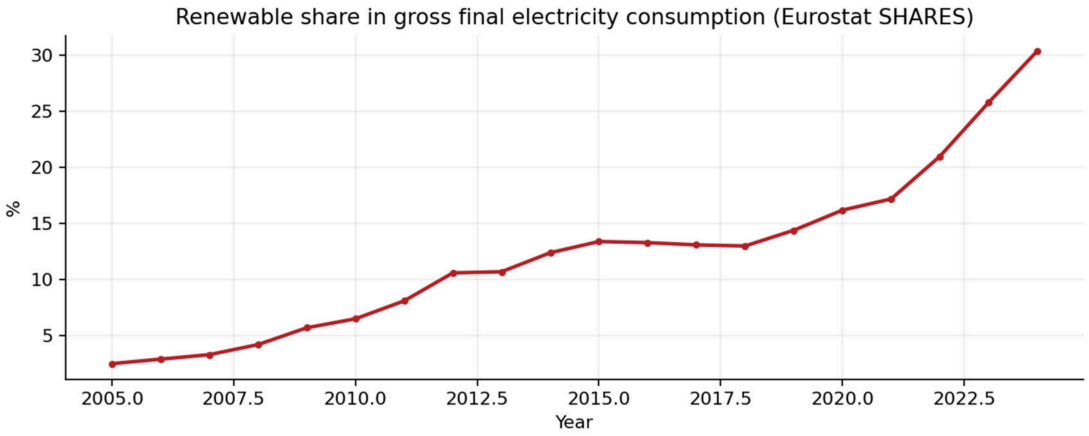


Figure 3. Renewable electricity as a share of gross final electricity consumption, Poland, 2005–2024 (%), Eurostat SHARES [3].

The Eurostat SHARES electricity value reached 30.4% in 2024, compared with 2.5% in 2005. This percentage is not a gross-final-energy share for electricity, heating and transport together and should not be compared directly with national all-energy renewable policy targets. Descriptive time trends remain distinct from forecasts or formal target-achievement assessments.

Descriptive Electricity, Emissions and Renewable Associations

RQ2 (calendar-period contrasts). Gross generation changed by +1.8% in 2005–2019 and +5.2% in 2019–2024; gross consumption increased by 16.9% and then declined by 0.3%, respectively. The public electricity-and-heat fuel total decreased by 12.7% in 2005–2019 and a further 15.2% in 2019–2024. Within the directly published CO_2 series, emissions decreased by 10.9% in 2014–2019 and 17.4% in 2019–2024, while PSE generation increased by 1.4% and 5.2%. The prespecified segmented models additionally show a consumption-slope change of −1.532 TWh/year (HAC $p = 0.00396$), a public fuel-input slope change of −0.930 Mtoe/year ($p = 0.00698$), and a renewable SHARES slope change of +1.806 percentage points/year ($p = 0.000065$). The corresponding electricity-related CO_2 fitted slope change is not statistically significant ($p = 0.316$). No year is claimed as a statistically identified structural break.

RQ3 (associations and descriptive decoupling). Directly published emissions declined as PSE gross generation increased in both 2014–2019 and 2019–2024. Define the fixed-period emissions/output decoupling index $D(s,e) = [C_e(e)/C_e(s)]/[Ggross(e)/Ggross(s)]$. It was 0.879 for 2014–2019 and 0.786 for 2019–2024 (below 1 indicates lower allocated CO_2 per unit of gross generation); both intervals also satisfy the stricter descriptive condition of falling CO_2 with rising gross generation. This is not a fuel-efficiency coefficient or a causal decoupling estimate, because the two institutions' statistical coverage differs. The level Spearman correlation between Eurostat SHARES and directly reported CO_2 is $\rho = -0.867$ ($p = 0.00117$; n = 10); the corresponding consecutive first-difference association is $\rho = -0.707$ ($p = 0.0501$; n = 8). These trends and correlations are exploratory, not evidence of contemporaneous displacement.

The Mann–Kendall/Sen trend summaries, Durbin–Watson/Ljung–Box diagnostics, two-lag Newey–West fixed-break slopes and rank associations are presented in Appendix A. Emissions inference uses only ten directly reported KOBiZE mass observations, and consecutive-year differences require two adjacent directly published values. All resulting *p*-values are exploratory and not causal.

8. Statistical Interpretation and Electricity CO_2 Intensity

Section 8 summarises the source-bounded CO_2/output ratio I(t) = 1000 C_e(t)/Ggross(t) [g CO_2/kWh] and the fixed-interval decoupling index D(s,e) = (C_e(e)/C_e(s))/(Ggross(e)/Ggross(s)). For 2014–2019, I(t) decreased from 769.2 to 676.2 g CO_2/kWh and D = 0.879; for 2019–2024, it decreased to 531.3 g CO_2/kWh and D = 0.786. The respective PSE gross-output changes were +1.4% and +5.2%, while electricity-attributed CO_2 fell by 10.9% and 17.4%. Thus, the documented evidence is a descriptive separation between these two reported quantities, not an electricity-only fuel/CHP conversion-efficiency improvement. The complementary normalisation Fpublic/Ggross is included solely as a boundary-qualified audit indicator in the workbook, not as an independent efficiency finding.

Appendix A Tables A1–A3 report OLS descriptive slopes, nonparametric tests, residual diagnostics and two-lag Newey–West inference for a fixed 2019 knot. Residual Ljung–Box *p*-values below 0.05 for gross generation, CO_2 and renewable share signal dependence in some OLS fits; nominal OLS confidence intervals should therefore not be interpreted as fully dependence-robust inferential intervals. The fixed-knot HAC tests are exploratory, and neither the knot nor a causal policy effect is estimated from the data.

The common historical context for fuel input and electricity-related CO_2 is the changing Polish generation mix. The former includes public electricity and useful heat, whereas the latter attributes combustion CO_2 to electricity. It is therefore important to report both as separate series rather than manufacture a seemingly precise national t CO_2/TJ coefficient.

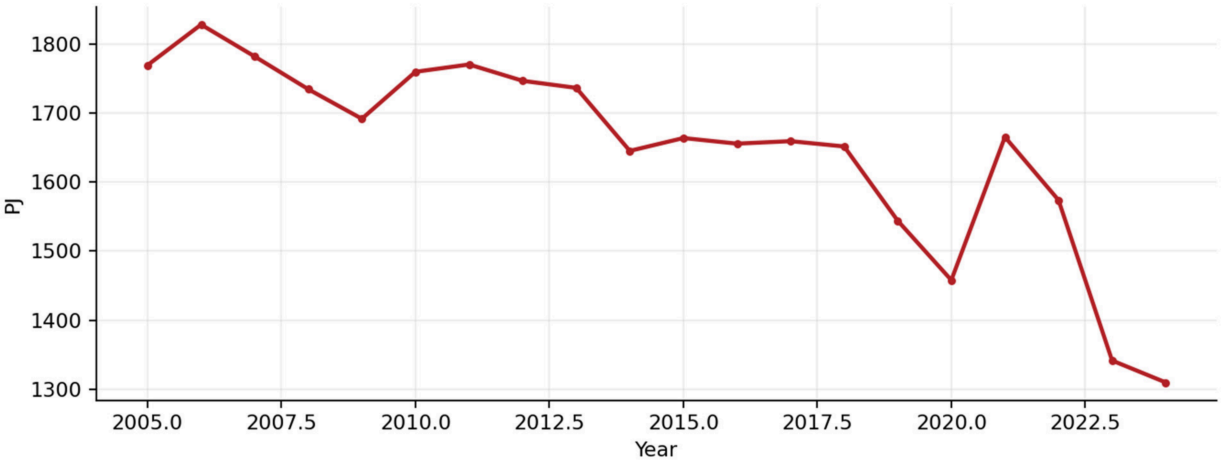


Figure 4. Published fuel-energy input to public electricity and heat production (IPCC 1.A.1.a), Poland, 2005–2024 (PJ; KOBiZE NID 2026, Table 3.2.6.1) [26].

The complete twenty-year official public electricity-and-heat fuel series declines by 26.0% between 2005 and 2024. The figure describes an IPCC inventory category that contains heat production and should not be interpreted as direct electricity-only combustion energy or as thermal efficiency.

Electricity-output CO_2 intensity decreased over the directly published KOBiZE endpoint years, but the unit-specific physical determinants of this reduction cannot be identified from the national annual accounts. The difference between the input and emissions source boundaries is maintained explicitly in Tables 2 and 3.

9. Limitations of the Study

The study uses two source-defined energy/emissions reporting populations: fuel input for public electricity AND heat production (IPCC 1.A.1.a) and CO_2 assigned to electricity under KOBiZE annual emission-factor reports. Their quotient is not used to calculate a combustion-fuel emission factor. Likewise, the indicative electricity-output intensity refers

to PSE gross output and is not the exact KOBiZE combustion-only factor. The European Commission's EU ETS scope guidance [65] and Union Registry information on verified installation emissions [66] concern a different reporting and compliance perimeter and are not treated as interchangeable with the KOBiZE electricity-attributed totals.

The annual PSE gross electricity, KOBiZE 1.A.1.a public electricity-and-heat fuel, Eurostat SHARES and ten directly published KOBiZE electricity-related CO_2 observations are identified by official source and calendar year in the workbook. Nine early CO_2 figures and the 2017 entry are computations, not independent source observations. The original institutional extraction workbooks, heat-only exclusion ledger, unit-level CHP input/output and fuel/emissions allocations, and RES-generation adjustment components have not been recovered or supplied. The document therefore cannot establish a single physically matched electricity-only source population; reproducibility of formulas and published annual entries must not be confused with an independent verification of upstream compilation methods.

The emission/output ratio and decoupling index compare electricity-related KOBiZE CO_2 with PSE gross national output, not identically bounded generation populations. A fuel-derived emissions factor, generation efficiency or verified technology-level renewable TWh would need matched generation, calorific inputs, source categories, public heat exclusions, CHP and biomass accounting, net imports, normalisation and prosumer self-consumption. Such matched raw observations are not included. In consequence, the manuscript does not claim those physical quantities, does not use 2005–2013/2017 calculated CO_2 as measured observations, and does not infer fuel-mix causes of the 2022–2023 decline.

The 2019 knot was set in advance; the segmented regressions assess a difference in fitted slopes under that specification and do not locate a structural break. Diagnostics of the ordinary OLS trends include Durbin–Watson and Ljung–Box tests (Appendix A); serial dependence is addressed for the segmented slope-difference test using a two-lag Newey–West covariance estimate. A limited post-2019 horizon, ten nonconsecutive direct CO_2 years, missing policy and market covariates, and multiple exploratory tests constrain precision. Endpoint decoupling indices are descriptive and use no confidence intervals.

Causal attribution. Price signals, EU ETS allowances, national support instruments, RES capital expenditure, grid constraints, weather, electricity demand and fuel prices evolve simultaneously. Without a matched counterfactual, linked covariates and an identification design, none of the tests estimates an individual policy effect. This manuscript tests the direction and timing of annual series only; mechanisms are cited to earlier research [2,20–22,24,25] as externally supported context. Evidence on EU ETS price drivers and pass-through in the power sector [58] offers relevant external market context, but does not identify the causal effects of ETS price movements in the present Polish annual indicators.

Generalisability and issues beyond the analytical scope: The analysis describes one national electricity system with a particular historical dependence on coal; its results cannot be directly extrapolated to other countries or to the Polish economy as a whole. The selected indicators do not provide a comprehensive appraisal of investment and operating costs, consumer prices, security of supply, network congestion and curtailment, flexibility and storage requirements, regional heterogeneity, employment effects or the distributional consequences of transition. In addition, the 2005–2024 historical record does not by itself justify deterministic forecasts of future RES shares, electricity demand or progress towards 2030 objectives. Scenario and target limitations: no 2030 point estimates are obtained from Figures 1–4 or Tables 1–4. The government-adopted NECP WEM/WAM outcomes and PSE network-development forecasts are external conditional scenarios rather than extrapolations or independent findings of this study [5,6,46]. Comparing renewable-generation

shares, SHARES-based gross-final-energy percentages and legally distinct emissions targets without matching definitions can produce spurious conclusions. Moreover, annual TWh totals alone do not describe peak GW, loss-of-load risk, dispatchable reserves, storage, network security or the ability to maintain supply during low-wind/low-solar hours. No claim of system stability or reduced firm-capacity requirements is made.

10. Conclusions

The documented contribution is a transparent, bounded comparison of four official or explicitly calculated annual indicators for Poland, rather than the construction of a fully harmonised electricity-only fuel–CO_2 balance. Annual reporting populations, directly observed and modelled entries, fixed-period differences and relevant source limitations are explicitly separated. No causal effect of a policy is identified.

- Gross domestic electricity consumption increased from 144.838 TWh in 2005 to 168.956 TWh in 2024 (+16.7%, or +24.118 TWh). It reached a temporary maximum of 174.402 TWh in 2021 and decreased thereafter. The 2005–2024 change should not be confused with a comparison to the higher 2021 peak. The relationship among electricity demand, GDP growth and energy-efficiency measures remains descriptive and does not yield causal contributions from the available aggregate data. A stable recent annual level should not be extrapolated as 170–175 TWh in 2030 without an identified prospective scenario; the corresponding hourly peak and adequacy conditions would require separate analysis [46].
- According to the internally reconciled PSE balance, gross domestic production increased from 156.024 TWh in 2005 to 166.990 TWh in 2024 (+7.0%). Poland experienced both net-export and net-import years rather than a one-directional move towards imports: net imports reached 13.224 TWh in 2020, net exports were 1.678 TWh in 2022, and net imports amounted to 3.889 TWh in 2023 and 1.966 TWh in 2024 (approximately 1.16% of gross consumption). Import and export balances represent the difference between domestic consumption and generation under the PSE reporting convention, not independent generation sources.
- Official fuel-energy input in public electricity and heat production (KOBiZE IPCC 1.A.1.a) fell from 1769.038 PJ (42.253 Mtoe) in 2005 to 1309.951 PJ (31.288 Mtoe) in 2024, a 26.0% decrease. The values also include fuel used for public heat generation and cannot be interpreted as electricity-only fuel input.
- KOBiZE's directly reported combustion CO_2 attributed to electricity fell from 120.436 Mt in 2014 to 88.716 Mt in 2024 (−26.3%). The indicative emissions-to-PSE-gross-generation ratio decreased from 769.2 to 531.3 g CO_2/kWh. In 2014–2019 and 2019–2024, electricity-related CO_2 declined while PSE gross generation increased, producing descriptive decoupling indices D = 0.879 and D = 0.786, respectively. The early-year (2005–2013) and 2017 emissions entries remain clearly labelled as calculations, and no plant-level fuel/heat allocation or causal attribution is inferred.
- The renewable-electricity share of gross final electricity consumption reported by Eurostat SHARES rose from 2.5% in 2005 to 30.4% in 2024. This electricity-specific gross-final indicator is distinct from the renewable fraction of national gross generation and from renewable energy in final energy consumption across all sectors.
- No generating-efficiency claim is derived from a public electricity-and-heat fuel total divided by all PSE output. The former A(t) fuel-only ratio is not retained as an efficiency indicator; an explicitly qualified fuel-per-gross-output normalisation appears only in the Supplementary Workbook. The paper's I(t) and fixed-period CO_2–generation decoupling index describe changes in reported electricity-related CO_2 relative to gross national generation, with coverage limitations set out in Section 9.

- The fixed-2019 segmented models, residual diagnostics and rank tests appear in Appendix A and remain exploratory. They document fitted changes in demand, fuel and Eurostat SHARES trajectories but do not identify a statistically optimised turning year. The matched-period endpoint contrasts provide a separate, transparent answer to the timing questions. Observed CO_2 data are used without treating reconstructed values as additional inferential observations.
- EU and national policy measures formed an important part of the institutional setting of the energy transition, but their individual effects cannot be determined from this descriptive analysis. Implementation of the EU 20-20-20 framework coincided with expanding renewable generation and energy-efficiency initiatives, while progress varied across indicators and years. Higher EU ETS allowance prices after 2018 are consistent with increasing cost pressure on coal-fired generation; however, the observed decrease in coal generation cannot be apportioned among allowance prices, renewable deployment, fuel costs, electricity demand and other influences using the present data. At the national level, Poland's Energy Policy 2040 outlines goals for reducing coal dependence and developing new technologies (including nuclear and offshore wind), but the existence of strategic targets should not be equated with measured effects on outcomes during 2005–2024. The documented reduction in emissions and growth in RES should be evaluated against the relevant EU targets using their specific coverage and base years. The historical series and OLS diagnostics describe sectoral trajectories alongside policy milestones. Mechanisms discussed in external studies offer context, not effect sizes identified here. In particular, none of the regression slopes or R^2 values in Figures 2 and 3 or Appendix A Table A2 identify a causal ETS, subsidy, technology-cost, weather, demand or import effect. Further inference would require an explicitly designed comparative, quasi-experimental or structural analysis. Prospective electricity-consumption levels, RES shares and power-system adequacy should be evaluated against named, dated WEM/WAM or operator scenarios with stated modelling assumptions. In particular, a flat or moderately growing annual electricity volume gives no information by itself about peak power, firm capacity, reserve margins or reliability in extreme weather. Neither a guaranteed 170–175 TWh demand level nor stability of the Polish power system through 2030 is claimed [5,6,46].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19215078/s1.

Author Contributions: Conceptualisation, A.M.-K. and M.K.; methodology, A.M.-K. and M.K.; validation, A.M.-K. and M.K.; formal analysis, A.M.-K. and M.K.; resources, A.M.-K. and M.K.; data curation, A.M.-K. and M.K.; writing—original draft preparation, A.M.-K. and M.K.; writing—review and editing, A.M.-K. and M.K.; visualisation, A.M.-K. and M.K.; supervision, A.M.-K. and M.K.; funding acquisition, A.M.-K. All authors have read and agreed to the published version of the manuscript.

Funding: Ministry of Science and Higher Education: number 202/26/B.

Data Availability Statement: The Supplementary Workbook contains the annual published and calculated series (2005–2024), report URLs and status flags for individual CO_2 years, statistical summaries, an explicit source-boundary audit and formula-based period/decoupling comparisons. The workbook does not contain original source-institution extraction files, unit-level heat-only/CHP allocations or Eurostat's underlying renewable-normalisation and prosumer accounting worksheets; these are not claimed to have been independently reproduced. Reproducibility boundary. The Supplementary Workbook contains PSE annual gross-output/consumption observations, KOBiZE public electricity-and-heat fuel totals, Eurostat SHARES annual percentages, ten directly reported KOBiZE electricity-attributed CO_2 masses and the equations for calculated early-year and 2017 values. Dedicated audit and decoupling worksheets separate available official publications from missing

primary extraction and heat/CHP/RES allocation components. The annual data tables are not a reconstructed matched fuel-and-emissions inventory.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Statistical Analyses of Sourced Annual Indicator Series

This appendix presents model coefficients, trends and associations underpinning the substantive statements. Directly published CO_2 masses only (n = 10) are used for emissions inference; adjacent-year CO_2 changes are evaluated only when both original masses were published. Calculated CO_2 entries are displayed in Table 3 but do not inflate inferential sample sizes.

Table A1. OLS trend slope and R^2, two-sided Mann–Kendall *p*-value and Sen's median slope. Sample sizes are reported for every indicator; directly published annual CO_2 masses only (n = 10) enter emission inference.

Indicator	n	OLS Slope	OLS R^2	Kendall p	Sen Slope
Gross generation	20	+0.610	0.338	0.00378	+0.576
Gross consumption	20	+1.342	0.862	9.06×10^{-9}	+1.356
Electricity + heat fuel	20	−0.485	0.721	8.33×10^{-7}	−0.412
Electricity-related CO_2	10	−2.797	0.611	0.000946	−3.083
RES in gross final electricity	20	+1.200	0.900	1.37×10^{-13}	+1.087

Complementary Sen-slope 95% intervals (units per year) were: gross generation [+0.178,+1.072] TWh; gross consumption [+0.998,+1.685] TWh; public electricity-and-heat fuel [−0.631,−0.259] Mtoe; electricity-related CO_2 [−3.951,−0.617] Mt; and Eurostat renewable electricity [+0.927,+1.300] percentage points. Durbin–Watson statistics and Ljung–Box lag-2 *p*-values, respectively, were: generation 1.872/0.0251; consumption 1.434/0.1403; fuel 1.302/0.1010; electricity CO_2 1.760/0.0235; renewable share 0.396/0.0168. These diagnostics warrant caution about dependence in OLS residuals; the fixed-2019 segmented model consequently reports Newey–West HAC inference. Neither the reported trend *p*-values nor the confidence intervals establish causal mechanisms.

Table A2. Fixed-2019 segmented regression: pre-/post-2019 slopes, their difference and two-lag Newey–West HAC significance. Short post-break intervals limit inference.

Indicator	Pre-2019	Post-2019	Δ Slope	HAC p
Gross generation	+0.442	+1.352	+0.910	0.334
Gross consumption	+1.624	+0.092	−1.532	0.00396
Public electricity + heat fuel	−0.314	−1.243	−0.930	0.00698
Electricity-related CO_2	−1.646	−3.984	−2.338	0.316
RES in gross final electricity	+0.867	+2.674	+1.806	6.48×10^{-5}

Table A3. Spearman rank correlations in observed levels and consecutive first differences; two-sided p and sample size. Calculated CO_2 data are excluded from inference.

Series Pair	n Levels	ρ Levels	p Levels	n Δ	ρ Δ	p Δ
Gross generation/Electricity-related CO_2	10	−0.200	0.58	8	+0.881	0.00385
RES in gross final electricity/Electricity-related CO_2	10	−0.867	0.00117	8	−0.707	0.0501
Gross generation/RES in gross final electricity	20	+0.595	0.0056	19	−0.321	0.181

Appendix A presents exploratory statistical tests of the defined published series. The fixed 2019 knot is chosen a priori and is not a detected breakpoint; conventional OLS slopes and R^2 are descriptive, residual serial-dependence diagnostics are given, and two-lag

Newey–West tests are reported for segmented slope differences. CO_2 tests use only directly published emissions observations. The Supplementary Workbook provides separate fixed-period endpoint comparisons and a descriptive CO_2/gross-generation decoupling index; these are not inferential causal estimates.

References

1. International Energy Agency (IEA). *Poland 2022: Energy Policy Review*; IEA: Paris, France, 2022. Available online: https://www.iea.org/reports/poland-2022 (accessed on 1 October 2026).
2. Nikas, A.; Szpor, A.; Doukas, H.; Witajewski-Baltvilks, J.; Antosiewicz, M. Pathways for the transition of the Polish power sector and associated risks. *Environ. Innov. Soc. Transit.* **2020**, *35*, 271–291. [CrossRef]
3. Eurostat. Renewable Energy Share (nrg_ind_ren); Annual SHARES-Methodology Indicators, Including Renewable Electricity as a Share of Gross Final Electricity Consumption; Data Update 15 September 2026. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren/default/table?lang=en (accessed on 8 October 2026).
4. European Parliament and Council. Directive (EU) 2023/2413 of 18 October 2023 Amending Directive (EU) 2018/2001 (Renewable-Energy Targets and SHARES-Related Provisions). Official Journal of the European Union, 2023. Article 3: EU-Wide 42.5% 2030 Gross-Final-Energy Target. Available online: https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng (accessed on 3 October 2026).
5. Ministry of Energy of Poland. Krajowy Plan w Dziedzinie Energii i Klimatu Do 2030 r. z Perspektywą Do 2040 r.; Adopted by the Polish Council of Ministers 8 June 2026 (Government-Approved Updated NECP). National Gross-Final-Energy RES Planning Range 30–32% and National 2030 GHG Planning Range. Available online: https://www.gov.pl/attachment/5d1de0a5-7b21-4d8b-9b59-6673505e8ac8?utm_source=chatgpt.com (accessed on 2 October 2026).
6. Ministry of Energy of Poland. Updated NECP 2026, Annex 1: Scenariusz Przyspieszonej Transformacji (WAM; with Additional Measures), and Annex 2: Scenariusz Referencyjny (WEM; with Existing Measures). Renewable-Electricity Generation Share for 2030: WEM 51.6%; WAM 53.2%; Explicitly Scenario-Dependent. Official Annexes Linked under the Government-Approved NECP. Available online: https://naszerozmowy.pl/pdf/index/2602281216_OZE-Projekt_aKPEiK.pdf (accessed on 2 October 2026).
7. European Commission. Report from the Commission on the Operation of the European Climate Law and of the Effort Sharing Regulation, COM(2024) 196 Final, 15 May 2024. EU-Wide at-Least-55% Net GHG Reduction in 2030 Relative to 1990. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024DC0196 (accessed on 3 October 2026).
8. European Commission; Directorate-General for Climate Action. Effort Sharing 2021–2030: Targets and Flexibilities; Member State Table, Revised 2023; Poland's 2030 Non-ETS GHG Target −17.7% Relative to 2005. Available online: https://climate.ec.europa.eu/areas-action/effort-sharing-member-states-emission-targets/effort-sharing-2021-2030-targets-and-flexibilities_en (accessed on 3 October 2026).
9. Tarasova, E. Multiple just transitions? A study of how a just transition is envisioned in Poland. *Energy Policy* **2024**, *194*, 114322. [CrossRef]
10. International Energy Agency (IEA). *Electricity 2024: Analysis and Forecast to 2026*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/electricity-2024 (accessed on 1 October 2026).
11. Jonek-Kowalska, I. Demonstrating the need for a just transition: Socioeconomic diagnosis of Polish cities living on hard coal mining. *Resour. Policy* **2024**, *89*, 104576. [CrossRef]
12. International Energy Agency (IEA). *Electricity Grids and Secure Energy Transitions*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions (accessed on 5 October 2026).
13. Neska, E.; Bielecki, M.; Kowalska-Pyzalska, A. Bridging the implementation gap: Expert, systemic, and policy perspectives on renewable energy communities in Poland. *Energy Strategy Rev.* **2025**, *62*, 101856. [CrossRef]
14. Dogan, E.; Hodžić, S.; Fatur Šikić, T. Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union? *Renew. Energy* **2023**, *202*, 1138–1145. [CrossRef]
15. Council of Ministers of the Republic of Poland. Polityka Energetyczna Polski Do 2040 r. (Energy Policy of Poland Until 2040, PEP2040); Adopted on 2 February 2021. Ministry of Climate and Environment, Government Publication and Original Document. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski-do-2040-r-przyjeta-przez-rade-ministrow (accessed on 7 October 2026).
16. Ministry of Climate and Environment (Poland). Załącznik 2 Do PEP2040: Wnioski z Analiz Prognostycznych dla Sektora Energetycznego (PEP2040, Annex 2: Conclusions from Forecast Analyses for the Energy Sector); 2 February 2021. Official Document Linked under "Materiały". Available online: https://www.gov.pl/attachment/dc6659e5-d8ae-45fe-b5f3-84ec4fd5bcb1?utm_source=chatgpt.com (accessed on 5 October 2026).

17. Ministry of Energy of Poland. Krajowy Plan na Rzecz Energii i Klimatu na Lata 2021–2030—2019 Edition; Historical Planning Framework (21–23% RES in Gross Final Energy by 2030; Superseded by the Nationally Adopted Updated NECP of June 2026). Available online: https://www.gov.pl/web/energia/krajowy-plan-na-rzecz-energii-i-klimatu-na-lata-2021-2030---wersja-z-2019-r2 (accessed on 6 October 2026).
18. European Commission. *The European Green Deal; Communication COM(2019) 640 Final*; European Commission: Brussels, Belgium, 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed on 14 October 2026).
19. European Environment Agency (EEA). *Trends and Projections in Europe 2024*; EEA Report No. 11/2024; EEA: Copenhagen, Denmark, 2024.
20. Brauers, H.; Oei, P.-Y. The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels. *Energy Policy* **2020**, *144*, 111621. [CrossRef]
21. Skoczkowski, T.; Bielecki, S.; Węglarz, A.; Włodarczyk, M.; Gutowski, P. Impact assessment of climate policy on Poland's power sector. *Mitig. Adapt. Strateg. Glob. Change* **2018**, *23*, 1303–1349. [CrossRef]
22. Jorge-Vazquez, J.; Kaczmarek, J.; Knop, L.; Kolegowicz, K.; Náñez Alonso, S.L.; Szymla, W. Energy transition in Poland and Spain against changes in the EU energy and climate policy. *J. Clean. Prod.* **2024**, *468*, 143018. [CrossRef]
23. Cholewa, M.; Mammadov, F.; Nowaczek, A. The obstacles and challenges of transition towards a renewable and sustainable energy system in Azerbaijan and Poland. *Mineral. Econ.* **2022**, *35*, 155–169. [CrossRef]
24. Gołaś, Z. Decoupling Analysis of Energy-Related Carbon Dioxide Emissions from Economic Growth in Poland. *Energies* **2023**, *16*, 3784. [CrossRef]
25. Gajdzik, B.; Wolniak, R.; Grebski, W.W. Structural Drivers of Poland's Renewable Energy Transition (2010–2023): Empirical Insights from Regression and Cluster Analysis. *Energies* **2025**, *18*, 4754. [CrossRef]
26. KOBiZE/Poland. Poland's National Inventory Document 2026 (NID 2026); UNFCCC Submission 31 March 2026, Published 1 April 2026; National GHG Inventory Covering 1988–2024, IPCC 1.A.1.a Public Electricity and Heat Production and Associated Fuel/CO_2 Sections. Available online: https://unfccc.int/documents/656247 (accessed on 5 October 2026).
27. KOBiZE/Poland. Poland 2026 Common Reporting Tables (CRT); Submitted to UNFCCC 31 March 2026, National Inventory Tables Covering 1988–2024, IPCC Fuel-Combustion Categories and CO_2 by Subcategory. Available online: https://unfccc.int/documents/656246 (accessed on 4 October 2026).
28. Statistics Poland (GUS). Gospodarka Paliwowo-Energetyczna w Latach 2023 i 2024; Annual Energy-Balance Report, Published 27 November 2025; Associated XLSX/CSV Statistical Tables (Energy-Carrier Balances in Physical and Energy Units). Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/gospodarka-paliwowo-energetyczna-w-latach-2023-i-2024,4,20.html (accessed on 8 October 2026).
29. PSE. *Raport 2024 KSE—Zestawienie Danych Llościowych Dotyczących Funkcjonowania KSE w 2024 Roku*; Section 6.3, Table 6.2 (1990–2024), and Section 6.2, Table 6.1 (2022–2024); Operational Gross Electricity Data [GWh], Reporting Year 2024; PSE: Metro Manila, Philippines, 2024.
30. KOBiZE. Wskaźniki Emisyjności dla Energii Elektrycznej; Annual Reporting-Year Editions 2014–2024. Electricity-Related Combustion CO_2 Emission Totals and the 2017 Rounded Combustion-Generation Factor. Available online: https://www.kobize.pl/pl/fileCategory/id/28/wskazniki-emisyjnosci (accessed on 17 October 2026).
31. Schwenk-Nebbe, L.J.; Victoria, M.; Andresen, G.B. Dataset: A proxy for historical CO_2 emissions related to centralised electricity generation in Europe. *Data Brief.* **2021**, *36*, 107016. [CrossRef]
32. Schwenk-Nebbe, L.J. Proxy for Historical CO_2 Emissions Related to Centralised Electricity Generation in Europe; Mendeley Data, Version 3, 2021; Annual Comparative Dataset 1990–2018 Including Separate Autoproducer Estimate and Replication Scripts. Available online: https://data.mendeley.com/datasets/cmngb4vdb5/3 (accessed on 15 October 2026).
33. Eurostat; International Energy Agency. Annual Electricity and Heat Questionnaire: Reporting Instructions; Section "Methodology for Apportioning Fuel Input in a CHP Plant/Unit". pp. 5–6. Available online: https://ec.europa.eu/eurostat/documents/d/energy/electricity_heat-questionnaire_instructions (accessed on 17 October 2026).
34. Marciniuk-Kluska, A.; Kluska, M. Transformation of the Energy Market in Poland in the Context of the European Union over the Last 20 Years. *Energies* **2025**, *18*, 3410. [CrossRef]
35. Agencja Rynku Energii S.A. (ARE). Wynikowe Informacje Statystyczne: Statystyka Elektroenergetyki Polskiej; Bilans Energii Pierwotnej; Biuletyn Elektroenergetyki; EMITOR. Publication-Series Catalogue and Annual Statistical Products, Not a Demonstrated Direct 2005–2024 Input Table for This Manuscript. Available online: https://www.are.waw.pl/badania-statystyczne/wynikowe-informacje-statystyczne (accessed on 2 October 2026).
36. Energy Regulatory Office (URE). Charakterystyka Rynku Energii Elektrycznej—2024; Annual Electricity-Market Data, Gross Electricity Production, Consumption and Reported Fuel/Source Breakdown. Available online: https://www.ure.gov.pl/pl/energia-elektryczna/charakterystyka-rynku/12744,2024.html (accessed on 2 October 2026).

37. Energy Regulatory Office (URE). Raport Dotyczący Energii Elektrycznej Wytworzonej z Odnawialnego Źródła Energii w Mikroinstalacji (w Tym Przez Prosumentów) i Wprowadzonej Do Sieci Dystrybucyjnej w 2024 r. (Article 6a of the RES Act); Published 17 March 2025. Available online: https://www.ure.gov.pl/pl/urzad/informacje-ogolne/edukacja-i-komunikacja/publikacje/raport-wytwarzanie-ener-1/8833,Raport-dotyczacy-energii-elektrycznej-wytworzonej-z-OZE-w-mikroinstalacji-i-wpro.html (accessed on 4 October 2026).
38. Eurostat. Complete Energy Balances (nrg_bal_c); Annual Dataset, Poland, Energy Products and Energy-Flow Categories; Data Update 2 June 2026. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table?lang=en (accessed on 3 October 2026).
39. Eurostat. *Energy Balance Guide; Nomenclature and Statistical Accounting of Electricity and Heat Energy-Balance Flows*; Eurostat: Luxembourg, 2019. Available online: https://ec.europa.eu/eurostat/documents/38154/4956218/ENERGY-BALANCE-GUIDE.pdf (accessed on 17 October 2026).
40. International Energy Agency (IEA). *Understanding and Using the Energy Balance*; IEA Commentary: Paris, France, 2017. Available online: https://www.iea.org/commentaries/understanding-and-using-the-energy-balance (accessed on 8 October 2026).
41. International Energy Agency (IEA); Eurostat. *Energy Statistics Manual*; OECD/IEA: Paris, France, 2004. Available online: https://www.iea.org/reports/energy-statistics-manual (accessed on 8 October 2026).
42. International Energy Agency (IEA). World Energy Balances, July 2026 Edition (Summary and Extended Energy Balances; Units Ktoe/TJ; Historic Data to 2024). Available online: https://www.iea.org/data-and-statistics/data-product/world-energy-balances (accessed on 7 October 2026).
43. Statistics Poland (GUS). Gospodarka Paliwowo-Energetyczna w Latach 2022 i 2023; Published 28 November 2024; XLSX Appendix Worksheet XVII Corrected 17 December 2024. Available online: https://publikacje.new.stat.gov.pl/portal-publikacje/gospodarka-paliwowo-energetyczna-w-latach-2022-i-2023 (accessed on 17 October 2026).
44. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022: Mitigation of Climate Change, Working Group III, Chapter 6: Energy Systems*; Cambridge University Press: Cambridge, UK, 2022. Available online: https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-6/ (accessed on 8 October 2026).
45. Statistics Poland (GUS). Energy from Renewable Sources in 2024; Statistical News Release, 8 December 2025. Poland's 2024 Renewable Share in Gross Final Energy Consumption: 17.7%, with a Noted Post-2021 Methodological Change. Available online: https://stat.gov.pl/en/topics/environment-energy/energy/energy-from-renewable-sources-in-2024,9,4.html (accessed on 5 October 2026).
46. Polskie Sieci Elektroenergetyczne S.A. Development Plan for Meeting Current and Future Electricity Demand for the Years 2025–2034; December 2024; Section 4.4, Figures 4-1 to 4-5 (Net Electricity-Demand Scenarios, Climate Years, Peak-Power Profiles), Section 10 (Generation Adequacy). Available online: https://www.pse.pl/documents/31287/22159050/Development_plan_2025_2034_main_document_20_12_2024.pdf (accessed on 6 October 2026).
47. International Energy Agency (IEA). *World Energy Outlook 2023*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/world-energy-outlook-2023 (accessed on 8 October 2026).
48. International Energy Agency (IEA). *Secure Energy Transitions in the Power Sector; Electricity Security 2021*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/secure-energy-transitions-in-the-power-sector (accessed on 8 October 2026).
49. International Renewable Energy Agency (IRENA). *REmap 2030: Renewable Energy Prospects for Poland*; IRENA: Abu Dhabi, United Arab Emirates, 2015. Available online: https://www.irena.org/Publications/2015/Oct/REmap-2030-Renewable-Energy-Prospects-for-Poland (accessed on 12 October 2026).
50. International Energy Agency (IEA). *Renewables 2024: Analysis and Forecasts to 2030*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/renewables-2024 (accessed on 11 October 2026).
51. European Commission; Directorate-General for Climate Action. EU Emissions Trading System (EU ETS): Policy Framework, Coverage and Operation. Available online: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed on 5 October 2026).
52. Eurostat. Greenhouse Gas Emission Accounts—Statistics Explained. 2025. Available online: https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/132197.pdf (accessed on 8 October 2026).
53. Energy Regulatory Office (URE). Sprawozdanie z Działalności Prezesa Urzędu Regulacji Energetyki w 2024 r. (Report on the Activities of the President of URE in 2024). Published 2025. Available online: https://www.ure.gov.pl/download/9/15926/BiuletynURE1-2025.pdf (accessed on 5 October 2026).
54. Kuc-Czarnecka, M.; Markowicz, I.; Sompolska-Rzechuła, A.; Stundziene, A. Assessing sustainable development goal 7 implementation and its nexus with social, economic and ecological factors in EU countries. *Sustain. Dev.* **2025**, *33*, 847–860. [CrossRef]

55. National Centre for Emissions Management (KOBiZE). Krajowy Raport Inwentaryzacyjny 2024: Raport Syntetyczny (National Emissions Inventory Reporting Edition 2024); Statistical Boundary and Period as Specified in the Publication. Available online: https://www.kobize.pl/uploads/materialy/materialy_do_pobrania/krajowa_inwentaryzacja_emisji/NIR_2024_raport_syntetyczny_PL.pdf (accessed on 7 October 2026).
56. Statistics Poland (GUS). Ochrona Środowiska 2024 (Environment 2024); Published 28 November 2024; Environment Statistics Referring Principally to 2023. Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2024,1,25.html (accessed on 7 October 2026).
57. Ember. European Electricity Review 2025; Published 23 January 2025; Underlying Annual/Monthly Electricity Dataset and Documented Estimated Gross Generation for 2024 (Poland's Solar Data from ARE via Instrat). Available online: https://ember-energy.org/latest-insights/european-electricity-review-2025/supporting-materials/ (accessed on 3 October 2026).
58. Forum Energii. Transformacja Energetyczna w Polsce. Edycja 2025 [Energy Transition in Poland, 2025 Edition]; Published 2 July 2025; Retrospective Analytical Report with 2024 Indicators and Underlying Sources Described as ARE, GUS, EEA, ARP, ENTSOG, KOBiZE and Eurostat. Available online: https://www.forum-energii.eu/transformacja-energetyczna-w-polsce-edycja-2025 (accessed on 7 October 2026).
59. Statistics Poland (GUS). Energia ze Źródeł Odnawialnych w 2024 r.; Annual Report Issued 22 December 2025, with Downloadable XLSX Tables for Electricity and Other Renewable-Energy Indicators (Main Statistical Release: 8 December 2025). Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/energia-ze-zrodel-odnawialnych-w-2024-r-,3,19.html (accessed on 1 October 2026).
60. International Renewable Energy Agency (IRENA). *Renewable Energy Statistics 2025*; IRENA: Abu Dhabi, United Arab Emirates, 2025; ISBN 978-92-9260-675-6. Available online: https://www.irena.org/Publications/2025/Jul/Renewable-energy-statistics-2025 (accessed on 14 October 2026).
61. International Renewable Energy Agency (IRENA). *Renewable Capacity Statistics 2025*; IRENA: Abu Dhabi, United Arab Emirates, 2025; ISBN 978-92-9260-652-7. Available online: https://www.irena.org/Publications/2025/Mar/Renewable-capacity-statistics-2025 (accessed on 15 October 2026).
62. International Energy Agency (IEA). *Offshore Wind Outlook 2019*; World Energy Outlook Special Report; IEA: Paris, France, 2019. Available online: https://www.iea.org/reports/offshore-wind-outlook-2019 (accessed on 15 October 2026).
63. International Renewable Energy Agency (IRENA). *Renewable Power Generation Costs in 2023*; IRENA: Abu Dhabi, United Arab Emirates, 2024; ISBN 978-92-9260-621-3. Available online: https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023 (accessed on 10 October 2026).
64. European Commission. DG CLIMA (2024). Guidance on Interpretation of Annex I of the EU ETS Directive (Excl. Aviation and Maritime Activities). EU ETS Guidance Document No. 0, Updated 4 December 2024. Climate Action. Available online: https://climate.ec.europa.eu/document/download/edc93136-82a0-482c-bf47-39ecaf13b318_en?filename=policy_ets_gd0_annex_i_euets_directive_en.pdf (accessed on 10 October 2026).
65. European Commission; Directorate-General for Climate Action. Union Registry: Verified Emissions and Compliance Data for EU ETS Installations. Available online: https://climate.ec.europa.eu/areas-action/carbon-markets/eu-emissions-trading-system-eu-ets/union-registry_en (accessed on 2 October 2026).
66. Bai, Y.; Okullo, S.J. Drivers and pass-through of the EU ETS price: Evidence from the power sector. *Energy Econ.* **2023**, *123*, 106698. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.