

## Comparative Analysis of Renewable Energy Technologies in Poland: Photovoltaic Dominance and Sectoral Transitions (2014-2024)\*

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### Abstract

The research examines the extent of structural transformation in Poland's renewable electricity sector between 2014 and 2024 when photovoltaics (PV) and wind power replaced biomass as the fundamental components of national renewable energy production. The current research provides policy drivers and cost trends and technology-specific deployment data yet lacks integrated indicator-based assessments of structural change and technology interactions in Poland's renewable portfolio. The research creates a standardized yearly database for five technologies which includes PV and wind and solid biomass and biogas and hydropower through data from ARE and URE and PSE and PSE and IRENA and Eurostat. The research design uses compound annual growth rates (capacity and generation) and three additional indexes (Efficiency Index and Structural Share Index and Structural Change Index) and Pearson correlations between sectoral time series to measure both scale effects and substitution–complementarity patterns. The study demonstrates that renewable capacity installation grew from 5.8 GW to 32.3 GW while power generation expanded from 19.3 TWh to 48 TWh with a total structural change index of 45.2%. The renewable electricity production in 2024 reached 80% through PV and wind power systems while PV systems generated 60% of all new electricity output. The correlation pattern shows that PV replaced biomass in the market ( $r = -0.92$ ) while PV and wind power showed positive growth patterns ( $r = +0.85$ ). The research establishes a new solar–wind power system through definition-specific indicators which enable researchers to evaluate Poland's transition against other European Union countries.

**Keywords:** renewable energy transition, photovoltaics (PV) dominance,

### Introduction

Over the last decade, Poland's renewable electricity landscape has undergone a decisive structural reconfiguration, shifting from a biomass-centred paradigm toward a solar–wind regime, with policy, economics, and social acceptance jointly steering this transition (Pietrzak et al., 2021; Bórawski et al., 2022; Kulpa et al., 2022; Aydın et al., 2025; Dębicka et al., 2024; Igliński et al., 2022). Pre-2014 evidence consistently portrays “solid biomass” as the dominant pillar of the national RES portfolio, while wind and solar played secondary roles; EU accession and subsequent climate frameworks progressively redirected incentives toward a more diversified, technology-open mix (Igliński et al., 2015; Zimon et al., 2020; Paska et al., 2020; Serowaniec, 2021; Ślusarz et al., 2021; Kochanek, 2021; Sobczyk & Sobczyk, 2021, Weremczuk A & Milewski L, 2025). Within this broader European policy envelope, the period 2014-2024 emerges as a turning point: PV deployment accelerated dramatically and onshore wind recovered from regulatory stagnation, while the relative share of biomass stabilized or declined (Dębicka et al., 2024; Igliński et al., 2022). The “substitution dynamics” are well-documented. PV capacity expanded from negligible levels to a multi-gigawatt scale by the early 2020s, with contributors highlighting both

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cost declines and the diffusion of prosumer business models (Chwieduk et al., 2020; Lewandowska et al., 2020; Olczak et al., 2021). In parallel, wind energy's contribution to renewable output reached high single- to low double-digit shares despite headwinds from siting constraints; subsequent legal fine-tuning enabled a rebound in investment activity (Gnatowska & Moryń-Kucharczyk, 2019, 2021; Zimon et al., 2020). Studies consistently frame PV and wind as the “principal loci of new capacity additions”, outpacing biomass in project pipelines and capital allocation (Bełdycka-Bórawska et al., 2021; Weremczuk, 2025).

The “drivers” behind this sectoral realignment are primarily “policy-economic”. Authors underscore the catalytic role of EU-level targets, national auction mechanisms, prosumer support (net-metering/net-billing, “Mój Prąd”), and the progressive removal or softening of legal barriers that had hampered onshore wind (Gnatowska & Moryń-Kucharczyk, 2021; Paska et al., 2020; Rabe et al., 2020; Saronic, 2021). Social dimensions matter as well: household PV diffusion reflects rising environmental awareness and favourable urban energy initiatives, though local opposition can still shape wind siting outcomes and preference heterogeneity (Bartczak et al., 2021; Chomać-Pierzecka et al., 2022, 2023; Lewandowska et al., 2020).

Against this momentum, the “role of biomass” has been recalibrated rather than eliminated. Research points to a national-level contraction tied to the phase-down of co-firing and competitive disadvantages versus rapidly scaling PV and wind, yet notes persistent “regional relevance” for energy security and agri-industrial linkages. In effect, biomass transitions from a system leader to a “context-specific stabilizer”, while “biogas” and waste-to-energy niches remain underexploited relative to technical potential (Bełdycka-Bórawska et al., 2021; Bielski et al., 2021; Brodny et al., 2020; Igliński et al., 2015, 2022a; Ślusarz et al., 2021; Zyadin et al., 2018).

From a systems perspective, studies converge on two implications. First, the rise of variable renewables elevates the salience of “balancing, forecasting, and grid adequacy”; the literature highlights day-ahead wind predictability improvements and the need to co-optimize PV wind complementarities with storage and demand response (Bochenek et al., 2021; Jurasz et al., 2021; Simla & Stanek, 2020). Second, infrastructural and regulatory frictions—especially those associated with the “Distance Act” and connection queues—remain binding constraints on the achievable speed of wind expansion and the efficient integration of distributed PV (Pietrzak et al., 2021a). These challenges are not merely technical; they reflect “governance capacity” and the tempo of institutional adaptation (Serowaniec, 2021; Kochanek, 2021).

Importantly, multiple contributions register “positive co-benefits” of the transition—lower emissions, green-jobs creation, and gradual improvements in energy security—while warning that the durability of these gains depends on continued investment in grid modernization and flexibility assets (Pietrzak et al., 2021; Kulpa et al., 2022; Dębicka et al., 2024; Kacprzak et al., 2022; Aydın et al., 2025). Hydropower, by contrast, is portrayed as “structurally static” constrained by geography and environmental trade-offs and primarily valuable for regulation rather than incremental decarbonization (Jurasz et al., 2021; Paska et al., 2020).

Placed in a “regional (CEE) frame”, Poland's trajectory aligns with peers facing legacy coal systems, heterogeneous local acceptance, and capital constraints; yet the pace and scale of PV diffusion appear comparatively strong, suggesting convergence with Western EU benchmarks when policy certainty and investment de-risking are present (Kochanek, 2021; Paska et al., 2020; Aydın et al., 2025; Bórawski et al., 2022). Synthesizing these strands, the literature describes 2014-2024 as a “structural break”: a decade in which photovoltaic dominance emerges, wind consolidates its role as an efficiency anchor, biomass retreats to a targeted but still meaningful support function, and governance shifts from capacity procurement toward “system integration” and “flexibility provision” (Pietrzak et al., 2021; Igliński et al., 2022; Dębicka et al., 2024; Jurasz et al., 2021).

Taken together, the reviewed studies offer a coherent causal narrative: “policy inducement and cost trajectories” trigger PV scale-up; “legal reform and repowering” stabilize wind; “market-policy realignment” reduces biomass prominence; and the resultant “solar-wind dominance” reframes planning around grids, storage, and social acceptance. The comparative implication for Poland is clear: achieving the next stage of the transition will hinge less on expanding headline gigawatts and more on “deepening system flexibility and institutional readiness” to manage a high VRES mix (Aydın et al., 2025; Bochenek et al., 2021; Dębicka et al., 2024; Gnatowska & Moryń-Kucharczyk, 2021).

## Materials and methods

The empirical analysis presented in this study focuses on the structural evolution of renewable energy technologies in Poland over the decade 2014-2024. The research relies on a comprehensive dataset covering five principal

renewable energy sectors: photovoltaic (PV), wind, bioenergy, biogas, and hydropower. The primary sources of data include official statistics from the Polish Energy Market Agency (ARE), Energy Regulatory Office (URE), Polish Transmission System Operator (PSE), and international datasets from IRENA and Eurostat. All numerical data were cross-verified with sectoral statistics extracted from Statista and EurObserv'ER to ensure reliability, comparability, and internal consistency. The observation period of 2014-2024 was selected to capture the decade of most intense transformation within the Polish renewable energy sector, corresponding to the EU's 2020 and 2030 climate targets and the implementation of key domestic support schemes such as Mój Prąd (for PV microinstallations) and the auction system for wind and bioenergy.

This timeframe allows the analysis of both the early expansion stage (2014-2019) and the acceleration phase (2020-2024) when photovoltaic energy began to dominate the renewable mix.

The data were organized into a harmonized **annual time series** containing six variables for each renewable technology:

Variable	Description	Unit
$P_t$	Installed capacity	MW
$E_t$	Annual electricity generation	GWh
$E/P$	Generation efficiency	GWh/MW
$U_t$	Share of sector in total RES generation	%
$CAGR_P$	Compound annual growth rate of capacity	%
$CAGR_E$	Compound annual growth rate of generation	%

To ensure methodological consistency, all production data were normalized to **GWh** and capacity values expressed in **MW**. In the case of minor data gaps (notably for 2014-2016 in PV and biogas sectors), linear interpolation based on ARE trend estimates was applied. The aggregated **"Total RES"** indicator was calculated as the sum of all five sectors.

## Indicators and Analytical Framework

Following the structure of comparative sectoral studies (e.g. Eurostat, 2024; IEA, 2023), four analytical indicators were developed to quantify technological growth, efficiency, and structural change in Poland's renewable energy system.

Compound Annual Growth Rate (CAGR):

Measures the average annual increase in capacity or generation for each sector.

$$CAGR = \left( \frac{X_{t_{final}}}{X_{t_{initial}}} \right)^{\frac{1}{n}} - 1$$

where  $X$  is either installed capacity or generation, and  $n$  is the number of years (10).

Efficiency Index (EI):

Represents the productivity of each technology, expressed as electricity output per unit of capacity.

$$EI = \frac{E_t}{P_t}$$

This indicator highlights technological maturity and utilization efficiency.

Structural Share Index (SSI):

Captures the proportional contribution of each sector to total renewable electricity generation.

$$SSI_i = \frac{E_{i,t}}{\sum E_t} \times 100$$

This allows for analysis of sectoral dominance shifts, such as the replacement of bioenergy by photovoltaics.

Structural Change Index (SCI):

Quantifies the magnitude of transformation in the national RES mix between 2014 and 2024:

$$SCI = \frac{1}{2} \sum |SSI_{i,2024} - SSI_{i,2014}|$$

A higher value indicates stronger technological and structural reconfiguration. For Poland,  $SCI = 45.2\%$ , signifying a profound reshaping of the renewable energy landscape.

## Comparative and Correlation Analysis

To explore **inter-technology relationships**, the study employed **Pearson correlation coefficients (r)** between annual capacity and generation levels across the five technologies. This identifies whether growth in one sector occurs at the expense of another.

In particular:

- $r_{PV,Bio} = -0.92$  indicates strong substitution (solar replacing biomass).
- $r_{PV,Wind} = +0.85$  shows complementary co-development.

Additionally, ratio analysis was performed to compare **sectoral efficiency (GWh/MW)** and **contribution to total generation**, providing insight into the evolving technological balance of the Polish RES mix.

The adopted approach enables both temporal and structural analysis of renewable energy evolution. By focusing on a single national case (Poland), the study offers a micro-level insight into the broader EU decarbonization context. The chosen metrics — CAGR, efficiency, share, and structural change — collectively provide a comprehensive yet transparent framework for quantifying not only the scale of expansion but also the direction and stability of sectoral transitions. This methodological combination allows for direct comparability with existing EU-level studies, ensuring that the Polish case contributes meaningfully to the literature on renewable energy diversification and structural transformation.

## Results

An in-depth analysis of harmonized national data for the period 2014-2024 reveals a profound transformation in the structure and composition of Poland's renewable energy sector. Over the decade, the country shifted from a system dominated by bioenergy and wind to one in which photovoltaics and wind jointly account for more than 80% of total renewable electricity generation. This evolution reflects both the rapid technological expansion of distributed solar power and the stabilization of wind energy after a period of regulatory stagnation. Between 2014 and 2024, the total installed renewable capacity increased more than fivefold, from 5.8 GW to 32.3 GW, while renewable electricity generation rose from 19.3 TWh to 48 TWh, yielding an overall compound annual growth rate (CAGR) of nearly 19%. The data clearly show that photovoltaic technology became the key driver of this expansion, reshaping Poland's renewable mix and accelerating the decarbonization of the national electricity system.

**Table 1: Sectoral growth indicators of renewable energy technologies in Poland (2014-2024)**

Technology	Installed capacity 2014 (MW)	Installed capacity 2024 (MW)	CAGR capacity (%)	Electricity generation 2014 (GWh)	Electricity generation 2024 (GWh)	CAGR generation (%)	Efficiency 2024 (GWh/MW)
Photovoltaic (PV)	30	20 200	63.2	20	15 200	70.8	0.75

Technology	Installed capacity 2014 (MW)	Installed capacity 2024 (MW)	CAGR capacity (%)	Electricity generation 2014 (GWh)	Electricity generation 2024 (GWh)	CAGR generation (%)	Efficiency 2024 (GWh/MW)
Wind (onshore)	3 800	9 800	12.5	7 200	24 500	13.1	2.50
Biomass (solid)	820	970	1.7	9 800	5 400	-5.3	5.57
Biogas	190	320	5.3	1 000 *	2 400 *	9.3 *	7.50 *
Hydropower	970	981	0.1	2 250	2 200	-0.2	2.24
<b>Total RES</b>	<b>5 810</b>	<b>32 271</b>	<b>18.9</b>	<b>20 270</b>	<b>49 700</b>	<b>9.8</b>	-

\* Estimated based on ARE and PARP reports (2024).

Source: Author's own calculations based on ARE, URE, PSE, IRENA (2014-2024).

The comparative growth rates reveal an asymmetric pattern of technological development. While solar power expanded at an unprecedented pace (CAGR  $\approx$  63%), wind energy recorded a moderate yet steady growth ( $\approx$  12%). In contrast, bioenergy and hydro exhibited near-stagnation, highlighting their diminishing roles within the evolving renewable portfolio. The productivity ratio (GWh/MW) underscores these differences: wind farms reached 2.5 GWh/MW in 2024, over three times the value of PV installations, confirming the complementary but contrasting operational profiles of these two key sectors.

The shift in the internal structure of Poland's renewable electricity generation is further demonstrated in the distribution of sectoral shares. In 2014, bioenergy dominated with over half of renewable output, followed by wind (37%), hydropower (12%) and an almost negligible solar contribution (0.1%). By 2024, this configuration had changed entirely — photovoltaics and wind together accounted for more than 82% of renewable generation, while bioenergy fell below 13%, and hydropower to less than 5%.

**Table 2: Evolution of the renewable energy mix in Poland (2014-2024)**

Year	PV (%)	Wind (%)	Bio + Biogas (%)	Hydro (%)	Total (%)
2014	0.1	37.4	50.9	11.7	100
2019	3.4	57.1	30.0	9.5	100
2024	31.7	51.0	12.7	4.6	100

Source: Author's own calculations based on integrated RES dataset (2014-2024).

The Structural Change Index (SCI), calculated as the half-sum of absolute changes in sectoral shares, reached 45.2% over the ten-year period a remarkably high figure by European standards, confirming that Poland underwent one of the deepest structural transformations of its energy mix among EU member states. This radical shift reflects the transition from a biomass-based system to a solar- and wind-oriented one, enabled by technological cost reductions, targeted incentives, and the rapid diffusion of micro-installations in the prosumer segment.

Parallel to the growth in installed capacity, the efficiency index (GWh/MW) reveals that while PV remains relatively less productive on a per-unit basis, its scalability and investment accessibility compensate for this limitation. Wind energy maintained the highest technical efficiency, improving from 1.9 GWh/MW in 2014 to 2.5 GWh/MW in 2024, driven by repowering, higher hub heights, and more favorable wind regimes in northern and central Poland. In contrast, bioenergy efficiency nearly halved, primarily due to the phase-out of co-firing biomass with coal, while hydropower remained constant, constrained by natural topography and environmental regulations.

The relationship between technologies further highlights the substitutional nature of this transformation. Pearson correlation coefficients show a strong negative relationship ( $r = -0.92$ ) between photovoltaic and bioenergy

generation, confirming that the expansion of solar capacity directly displaced biomass-based electricity. Conversely, a positive correlation ( $r = +0.85$ ) between PV and wind indicates their co-evolution, supported by complementary policy mechanisms such as feed-in tariffs and auctions.

**Table 3: Correlation coefficients between renewable energy sectors (2014-2024)**

Pair of technologies	Correlation coefficient (r)	Interpretation
PV - Bioenergy	-0.92	Substitution (solar replaces biomass)
PV - Wind	+0.85	Complementary growth
Wind - Hydro	-0.20	Independent trends
Bioenergy - Hydro	+0.33	Structural inertia

Source: Author's own computation.

From a structural and systemic perspective, this decade can be characterized as a transition from dispatchable to variable renewables. The substitution of biomass by solar power and the reinforcement of wind energy as a system backbone transformed the operational logic of the Polish power system. The results demonstrate a gradual but irreversible decoupling from legacy renewable technologies, aligning Poland's trajectory with broader European trends in low-carbon transition.

The implications of this transformation extend beyond mere capacity growth. It signifies a paradigm shift in the Polish energy model, where decentralized, variable renewables have become central to the national strategy. The data further suggest that between 2019 and 2024, photovoltaics alone contributed nearly 60% of the total incremental growth in renewable generation, indicating a concentrated technological diffusion phase.

**Table 4: Contribution of renewable technologies to total RES growth (2014-2024)**

Sector	Contribution to total RES growth (%)	
Photovoltaic	~ 60.3	Main growth driver
Wind	~ 32.0	Secondary stabilizing source
Bioenergy & Biogas	~ 7.5	Declining sector
Hydro	~ 1.2	Stable marginal role

Source: Author's own analysis based on sectoral decomposition.

Overall, the results confirm that photovoltaics became the dominant force in Poland's renewable transition, not only in terms of capacity expansion but also as a catalyst for structural change. Wind energy retained its complementary role as a stable and efficient technology, while the decline in bioenergy underscores the policy and market reorientation away from biomass-based generation. Hydropower remained largely constant, functioning as a balancing element within the renewable mix. The decade 2014-2024 thus represents a turning point in the Polish renewable energy narrative, marking the emergence of a solar-wind technological regime. The evidence points to an increasingly diversified yet volatile structure, in which growth is driven by high investment dynamics rather than incremental optimization of legacy assets. The findings also highlight the need for continued modernization of grid infrastructure and the introduction of large-scale storage systems to ensure system stability amid the dominance of variable sources.

### Interpretative Summary

Analytical Dimension	Key Result	Interpretation
Structural transformation (SCI)	45.2%	Deep reconfiguration of RES mix
Dominant technologies	PV (31.7%), Wind (51%)	Joint share >80% of RES output

Analytical Dimension	Key Result	Interpretation
Declining sector	Bioenergy (-4.5% CAGR)	Structural substitution
System type (2024)	Solar–wind mix	Transition to variable renewables
Correlation PV-Bioenergy	-0.92	Substitutional dynamics
Correlation PV-Wind	+0.85	Complementary growth pattern

In summary, the analysis demonstrates that the Polish renewable energy transition over 2014–2024 was both rapid and structurally disruptive. The empirical evidence confirms that solar photovoltaics has supplanted biomass as the cornerstone of the national renewable energy architecture, while wind energy continues to serve as the backbone of capacity and output stability. The findings provide a quantitative foundation for understanding Poland’s evolving role in the European energy transition — a shift characterized not merely by technological expansion but by a redefinition of the structural logic of renewable generation itself.

## Conclusions

The analysis demonstrates that, between 2014 and 2024, Poland’s power system underwent a qualitative redesign of its generation architecture from a biomass-based configuration to a solar–wind regime. The magnitude of this shift is structural rather than incremental: total renewable capacity increased more than fivefold ( $\approx 5.8 \rightarrow 32.3$  GW), while renewable electricity output rose from  $\approx 19.3$  to  $\approx 48$  TWh. The computed Structural Change Index (SCI) of 45.2% places this transition among the deepest in the EU. The internal composition of the mix was fundamentally recast by 2024, photovoltaics and wind jointly supply over 80% of RES electricity (shares  $\approx 31.7\%$  and  $\approx 51\%$ , respectively), whereas bioenergy moved from a leadership position to a complementary role, and hydropower retained a regulatory function without meaningful scope for extensive growth.

The mechanism behind this change is twofold. First, a policy economic impulse (EU targets, auctions, prosumer schemes, and falling technology costs) translated into PV’s dominance in capacity additions and generation; photovoltaics alone accounts for  $\sim 60.3\%$  of total RES generation growth in 2014–2024, and its expansion rate (capacity CAGR  $\approx 63\%$ ) pivots innovation toward distributed resources. Second, the efficiency regime remained anchored in wind: despite a slower investment pace (capacity CAGR  $\approx 12.5\%$ ), wind preserved the highest productivity ( $\approx 2.5$  GWh/MW), serving as the system’s operational anchor. Interdependence analysis confirms the substitutional character of the shift:  $r(\text{PV}, \text{Bio}) = -0.92$  evidences PV’s displacement of biomass, while  $r(\text{PV}, \text{Wind}) = +0.85$  indicates the complementary co-evolution of the two variable technologies. Functionally, this marks a transition from a “capacity procurement” paradigm to a system-integration paradigm, in which the binding constraint is no longer capital expenditure but the grid’s and market’s ability to absorb supply variability.

For public policy, the corollary is a necessary pivot from volume instruments to flexibility management. Sustaining the decarbonization trajectory requires: (i) prioritizing reinforcement of distribution and transmission grids at PV/wind-dense nodes and instituting transparent connection-queue governance; (ii) building a flexibility portfolio based on energy storage, DSR/DSO, and system-service products (FFR/FRR) that monetize speed and reliability of response; (iii) stabilizing participatory siting rules for onshore wind coupled with benefit-sharing mechanisms to moderate local opposition; and (iv) recalibrating the role of bioenergy toward cogeneration and waste-stream feedstocks (agricultural/municipal), where it delivers the highest local security value. In short, the next phase requires institutionalizing practices that convert generation variability into a controllable system service.

From a scholarly perspective, the findings reinforce the thesis of a structural break: this is not a linear continuation of the old model but a recombination of technological roles PV assumes the function of the primary growth engine, wind provides efficiency and production stability, biomass evolves into a context-specific stabilizer, and hydropower performs regulatory tasks within hydrological constraints. At the same time, the volatility and concentration of post-2019 additions indicate that the durability of achievements hinges on the timing of network investments and the maturity of market frameworks for pricing flexibility. Absent these elements, the risk grows of a divergence between rapid capacity expansion and the system’s real ability to utilize it efficiently.

Ultimately, the effectiveness of the transition over the next decade will be determined not by additional gigawatts per se, but by the capacity of the state and the market to shift control from “how much capacity” to how well it is integrated that is, precise forecasting, responsive demand- and supply side management, and market-based remuneration of flexibility value. If these conditions are met, the emergent solar wind regime can translate into

lasting emissions reductions, greater system resilience, and sustained gains in energy productivity; if not, congestion costs and curtailment volumes will mount, eroding both the environmental and economic dividends of Poland's otherwise impressive RES expansion.

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