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Development and potential of renewable energy sources in Poland

Abstract. The aim of the paper is to assess the potential of renewable energy sources (RES) in Poland. We analyse the installed capacity and the amount of electricity generated from renewable energy sources, as confirmed by issued certificates of origin. Additionally, the study examines the structure and dynamics of the capacity of renewable energy installations at the voivodeship level, covering the period from 2017 to 2023. The data comes the Energy Regulatory Office. The results reveal significant growth in renewable energy capacity over the analysed period, with wind and solar energy showing the most substantial increases. Wind power remains the largest contributor to Poland's renewable energy production, while solar power experienced rapid expansion. The analysis also highlights regional disparities. Podlaskie, West Pomeranian, and Kuyavian-Pomeranian voivodeships are leading in terms of installed capacity, particularly in wind energy, which remains the largest contributor to Poland's renewable energy production. Conversely, regions such as Lubusz, Opole, and Holy Cross show slower progress and lag behind in renewable energy development.

Keywords: renewable energy, renewable energy sources (RES), energy capacity, energy installations, Poland, voivodeships

Introduction

The development of renewable energy sources is a critical focus in addressing global energy challenges and promoting sustainability. They offer various environmental benefits, including pollution reduction, lower greenhouse gas emissions, and improved local and regional manufacturing (Al-Jawhari, 2021; Tovar-Facio, 2022). Renewable energy technologies provide benefits that go beyond energy alone and contribute to sustainable development in the economy, environment, and society (Algarni et al., 2023).

The advancement of renewable energy sources (RES) in Poland represents a critical element of the nation's energy transition strategy, which aims to reduce greenhouse gas emissions and enhance the share of clean energy in the national energy mix. This shift is driven by the urgent need to mitigate the escalating threat of climate change and

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to comply with the European Union's stringent environmental protection and carbon dioxide (CO_2) emissions reduction mandates, in alignment with European directives (Mazurek-Czarnecka et al., 2022). Unfortunately, Poland's energy mix is largely dependent on fossil fuels, particularly coal, which has historically been the backbone of its energy sector (Suwała et al., 2017). Thus, Poland has pledged to progressively increase the proportion of RES in its energy portfolio, a goal that necessitates the accelerated development of the wind, solar, and biomass energy sectors (Igliński et al., 2022). The Polish Energy Policy 2040 (PEP2040) outlines plans to reduce coal dependency and increase the share of renewable energy, but the timeline for these changes may not align with the EU's climate policy goals (Swora, 2023). Poland met its 2020 target of generating 15% of energy from renewable sources. By 2030, Poland aims to achieve a 23% share of renewable energy in its gross final energy consumption, aligning with EU directives (Jaworski et al., 2023; Zbroński et al., 2023). This transition is expected to bring about significant socio-economic benefits, including job creation, energy security, and reduction in greenhouse gas emissions (Dębicka et al., 2024). Investments in renewable energy also aim to alleviate energy poverty, which affects about 9% of Poland's population (Biernat-Jarka et al., 2021).

Despite the progress in expanding renewable energy, Poland's energy transition is fraught with considerable challenges. As one of the leading producers of fossil fuel--based energy in Europe, Poland faces a particularly complex task in modernizing its energy infrastructure. The shift towards RES demands not only substantial financial investment but also significant reforms in regulatory frameworks and the strategic planning of energy transmission networks. The government is aware of the necessity to reduce the role of coal, but the pace of transformation and the future energy mix remain uncertain (Suwała et al., 2017). Several barriers impede the growth of renewable energy, including restrictive legislation, investor uncertainty, and technical challenges related to integrating variable renewable energy sources into the national grid (Kurowska et al., 2022). Economic and political barriers, as high costs of renewable energy technologies and administrative hurdles pose significant challenges (Marks-Bielska et al., 2020). The potential of renewable energy depends on technological progress and infrastructure development (Jaworski et al., 2023). Moreover, societal resistance to certain RES projects (most notably wind farms) further complicates the implementation of these initiatives, as public opposition can delay or block the deployment of key installations (Żak-Skwierczyńska, 2022; Mazurek-Czarnecka et al., 2022). Additionally, as mentioned above, Poland's energy transition is influenced by socio-economic factors, including the significant role of the mining industry in the economy and the need for a just transition to protect jobs and communities.

Legal and regulatory conditions are crucial for RES development. Simplified legal regulations and effective financial support are needed to encourage investment (Igliński, 2016). The Polish government has introduced various regulatory mechanisms to stabilize RES operations, including energy clusters and cooperatives (Serowaniec, 2021). EU funds play a significant role in supporting RES projects, with substantial investments in wind and solar energy (Chodkowska-Miszczuk, 2016). The introduction

of new support mechanisms, such as auctions for RES projects, aims to increase the share of renewable energy in Poland's energy mix. However, a volatile support system may create uncertainty for investors, potentially hindering long-term growth (Mazurek-Czarnecka et al., 2022).

The regional development of renewable energy sources (RES) in Poland exhibits significant variability and potential across different voivodeships. Poland's regions show distinct differences in renewable energy generation capacity (Zarębski, 2021). For instance, voivodeships such as Greater Poland and Masovian are at the forefront of implementing solar and wind energy projects, whereas others, including Subcarpathian, continue to lag behind due to a combination of geographical constraints and infrastructural deficiencies (Zbroński et al., 2023; Pietrzak et al., 2021). In Northern Poland, particularly rural areas, wind and biogas energy play crucial roles in local development, providing energy security, employment opportunities, and promoting regional growth (Czapiewska, 2015). The uneven distribution of RES development across different regions underscores the importance of region-specific policies and strategies. (Halama & Majorek, 2022). A more tailored approach, sensitive to the unique conditions of each voivodeship, will be essential for fostering balanced and effective growth in Poland's renewable energy sector, ensuring that all regions contribute to and benefit from the national transition towards a cleaner energy future (Kryszk et al., 2023).

The aim of the paper is to assess the potential of renewable energy sources in Poland. In detail, we analyse the installed capacity and the amount of electricity generated from renewable energy sources (RES) in Poland, as confirmed by issued certificates of origin. Additionally, we examine the structure and dynamics of the capacity of renewable energy installations at the regional (voivodeship) level.

Methodology

From the national (Polish) perspective, we analyse the installed capacity of renewable energy installations and electricity production from 2005 to 2022, covering various types of renewable energy sources, including biogas, biomass, solar radiation (photovoltaics), wind energy, hydropower, and the technology of co-firing (as confirmed by issued certificates of origin). Additionally, from the regional (voivodeship) perspective, we present the status of renewable energy installations in Poland as of December 31, 2017, and 2023, highlighting the changes in installed capacity in megawatts (MW) for various energy technologies, such as biogas (BG), biomass (BM), thermal waste-to-energy plants (ITPO), photovoltaic installations (PVA), wind power (WIL), hydroelectric power plants (WO), and co-firing installations of conventional fuels and biomass (WS). The installed capacity is measured in MW, while the amount of electricity is presented in MWh.

The data used in this study comes from publicly available sources provided by the Energy Regulatory Office (ERO), a central body of the Polish government responsible for regulating the energy market. In the analysis we use descriptive statistics. Tabular and graphical methods are used to present research results.

Results

Figure 1 presents the installed capacity of renewable energy installations in Poland from 2005 to 2022.

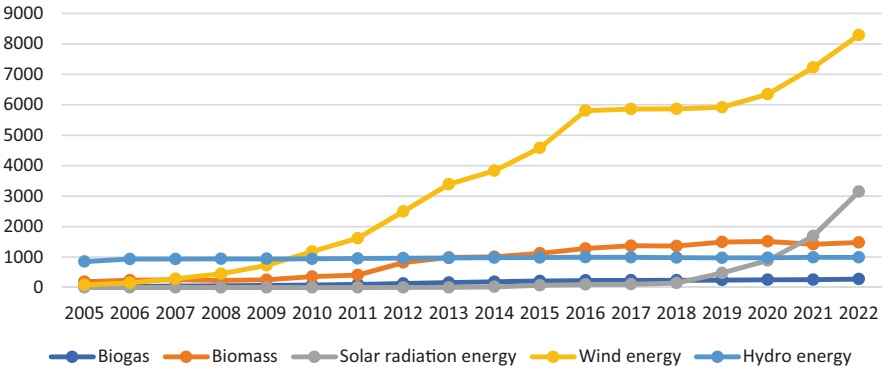

Figure 1. Installed capacity of renewable energy sources (RES) in Poland from 2005 to 2022 (in MW)

Source: own elaboration based on ERO data.

Over the analysed years, wind energy has experienced significant growth, making it the most substantial contributor to Poland's renewable energy capacity by 2022, with an installed capacity of over 8,287 MW. The development of wind energy can be attributed to favourable wind conditions and government policies supporting renewable energy expansion. Biomass installations also show considerable growth, peaking at around 1,512 MW in 2019. However, there were fluctuations in biomass capacity in subsequent years, an effect of shifts and challenges in biomass sourcing. Solar energy installations, which began contributing significantly around 2013, saw a rapid increase, especially between 2018 and 2022, culminating in an installed capacity of approximately 3,148 MW by 2022. Biogas installations, although more modest compared to wind and biomass, showed steady growth over the years, reaching around 276 MW in 2022. Hydropower exhibited a more stable trend, with installed capacity hovering around 950-990 MW throughout the entire period (Figure 1). The installed capacity of renewable energy sources (RES) in Poland does not necessarily correlate directly with the amount of electricity generated from these sources, as actual generation depends on factors such as weather conditions, maintenance, and grid stability.

Figure 2 illustrates the production of electricity from various types of renewable energy installations in Poland between 2005 and 2022.

The renewable energy sources covered include biogas, biomass, solar radiation (photovoltaic), wind energy, hydropower, and co-firing technologies (biomass, biofuels, biogas with other fuels). Over the years, wind energy has shown a significant and consistent upward trend, peaking in 2017 and remaining the largest contributor to renewable energy production in Poland, especially in coastal areas with favourable

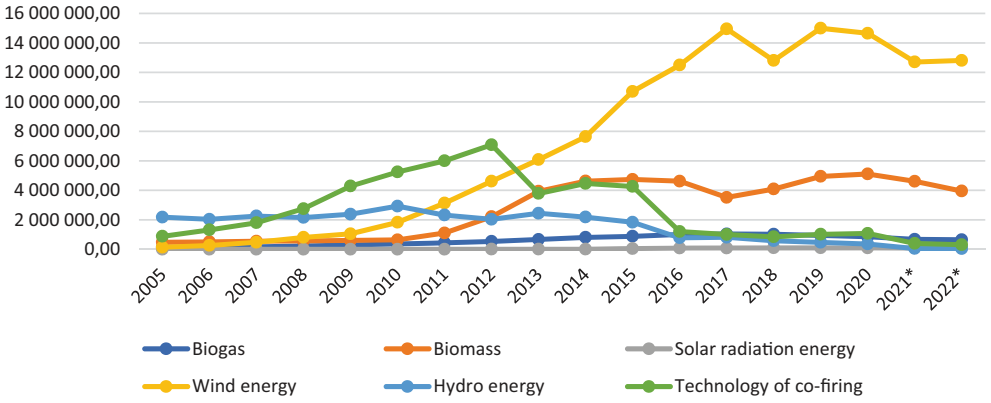

Figure 2. Amount of electricity generated from renewable energy sources (RES) in Poland from 2005 to 2022 (in MWh)

Source: own elaboration based on ERO data.

conditions. Biomass displayed substantial growth initially, reaching a peak around 2020, but experienced a decline afterwards. Solar energy, while initially minimal, has shown a notable increase starting in 2015, with steady growth thereafter. The biogas sector exhibited steady growth until 2017, followed by a gradual decline. Hydropower production declined significantly after 2014, likely due to ageing infrastructure and variable hydrological conditions. Co-firing technologies initially increased in production but saw a significant drop after 2016. The decreases observed in 2021 and 2022 can be attributed to the fact that the presented data reflect the volumes of electricity generated from renewable energy sources that were covered by certificates of origin issued by the President of the Energy Regulatory Office (Figure 2).

Overall, Figure 1 and Figure 2 indicate a dynamic evolution of renewable energy sources in Poland, emphasizing significant growth in wind and solar energy, with wind energy remaining the primary renewable source, while more traditional energy sources like hydropower and co-firing technologies are seeing a decline as the country transitions towards more advanced renewable technologies.

In the next step, we provide the analysis of renewable energy installations in Poland from the regional, i.e., voivodeship perspective. It provides insight into the development and spatial distribution of renewable energy sources (RES) across the country. We present the status of renewable energy installations in Poland as of December 31, 2017 and 2023, highlighting the changes in installed capacity in megawatts (MW) for various energy. Table 1 depicts the capacity of renewable energy installations as of 31 December 2017.

Wind power was the dominant renewable energy source in Poland in 2017. The voivodeships with the highest installed capacity in wind power were West Pomeranian (1489.02 MW), Greater Poland (698.97 MW), and Pomeranian (693.34 MW). This distribution indicates a predominance of coastal locations and areas with favourable

Table 1. Renewable energy installations in Poland from the voivodeship perspective (in MW, as of 31 December 2017)

Voivodeship	BG	BM	ITPO	PVA	WIL	WO	WS
Lower Silesian	21.93	100.00	0.00	3.59	176.36	73.89	1581.20
Kuyavian-Pomeranian	16.01	177.23	0.00	8.14	597.11	212.50	50.00
Lublin	13.76	2.60	0.00	30.93	138.90	1.39	6.00
Lubusz	5.01	1.80	0.00	3.39	192.00	117.97	0.00
Masovian	29.74	272.70	0.00	1.88	386.43	22.15	3977.12
Lesser Poland	10.81	3.15	16.90	9.23	6.68	192.40	560.00
Opole	3.81	0.00	0.00	0.94	138.15	30.76	1492.00
Subcarpathian	8.31	58.38	0.00	4.38	152.96	209.25	300.00
Podlaskie	12.37	84.54	9.01	12.67	197.01	0.81	0.00
Pomeranian	22.82	2.35	0.00	2.44	693.34	34.05	111.60
Warmian-Masurian	14.83	29.44	0.00	7.91	354.27	17.22	49.00
Greater Poland	24.46	116.36	25.30	6.70	698.97	12.65	820.50
West Pomeranian	17.15	83.23	0.00	3.80	1489.02	13.58	1374.00
Łódź	12.69	59.26	0.00	2.33	581.62	11.28	205.85
Silesian	21.46	90.26	0.00	8.90	33.33	36.65	5064.70
Holy Cross	2.14	238.66	0.00	0.54	22.07	2.90	1607.00

Source: own calculation and elaboration based on ERO data.

wind conditions. Photovoltaic installations were still a relatively minor source of energy in 2017, with the largest installed capacities found in the Lublin (30.93 MW) and Kuyavian-Pomeranian (8.14 MW) voivodeships. Biomass was particularly significant in Masovian (272.7 MW) and Kuyavian-Pomeranian (177.23 MW), while biogas also played an important role, with the highest concentration in Masovian (29.74 MW). Hydroelectric power had a significant share in Lower Silesian (73.89 MW) and Lubusz (117.97 MW). Calculating the average installed capacity for each type of RES across all voivodeships reveals that wind power had the highest average installed capacity of approximately 372.6 MW per voivodeship, confirming its dominance in the country. Biomass had an average installed capacity of about 82.1 MW per voivodeship, with Masovian having the highest capacity. Photovoltaics had an average capacity of only about 6.6 MW per voivodeship, indicating the limited development of this technology in 2017. Biogas had an average installed capacity of around 13.3 MW per voivodeship, with the highest concentration in Masovian. Significant differences exist in the development of RES among voivodeships, with coastal regions such as West Pomeranian and Pomeranian having the highest installed wind power capacity, while central voivodeships such as Masovian had a more diversified structure of RES, including biomass, biogas, and hydroelectric power (Table 1).

Table 2 provides an overview of renewable energy installations in Poland as of December 31, 2023, illustrating the installed capacity in megawatts (MW) for different energy technologies.

Table 2. Renewable energy installations in Poland from the voivodeship perspective (in MW, as of 31 December 2023)

Voivodeship	BG	BM	ITPO	PVA	WIL	WO	WS
Lower Silesian	22.34	111.25	0.00	297.18	326.59	84.66	1601.95
Kuyavian-Pomeranian	18.96	177.23	13.80	334.16	929.21	210.04	63.70
Lublin	17.13	14.60	0.00	381.15	256.45	0.91	6.00
Lubusz	9.32	3.47	0.00	431.38	244.20	113.67	0.00
Masovian	32.31	181.50	3.85	294.94	548.27	21.99	3560.12
Lesser Poland	12.55	0.00	16.90	104.26	5.77	185.83	755.40
Opole	5.65	0.00	0.00	99.06	147.69	36.41	0.00
Subcarpathian	9.16	2.80	8.99	147.50	188.92	209.19	0.00
Podlaskie	14.19	9.24	9.01	313.69	297.26	0.58	203.50
Pomeranian	27.37	8.33	0.00	417.97	1261.53	29.05	111.60
Warmian-Masurian	22.59	27.40	0.00	511.37	614.71	14.99	0.00
Greater Poland	38.53	232.06	26.94	870.24	1466.65	12.20	12.00
West Pomeranian	20.31	89.57	15.48	446.07	2436.40	13.56	924.13
Łódź	16.97	59.26	0.00	246.40	677.48	10.72	201.42
Silesian	23.07	90.21	76.50	118.31	110.30	36.12	4446.10
Holy Cross	4.83	243.17	0.00	166.10	49.06	2.22	1649.00

Source: own calculation and elaboration based on ERO data.

Wind power continued to be the dominant type of renewable energy in Poland in 2023. The voivodeships with the highest installed capacity in wind power were West Pomeranian (2436.4 MW), Greater Poland (1466.6 MW), and Pomeranian (1261.5 MW). The increase in wind power capacity in coastal regions confirms their key role in wind energy production. There was significant growth in photovoltaic installations in 2023, with Greater Poland (870.24 MW) and Lublin (381.15 MW) leading in terms of increased capacity. Biomass remained an important energy source, especially in the Greater Poland (232.06 MW) and Holy Cross (243.17 MW) voivodeships. Biogas installations also saw growth across most voivodeships, with the largest concentration in Greater Poland (38.53 MW) and Masovian (32.31 MW). Hydroelectric power maintained a stable contribution, and the highest capacities were in Lower Silesian (84.66 MW) and Lubusz (113.67 MW). Thermal waste-to-energy plants also increased their capacity, notably in Silesian (76.5 MW) and West Pomeranian (15.48 MW). In terms of average installed capacity for each type of RES in 2023, wind power continued to dominate with an average of approximately 672.9 MW per voivodeship, while photovoltaics showed a significant increase in average capacity, reaching around 259.3 MW per voivodeship. Coastal regions such as West Pomeranian continued to dominate in terms of wind power, whereas Greater Poland distinguished itself with significant shares in both wind and photovoltaic energy, highlighting diverse renewable energy development in the region. Between 2017 and 2023, there was substantial growth in photovoltaic installations, especially in Greater Poland and Lublin. West Pomeranian remained the

leader in wind power capacity, attributed to favourable geographical and atmospheric conditions. Silesian and Holy Cross experienced notable increases in thermal waste-to-energy plant capacity. The installed capacity of wind power increased across all voivodeships, with the most considerable growth observed in West Pomeranian and Greater Poland. Photovoltaic installations were the fastest-growing segment. Biomass capacity remained relatively stable, with some growth in Greater Poland and Holy Cross, but a decrease in Masovian. The increase in capacity for thermal waste-to-energy installations in Silesian and West Pomeranian underscores the growing importance of waste-to-energy as part of the circular economy and efforts to improve energy efficiency. Wind energy remains a crucial component of Poland's RES mix, particularly in coastal regions, while photovoltaic energy is becoming increasingly popular, especially in sun-rich voivodeships. The diversity in technologies and regional differences indicate a progressing energy transition aimed at increasing the share of clean energy in the national energy mix.

Discussion

The regional disparities in renewable energy deployment align with previous findings that geographical and infrastructural factors significantly influence growth potential (Pietrzak et al., 2021). For instance, the concentration of wind power in the coastal voivodeships of West Pomeranian and Pomeranian is consistent with (Zbroński et al., 2023), who identified favourable wind conditions as a major driver for wind energy investments. The growth in solar installations, particularly in voivodeships like Greater Poland and Lublin, parallels observations by Halama and Majorek (2022), who noted that photovoltaic systems are increasingly adopted due to financial incentives and technological advancements. This trend underscores the importance of tailored policy interventions that consider local conditions (Kryszk et al., 2023). Despite these advancements, challenges remain. Kurowska et al. (2022) emphasized regulatory barriers and investor uncertainty, which are still obstacles to renewable energy expansion. Societal resistance to projects like wind farms also resonates with Żak-Skwierczyńska (2022), who highlighted social acceptance as a critical factor for renewable energy projects in Poland. This research supports Mazurek-Czarnecka et al. (2022), asserting that balanced growth of renewable energy across regions necessitates strategic reforms in regulation and infrastructure. The findings highlight the need for region-specific strategies to enhance the participation of underperforming voivodeships, such as Subcarpathian, in renewable energy development (Igliński et al., 2022).

Conclusions

The findings of this study demonstrate the notable progress that Poland has made in expanding its renewable energy capacity, particularly in wind and solar power, between 2017 and 2023. Wind energy remains the dominant contributor to the country's RES (Renewable Energy Sources) generation, underscoring its pivotal role in Poland's renewable energy transition. Wind power capacity continues to grow rapidly due to technological advancements, increasing demand for clean energy, and supportive

policies, such as green certificates and auction systems. In parallel, solar energy, although starting from a lower base, has experienced a rapid expansion in recent years. This growth is driven by falling installation costs, increased private sector participation, and favourable conditions for photovoltaic (PV) installations.

The analysis also reveals substantial regional disparities in renewable energy development. While Podlaskie, West Pomeranian, and Kuyavian-Pomeranian lead in installed capacity, particularly in wind energy, other regions such as Lubusz, Opole, and Holy Cross have shown slower progress. Regions like Podlaskie and West Pomeranian have benefited not only from favourable natural conditions but also from targeted infrastructure investments and proactive regional policies.

The analysis of the structure and dynamics of renewable energy installations at the regional (voivodeship) level highlights disparities in installed capacity across regions. This suggests the need for targeted investment strategies, especially in regions where the potential for renewable energy has not been fully exploited. Government policies and incentives should focus on attracting more investment in underperforming regions to ensure a balanced development of RES infrastructure. As Poland continues its energy transition, it's important to regularly monitor progress against national and EU energy targets. If certain regions or sectors lag behind, policymakers should be ready to adjust strategies to ensure that national goals are met. Additionally, the system of certificates of origin used to confirm renewable energy production is crucial for tracking progress in the sector.

While the study uses publicly available data from the Energy Regulatory Office (ERO), the study emphasizes installed capacity. However, it does not necessarily translate to actual energy production or efficiency. There may be discrepancies between potential energy output and what is actually generated due to factors like weather conditions (for wind or solar energy), maintenance issues, or grid limitations. Future study could broaden the scope by comparing Poland's renewable energy development with that of other countries. This could help identify global best practices and provide insights into how different regulatory frameworks and policies impact renewable energy growth.

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