

Article

Assessing the Role of Energy Mix in Long-Term Air Pollution Trends: Initial Evidence from Poland

Mateusz Zareba 

Department of Geoinformatics and Applied Computer Science, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, 30-059 Krakow, Poland; zareba@agh.edu.pl

Abstract: Air pollution remains a critical environmental and public health issue, requiring diverse research perspectives, including those related to energy production and consumption. This study examines the relationship between Poland's energy mix and air pollution trends by integrating national statistical data on primary energy consumption and renewable energy sources over the past 15 years with air pollution measurements from the last eight years. The air pollution data, obtained from reference-grade monitoring stations, focus on particulate matter (PM). To address discrepancies in temporal resolution between daily PM measurements and annual energy sector reports, a bootstrapping method was applied within a regression framework to assess the overall impact of individual energy components on national air pollution levels. Seasonal decomposition techniques were employed to analyze the temporal dynamics of specific energy sources and their contributions to pollution variability. A key aspect of this research is the role of renewable energy sources in air quality trends. This study also investigates regional variations in pollution levels by analyzing correlations between geographic location, industrialization intensity, and the proportion of green areas across Poland's administrative regions (Voivodeships). This spatially explicit approach provides deeper insights into the linkages between energy production and pollution distribution at a national scale. Poland presents a unique case due to its distinct energy mix, which differs significantly from the EU average, its persistently high air pollution levels, and recent regulatory changes. These factors create an ideal setting to assess the impact of energy sector transitions on environmental quality. By employing high-resolution spatiotemporal big data analysis, this study leverages measurements from over 100 monitoring stations and applies advanced statistical methodologies to integrate multi-scale energy and pollution datasets. From a PM perspective, the regression analysis showed that High-Methane Gas had a neutral impact on PM concentrations, making it a suitable transition energy source, while renewables exhibited negative regression coefficients and coal-based sources showed positive coefficients. The findings offer new perspectives on the long-term environmental effects of shifts in national energy policies.

Keywords: air pollution; energy mix; renewable energy; environmental policy



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1. Introduction

Air pollution is a global issue that cannot be considered in isolation from the structure and usage of the energy system [1]. Research showed a direct correlation between household heating in winter and elevated particulate matter (PM) concentration (for moderate climate zones) [2,3], as well as similar relationships between residual heating and PM levels observed in climate zones with dry seasons like Thailand [4] and Brazil [5]. While seasonal heating and combustion are the primary drivers of extreme smog episodes (ESEs),

other factors also contribute to consistently high pollution levels year-round—including transportation, agriculture, manufacturing, natural sources, etc. [6]. Official data from the European Commission [7] indicate that as much as 58% of PM_{2.5} pollution in the European Union (EU) originates from energy consumption, with an additional 3% from energy supply. Manufacturing accounts for 14%, road transport for 9%, waste for 8%, and agriculture for only 7%. In the case of PM₁₀ pollution, the share of energy consumption is lower, at 44%, while agriculture's contribution rises to 19%. Despite significant expenditures and the implementation of strict environmental regulations across EU member states, estimates suggest that in 2021, over 90% of the EU population was exposed to excessive pollution levels during smog incidents. This is particularly dangerous because the small size of PM particles allows them to penetrate the lungs during respiration and subsequently enter the bloodstream [8]. In addition to well-documented health risks like asthma, cardiovascular diseases, and lung cancer, exposure to PM_{2.5} is estimated to have caused over 238,000 deaths in the EU [9,10]. Research indicates a significant link between prolonged exposure to PM concentrations and neurodegenerative diseases, including Alzheimer's disease [11]. Given the aging population in many EU countries, this could lead to considerable strain on healthcare and social care systems, as patients with Alzheimer's disease require specialized, round-the-clock care, as they are unable to function independently [12].

It was proven that some of the most polluted cities in the EU are located in Poland, including Nowy Sącz, Piotrków Trybunalski [7], and Kraków [13]. In Poland, air quality monitoring operates under Directive 2008/50/EC [14], which establishes pollution control standards and requires continuous assessment of air conditions. The country is divided into 46 designated air quality zones, which include agglomerations, cities, and the remaining areas of Voivodeships. These zones serve as the framework for monitoring pollution levels, ensuring compliance with EU regulations and implementing necessary corrective measures. Before 2020, Poland followed a 2012 regulation that categorized air quality zones into 12 large agglomerations, 18 cities exceeding 100,000 residents, and 16 broader Voivodeship regions. However, as urban populations declined, some cities no longer met the population criteria, reducing the number of official zones used for air quality assessments. In response, legislative changes in 2022 reinstated the total number of zones to 46, ensuring continued air quality evaluations in all previously monitored regions [15,16].

Poland adheres to standardized air quality measurement procedures to maintain consistency with EU policies, using PN-EN 12341

for gravimetric sampling and PN-EN 16450 for automatic monitoring. The legal limits for particulate matter are set at 25 µg/m³ for PM_{2.5} (annual average), while for PM₁₀, the thresholds are 50 µg/m³ (24 h average) and 40 µg/m³ (annual average). These benchmarks guide environmental strategies and pollution mitigation efforts across the monitoring network [17].

Poland, situated in the moderate climate zone in Central Europe, experiences a significant difference of nearly eight hours between the shortest and longest days of the year, which may explain why smog episodes peak during the cold season when temperatures drop. Poland has a zonal landform structure, with uplands extending south of the central part of the country and lowlands to the north. There are no natural geographical barriers in the form of hills to the east and west. Overall, the country's landscape is predominantly lowland, with an average elevation of 173 m above sea level. About 50% of its territory consists of uplands ranging from 100 to 200 m in height. Mountain ranges, including the highest peak, Rysy (2499 m) [18], are located in the south and southwest of the Polish Carpathians, divided into the Central Carpathians, Outer Carpathians, and Carpathian Foredeep. The Pieniny Klippen Belt separates the Outer and Central Carpathians. The region includes several basins, such as Zakopane or Nowy Targ, with diverse landscapes

shaped by river valleys and mountainous terrain [19,20]. These valleys often host tourist resorts and recreational centers, making the area popular. Unfortunately, due to poor air quality, there have been concerns that some towns, such as Rabka-Zdroj, could lose their official spa status and the “Zdroj” designation, which means “spa” or “spring”. Some places have already lost their status as health resorts, as pollution and other factors continue to be a serious issue [21]. The northern part of the country features a coastline along the Baltic Sea and a post-glacial landscape with numerous lakes. Air quality in Poland is often the poorest in large urban agglomerations situated in basins, such as the Upper Silesian, Krakow, and Rybnik-Jastrzebie conurbations. Topographical factors play a significant role in air pollution accumulation, exacerbating smog episodes in these regions [18]. Geomorphological and meteorological factors influence the dispersion and accumulation of pollution, but energy production and consumption are key determinants that should be prioritized in long-term policy planning [22].

Poland’s Energy Policy 2040 [23] outlines a strategic shift towards a sustainable, low-emission energy system, focusing on energy security, economic growth, and climate objectives. The plan emphasizes reducing coal usage, particularly in residential areas, while improving air quality. The transition is structured around three main goals: just transformation, zero-emission energy, and enhanced air quality. By 2030, Poland aims to double its renewable energy capacity to 23–25 GW, with offshore Wind projects contributing 5.9 GW. Nuclear power will add 6–9 GW, helping to achieve 50% zero-emission energy sources by 2040. The heating and transport sectors will be modernized with renewable energy, focusing on electromobility and hydrogen technologies. This energy transformation is expected to require an investment of approximately EUR 200 billion, with financial support from both national and EU funds, particularly for regions transitioning away from coal, ensuring a fair and balanced shift.

This study employs government statistical data on primary energy consumption and renewable energy sources in Poland over the past 15 years, integrating it with air pollution concentrations recorded over the last eight years. Air pollution data are derived from official governmental sources and reference-grade monitoring stations. While Jonek-Kowalska conducted a very good analysis of air quality improvement from the smart cities perspective [24], this paper adds an additional perspective in a broader national context, taking into account the impact of the energy mix. Given the difference in temporal resolution between particulate matter measurements (daily) and energy sector reporting (annual), a bootstrapping method was applied within a regression framework to quantify the overall impact of individual energy components on national air pollution levels, concentrating on particulate matter. A key focus of this analysis is the role of renewable energy sources, particularly energy derived from waste. The study explores regional variations in pollution levels by examining correlations between geographic location, industrialization intensity, and the proportion of green areas across administrative regions (Voivodeships). This spatially resolved assessment enhances the understanding of the interplay between energy production and air pollution at a national scale. An exogenous policy shock served as the instrumental variable, capturing changes in energy policies. Its validity is assessed through correlation analysis, rank testing, and Two-Stage Least Squares (2SLS) regression, ensuring unbiased causal estimates of the impact of energy sources on air pollution [25]. Poland serves as an ideal case study due to its distinct energy mix, which deviates significantly from the EU average, its persistently high pollution levels, and substantial regulatory changes in recent years. These factors create a unique setting to evaluate the influence of energy sector transitions on air quality. This research represents a novel contribution by employing high-resolution spatiotemporal big data analysis, leveraging measurements from over 100 monitoring stations across the country. The application of advanced statis-

tical methodologies to integrate multi-scale energy and pollution datasets provides new insights into the long-term environmental impacts of energy policy shifts. These studies aim to provide general trends and serve as a motivation for further, more targeted analyses due to the limitations of energy reporting.

2. Materials and Methods

2.1. Energy Production and Consumption Dataset

For quantitative analysis of energy transformation data, official reports about primary energy balance for 2005–2020 was used [26]. The primary energy data used in this study cover a wide spectrum of energy sources, including both renewable and non-renewable forms. This includes Hard Coal, Brown Coal, Crude Oil, High-Methane Gas, Nitrogen-Rich Gas, and various renewable resources such as Water, Wind, Solar, and Geothermal energy, as well as biomass from Wood and waste materials. Primary energy refers to the raw energy derived directly from natural resources before any conversion processes occur. In contrast, the renewable energy production dataset focuses specifically on energy generated from renewable sources, including Solar, Wind, hydropower, solid biomass, biogas (from landfills, sewage, agriculture, and other sources), liquid biofuels, and Geothermal energy.

A key area of focus in this study is renewable energy production linked to waste management. Utilizing waste-derived energy sources such as biogas from municipal waste or biomass offers a dual benefit: reducing waste volumes while simultaneously generating sustainable energy. This approach not only supports waste reduction but also contributes to cleaner energy production. The key point is to evaluate the potential effect on air pollution. Moreover, this method could decrease the need for coal consumption, aligning with broader environmental goals. The success of this strategy depends on the development and implementation of advanced waste-to-energy technologies, efficient waste management practices, and supportive regulatory frameworks. Therefore, it is possible to reduce waste, increase renewable energy generation, and improve air quality, provided the appropriate infrastructure and policies are in place to support these interconnected objectives. The data were reported in different units of PJ, TWh, TJ, etc. They have been standardized to TJ.

Key Political Events in Poland (2015–2020) Related to Energy Industry

Poland's energy system remains heavily based on coal, shaping both its economy and environmental landscape. Despite efforts to diversify the energy mix, coal dominates electricity production [27]. Isotopic analysis confirms that in the winter, air pollution—specifically the carbon fraction of PM10 particles—largely originates from coal combustion [28]. However, it is rather related to household heating systems, not electric energy production itself [13]. In 2015, the government stabilized the coal industry by approving a PLN 2.3 billion rescue plan. This initiative led to the closure of unprofitable mines, the transfer of viable coal assets to new entities, and workforce restructuring through severance packages or relocations [29]. While this intervention protected jobs and ensured coal supply for decades, it also prolonged dependence on coal, potentially limiting opportunities for cleaner alternatives and sustaining high emissions. In 2016, policymakers reinforced coal's dominance by passing the "10H Wind Act", which imposed strict distance regulations on Wind turbines [30]. This effectively halted the expansion of onshore Wind energy, slowing the shift toward a more diversified energy mix. This could have potentially prolonged reliance on coal and slowed Poland's progress in developing renewable energy. Recognizing the need for change, the government introduced the "My Electricity" (Polish: Moj Prąd) program in 2019, allocating PLN 1 billion to subsidizing household photovoltaic (PV) installations. This initiative increased Solar energy adoption, reducing some pressure on coal-fired power generation [31]. However, its impact remained limited compared to the scale of Poland's energy demand,

meaning coal continued to be the primary electricity source. The 2018 “Energy Policy of Poland until 2040” (EPP2040) set long-term goals for reducing coal dependence, expanding renewables, and introducing nuclear power. With plans for the first nuclear plant by 2033 and six reactors by 2043, the strategy aimed to reshape Poland’s energy landscape [32]. In 2020, the EU strengthened its climate targets, committing to a 55% reduction in greenhouse gas emissions by 2030. While Poland formally agreed at the end of 2020, its ongoing reliance on coal poses a major challenge to meeting these goals [33].

2.2. Air Pollution Dataset

Air quality data were obtained from the Chief Inspectorate For Environmental Protection repository (<https://powietrze.gios.gov.pl/> accessed on 11 February 2025). The data were sourced from 102 monitoring stations measuring both PM_{2.5} and PM₁₀ concentrations. The stations were selected to ensure the most even spatial coverage of the country, as well as to minimize the number of missing values. The data were recorded at hourly intervals and subsequently averaged both spatially and temporally. In the temporal context, the data were averaged to daily and annual frequencies, while in the spatial context, they were averaged at the level of administrative regions (Voivodeships) and aggregated for the entire country to facilitate comparisons with energy production and consumption data. Annual averages were used to compare with energy consumption data at the same resolution, capture overall pollution trends, and ensure consistency with PM reporting standards.

2.3. Data Analysis Pipeline

2.3.1. Energy Data in the Context of Air Pollution

To investigate the characteristics of changes in the energy mix in Poland, an analysis was conducted on the individual components of the primary energy mix and renewable energy production between 2005 and 2020 obtained from Poland’s data repository (<https://dane.gov.pl/> accessed on 11 February 2025). Information about energy plants was obtained from the InStrat Foundation (<https://energy.instrat.pl/> accessed on 11 February 2025). A detailed examination of the respective time series was performed using the Seasonal and Trend Decomposition with Loess method (STL) [34], adopting a two-year analysis period due to potential delays in the implementation and enforcement of legislative acts, which are not always aligned with an annual cycle. A time series can be considered as a superposition of several signals, and the STL method enables the decomposition of the time series into the trend component, which illustrates the general tendency, and the seasonal component, which highlights the recurring patterns of the phenomenon within a defined period, and the residual component, which captures irregular factors. After averaging data from all stations both spatially and temporally to an annual resolution, the bootstrap resampling method was used to analyze the relationships between specific energy sources and PM_{2.5} levels. A total of 1000 bootstrap samples were created by randomly selecting rows from the original dataset with replacements, ensuring each sample was the same size as the original dataset. This method helped provide more robust estimates of variability in the model coefficients, especially when the number of samples was limited. The next step was fitting a linear regression model to each bootstrap sample to examine the relationship between each energy factor and PM_{2.5} concentrations. The regression coefficients for each independent variable were extracted from each iteration and stored for subsequent analysis. To assess the variability and significance of the regression coefficients after bootstrapping, their distributions were analyzed and visualized across the bootstrap iterations. Histograms with kernel density estimates (KDEs) were used to represent the distributions, and 95% confidence intervals were calculated based on the 2.5th and 97.5th percentiles of the coefficient values. Boxplots were created to summarize the central tendency and

variability of the coefficients for each energy source. Confidence intervals were displayed as horizontal lines, sorted by their lower bounds, with a vertical reference line at zero to evaluate statistical significance.

The potential endogeneity in coal consumption is addressed using an instrumental variable (IV) approach with Two-Stage Least Squares (2SLS) estimation [35]. Hard coal consumption is considered endogenous due to its potential correlation with unobserved factors such as industrial production levels, economic cycles, and government energy policies, which also influence air pollution levels. Without accounting for these factors, regression results may be biased. To mitigate this issue, an exogenous policy shock is introduced as an instrumental variable. This shock represents changes in country or global policies or energy regulations (described in Section Key Political Events in Poland (2015–2020) Related to Energy Industry), which may affect Hard Coal consumption but not directly impact air pollution beyond its influence on coal use. The instrument was chosen because it is strongly linked to the endogenous variable while remaining unrelated to the regression error, ensuring a valid estimation. To validate the appropriateness of the instrumental variable, correlation structures between explanatory variables and the endogenous regressor are examined. A rank check is conducted to ensure that the instrument provides sufficient variation to estimate the causal effect. The final estimation uses 2SLS regression, wherein in the first stage, the endogenous variable is predicted using the instrument and exogenous regressors, and in the second stage, this predicted value is used in the main regression to obtain unbiased estimates of the relationship [25] between energy sources and air pollution.

The analysis was conducted using Python (version 3.10.16) [36] and a range of computational libraries, including NumPy (version 1.24.3) [37] for numerical operations, Pandas (version 2.0.1) (<https://pandas.pydata.org/>, accessed on 11 February 2025) for data manipulation, Matplotlib (version 3.7.1) [38] and Seaborn (version 0.13.2) [39] for data visualization, linermodels (version 6.1) [40] for 2SLS regression, and Scikit-learn (version 1.2.2) [41] for model implementation. A random seed was set to ensure the reproducibility of the bootstrap sampling process and the resulting analyses.

2.3.2. Regional Air Quality Trends in Poland

The dataset used in this study on regional air quality trends consists of temporal measurements for PM_{2.5}, PM₁₀, and their ratio, aggregated across various administrative regions of Poland. The data are organized in a tabular format, where each column corresponds to a specific region and time point. Each region is represented by a unique prefix, and the full names of these regions are mapped accordingly. The regions included in the analysis are Lower Silesian, Kuyavian–Pomeranian, Lublin, Lubusz, Lodz, Lesser Poland, Masovian, Opole, Subcarpathian, Podlaskie, Pomeranian, Silesian, Holy Cross, Warmian–Masurian, Greater Poland, and West Pomeranian. A custom function was developed to calculate the regional averages over time. The function groups columns by their shared prefix to identify those corresponding to each region. It then calculates the mean of these columns along the temporal axis, producing a single aggregated value per region at each time point. This ensures that each region is represented by an average value for the specified air quality parameter over the given time periods. The processed data were then structured into a new DataFrame with a temporal index based on the “Measurement date” column, which was converted to datetime format for consistency in time-based analysis. To visualize the regional air quality trends, heatmaps were generated to display the yearly averages of the regional air quality data. Separate heatmaps were created for different air quality parameters, such as PM_{2.5}, PM₁₀, and the PM_{2.5}/PM₁₀ ratio. Each heatmap represents the average values for each parameter over time, with each subplot corresponding to a specific parameter. Data were visualized using a consistent color scale to emphasize regional varia-

tions, and the heatmaps were presented side-by-side to offer a clear, comparative view of the temporal dynamics of air quality across regions. The spatial autocorrelation of PM_{2.5}, PM₁₀, and the PM_{2.5}/PM₁₀ ratio for 2015–2016 in 16 Polish Voivodeships was analyzed using Global Moran's I in ArcGIS Pro (version 3.4.0) [42]. The queen contiguity method was used to define spatial relationships. It accounts for all neighboring administrative units, guaranteeing a proper assessment of regional pollution patterns while minimizing the influence of administrative boundaries. To control for differences in the number of neighboring units, spatial weights were standardized (row standardization).

3. Results

Understanding energy trends in recent years is crucial. The consumption of primary energy has systematically declined since 2006, with a brief episode of growth in 2012–2013 (trend shown in Figure 1a). Residual analysis clearly indicates a negative anomaly in 2009 and a positive anomaly in 2013. A distinct seasonality is also observed. A similar but slightly different pattern can be seen in the trend for Hard Coal (Figure 1b). A continuous decline in primary energy derived from this resource is evident, with two periods of varying dynamics: a sharp decrease from 2006 to 2010, followed by a slower rate of decline until 2020. A negative residual is noticeable in 2007, while a positive residual appears in 2012. For Brown Coal (Figure 1c), the trend differs somewhat. Until 2014, consumption remained relatively stable, exhibiting clear seasonality and a positive residual in 2013. However, a significant decline in the share of this resource is observed from 2014 to 2020, with a positive residual in 2017. The trend for Crude Oil (Figure 1d) is entirely different. A distinct downward trend is visible from 2005 to 2011, followed by a rapid recovery from 2011 to 2014 and then stabilization at a constant level. For High-Methane Gas (Figure 1e), a steady, almost linear decline is observed from 2015 to 2020, with no distinct seasonality. The share of Nitrogen-Rich Gas in primary energy (Figure 1f) has remained stable over the past 15 years, with some increase between 2011 and 2013, as evidenced in both the trend and residuals. No apparent seasonality is observed. In the case of Water, Solar, and Geothermal energy (Figure 1g), a continuous and rapid increase is visible without clear seasonality between 2006 and 2012. However, in later years, a distinct seasonality emerges. Primary energy from Wood increased significantly until 2012, after which it remained at a stable level with a slight downward trend (Figure 1h). An interesting trend is observed in the share of Waste Fuels (Figure 1i). A clear upward trajectory is evident, characterized by three phases: rapid growth from 2005 to 2010, a stabilization period from 2011 to 2014, and renewed growth until 2020. A distinct seasonality is also present.

Figure 2 presents the acquisition of renewable energy carriers in aggregate form as well as broken down into individual components. The total energy from renewable sources has systematically increased since 2005 (Figure 2a). Two distinct phases are observed: a period of rapid growth from 2005 to 2012, followed by a slightly slower growth rate in subsequent years. A more pronounced seasonality is also evident until 2012. The share of municipal waste (Figure 2b), which remained nearly zero until 2010, exhibits a sudden increase and extremely rapid growth in the following years. Seasonality is observed, along with positive and negative residual values unevenly distributed over time. Solid biomass (Figure 2c) shows a significant increase in its share of renewables until 2012, followed by a declining trend until 2020. The decline period was preceded by a year with a distinct positive residual. Solar energy (Figure 2d) follows a trend very similar to that of municipal waste (Figure 2b), both in terms of overall pattern and the amount of energy acquired. Interestingly, no evident seasonality is observed until nearly 2013. The acquisition of energy from hydropower (Figure 2e) is characterized by distinct seasonality. Although a downward trend has been observed since 2010, it can generally be considered a stable

component, maintaining an average level of approximately 8000 TJ of energy. Wind energy (Figure 2f) exhibits a trend similar to that of municipal waste (Figure 2b) and Solar energy (Figure 2d) up until 2016. A significant increase is observed over the years, along with distinct seasonality from around 2012. However, from 2016 onward, the growth trend noticeably slows. Figures 2g–j present the share of biogas, categorized into sources related to landfills, sewage, agriculture, and other. Biogas from landfills exhibits three trend-based phases: an increase from 500 TJ to 2100 TJ between 2005 and 2010, stabilization between 2010 and 2015 at around 2100 TJ, and a decline leading up to 2020. Seasonality is also evident in energy acquisition from this source. Biogas from sewage and agriculture, on the other hand, follows a steady upward trend. In the case of agriculture, its share was negligible until 2009. Biogas from other sources demonstrates a much more dynamic and irregular pattern over time. Between 2005 and 2010, only a small amount of energy (0–200 TJ) was produced, followed by a sharp surge to 1000 TJ in 2015—clearly visible in STL decomposition as a strong residual—before rapidly declining again until 2020. Liquid biofuels (Figure 2k) exhibit a linear increase from nearly zero in 2005 to nearly 40,000 TJ in 2015, followed by a marked slowdown in growth. Geothermal energy (Figure 2l) maintained a marginal, near-zero share until 2015, after which it experienced a sharp increase, reaching nearly 15,000 TJ by 2020.

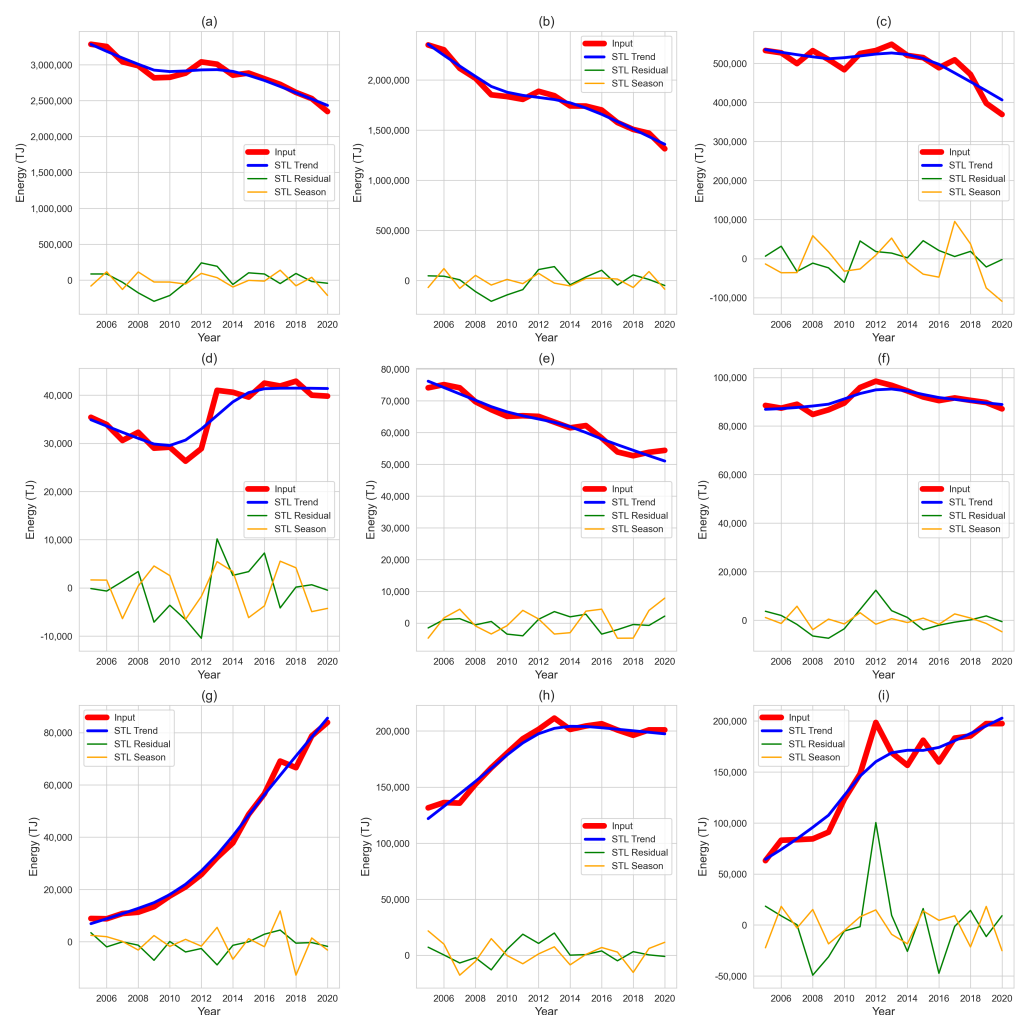


Figure 1. Trends in primary energy consumption: (a) total energy; (b) Hard Coal; (c) Brown Coal; (d) Crude Oil; (e) High-Methane Gas; (f) Nitrogen-Rich Gas; (g) Water, Solar, and Geothermal energy; (h) Wood; (i) Waste Fuels.

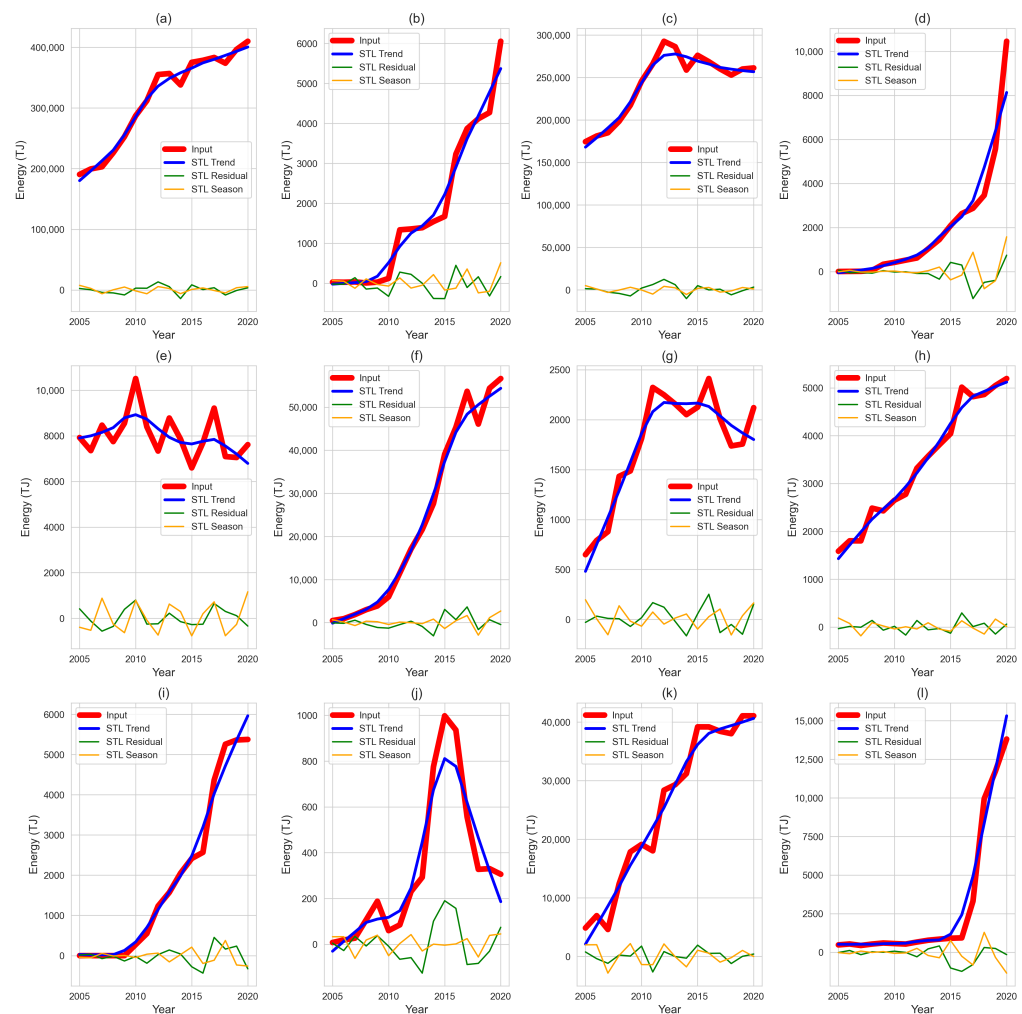


Figure 2. Trends in renewable energy acquisition: (a) total renewables; (b) municipal waste; (c) solid biomass; (d) Solar energy; (e) hydropower; (f) Wind energy; (g–j) biogas by source (landfills, sewage, agriculture, other); (k) liquid biofuels; (l) Geothermal energy.

Figure 3 presents the Pearson correlation matrix between the averaged values of PM1, PM2.5, and PM10 particulate matter from reference stations in Poland and primary energy components for the period 2015–2020. A strong positive correlation is observed between PM concentrations and Brown Coal, reaching as high as 0.95 for PM10 and 0.97 for PM2.5. A similarly high correlation is found for Nitrogen-Rich Gas, with values of 0.91 for PM10 and 0.92 for PM2.5. For Hard Coal, a strong correlation is also present, though slightly lower than for Brown Coal—0.80 for PM10 and 0.81 for PM2.5. Crude Oil exhibits a small positive correlation, with values of 0.54 for PM10 and 0.59 for PM2.5. High-Methane Gas shows a low positive correlation, at 0.38 for PM10 and 0.34 for PM2.5. An interesting observation is the near-absence of correlation between PM10, PM2.5, and primary energy from Wood, with correlation values of only 0.04 for PM10 and 0.09 for PM2.5. For energy obtained from Wind, Solar, and Geothermal sources, a clear negative correlation is evident, at -0.84 for PM10 and -0.81 for PM2.5. A somewhat weaker, yet still significant, negative correlation is observed for Waste Fuels, with values of -0.61 for PM10 and -0.66 for PM2.5.

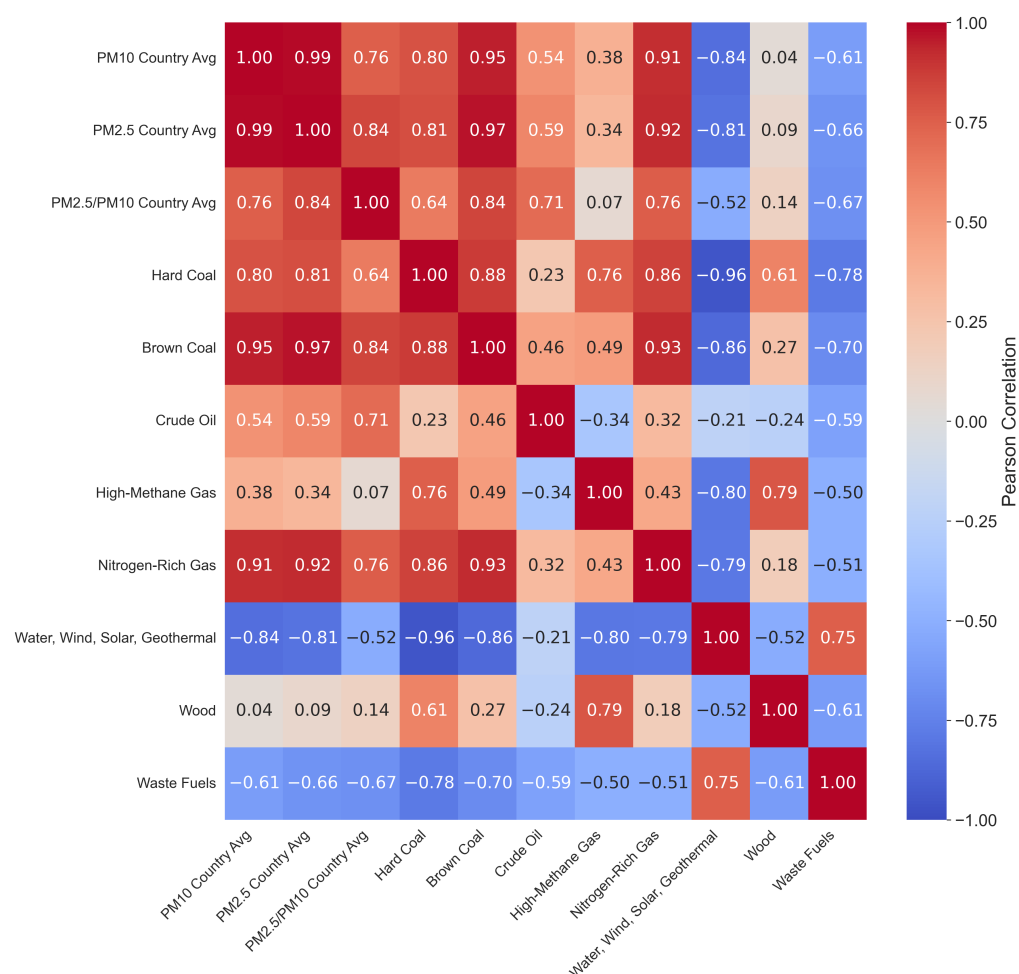


Figure 3. Pearson correlation matrix between air pollution (PM2.5, PM10) and primary energy components in Poland (2015–2020).

Bootstrapping was employed to address the limited number of samples, allowing for a more robust estimation of coefficient variability and providing a better understanding of the uncertainty in the relationships between energy sources and PM2.5 concentrations. Figure 4 presents a series of histograms with Kernel Density Estimation (KDE) overlays, illustrating the distribution of bootstrap-estimated regression coefficients for various energy sources in relation to PM2.5 levels. The red dashed lines indicate the 2.5th and 97.5th percentiles, representing the bounds of the 95% confidence intervals. The distributions suggest distinct relationships between different energy sources and PM2.5. Notably, Hard Coal, Brown Coal, Crude Oil, and Nitrogen-Rich Gas show predominantly positive coefficients. That suggests a possible contributing role in air pollution. In contrast, renewable sources like Water, Wind, Solar, Geothermal, Wood, and Waste Fuels tend to have coefficients near or below zero, implying that their increased use is either associated with a reduction in PM2.5 levels or has a negligible effect. The width of the confidence intervals varies significantly among energy sources. Brown Coal and Nitrogen-Rich Gas have relatively narrow distributions, suggesting more stable and consistent estimates, whereas Wood and Waste Fuels have wider confidence intervals, indicating greater variability in their estimated effects. Some distributions, such as those for High-Methane Gas and Waste Fuels, exhibit bimodal characteristics, which may suggest the presence of multiple underlying trends or interactions with other variables. A slight right-skewed distribution is visible for Crude Oil. It indicates that while most coefficient estimates cluster around a central range, occasional higher values extend the upper tail of the distribution.

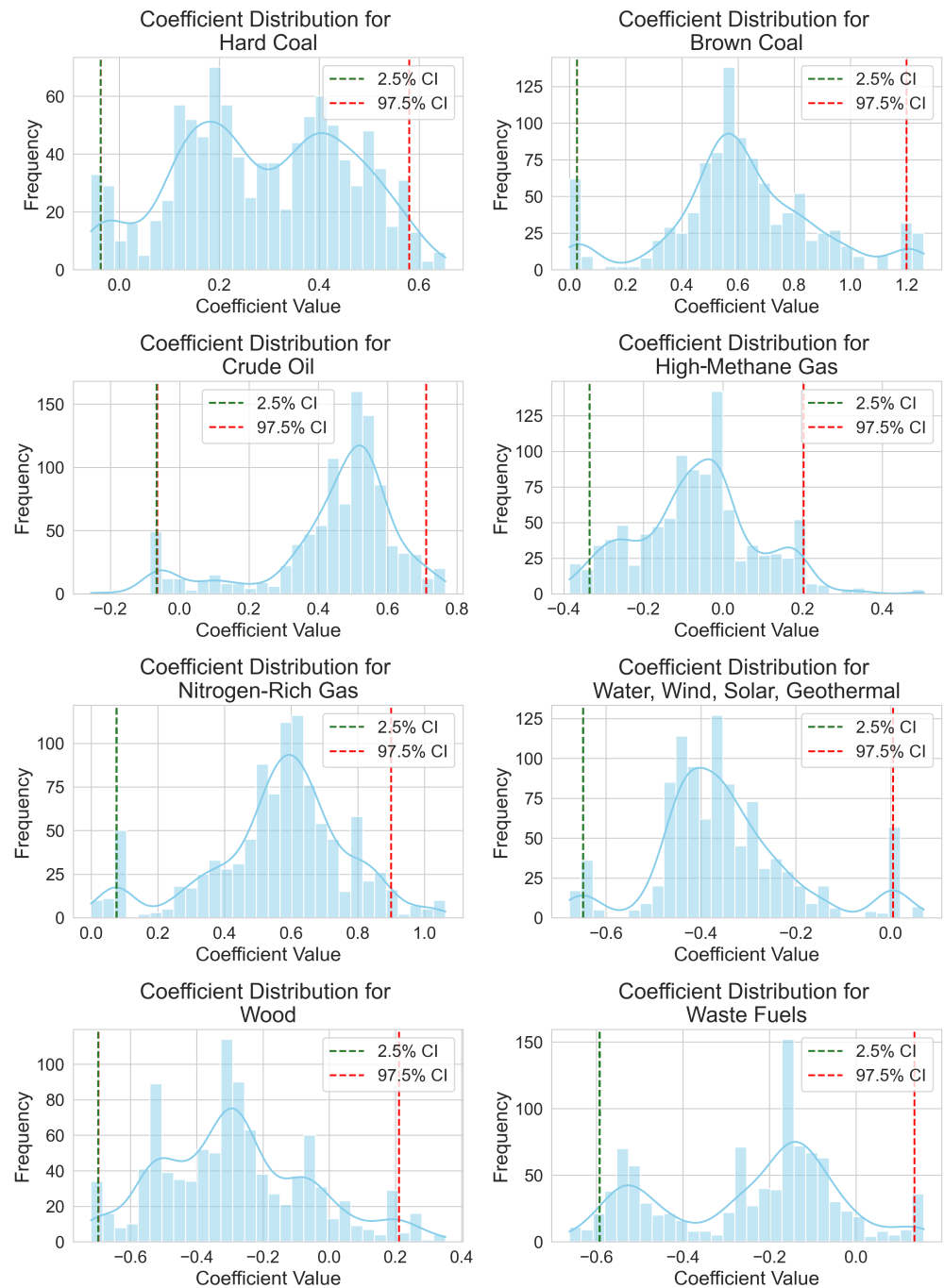


Figure 4. Histograms and KDE of bootstrapped regression coefficients for energy sources in relation to PM2.5 levels.

The boxplot in Figure 5 presents the distribution of bootstrap-estimated regression coefficients for various energy sources. Each box represents the interquartile range (IQR), with the central line representing the median value. The whiskers extend to 1.5 times the IQR, capturing general tendency among the data points. Points outside whiskers are outliers.

Hard Coal, Brown Coal, Crude Oil, and Nitrogen-Rich Gas all exhibit positive median coefficient values. Brown Coal and Hard Coal show relatively narrow IQRs. It suggests that their effect on PM2.5 is consistently estimated across different bootstrap samples. Crude Oil and Nitrogen-Rich Gas show a wider spread and a notable number of outliers, reflecting greater uncertainty or variability in their estimated impact. In particular, Crude Oil exhibits

significantly more outliers toward the minimum, making a clear interpretation of its effect more uncertain. Water, Wind, Solar, Geothermal, Wood, and Waste Fuels show median coefficients that are either near zero or negative. Water, Wind, Solar, and Geothermal exhibit a consistently negative effect, with a relatively compact distribution, suggesting a more stable relationship with reduced PM2.5 concentrations. Wood and Waste Fuels show a broader spread, which may be related to their more variable impact on air quality.

High-Methane Gas appears to be a special case, with a coefficient distribution centered around zero but showing both positive and negative values. Its effect on PM2.5 is not specific and may vary depending on other conditions.

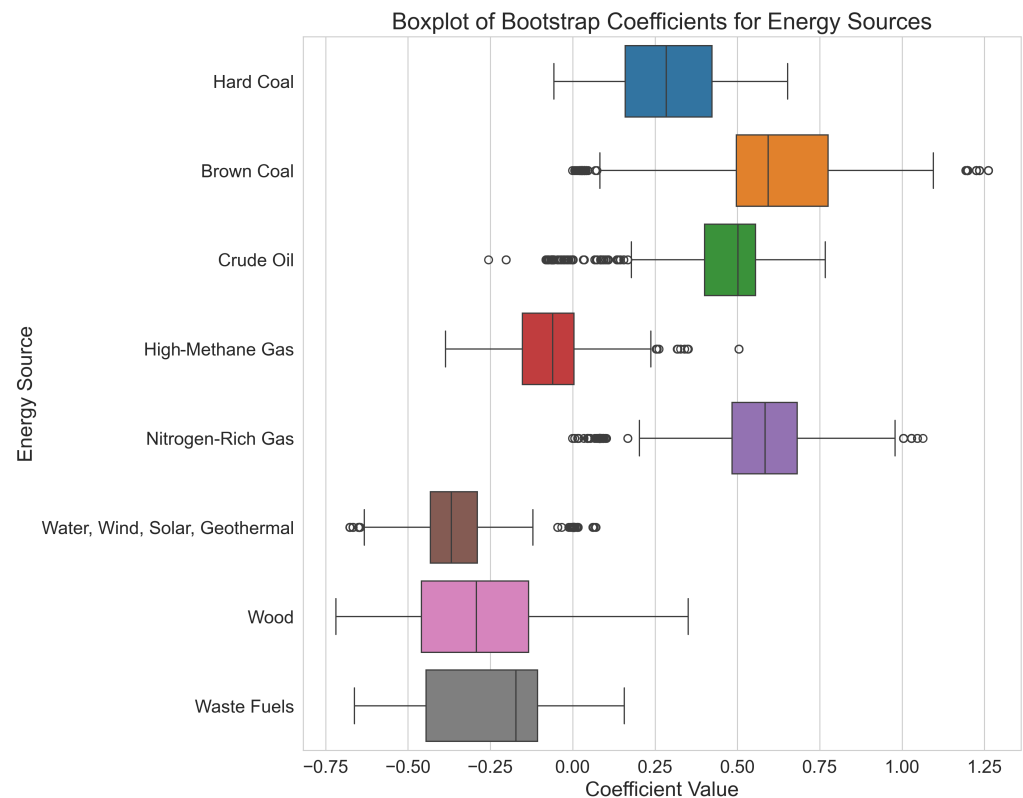


Figure 5. Bootstrapped regression coefficients for the impact of energy sources on PM2.5 levels.

The plot in Figure 6 shows the 95% confidence intervals (CIs) for the bootstrap-estimated regression coefficients of different energy sources, allowing for uncertainty and significance estimation of their impact on PM2.5 concentrations. Each horizontal line represents the range between the lower (2.5th percentile) and upper (97.5th percentile) bounds of the coefficient distribution, while the central point marks the median coefficient value. The vertical dashed line at zero serves as a reference, helping to distinguish between energy sources that have a statistically significant impact (CIs that do not cross zero) and those where the effect is more uncertain.

Hard Coal, Brown Coal, Crude Oil, and Nitrogen-Rich Gas exhibit confidence intervals that are entirely above zero. Among them, Brown Coal and Nitrogen-Rich Gas have relatively wider CIs, reflecting greater variability in their estimated effects, while Hard Coal shows tighter intervals, indicating a more stable and predictable influence on PM2.5 concentrations.

On the other hand, Water, Wind, Solar, Geothermal, Wood, and Waste Fuels have confidence intervals that either include or are entirely below zero. The fact that renewable energy sources and waste-based fuels exhibit negative median coefficients suggests a potential mitigating effect on PM2.5 pollution, though the wide CIs—particularly for Wood

and Waste Fuels—indicate substantial variability in their estimated impact. In contrast, Water, Wind, Solar, and Geothermal display a more consistently negative effect with relatively tighter confidence intervals, reinforcing the hypothesis that increasing the share of renewable energy may contribute to lower PM2.5 levels.

High-Methane Gas presents a more ambiguous relationship, with a confidence interval that straddles zero, suggesting that its impact on PM2.5 is uncertain and potentially context-dependent. This could be due to variations in methane combustion efficiency, regional differences in gas composition, or interactions with other pollutant sources that are not captured in the model.

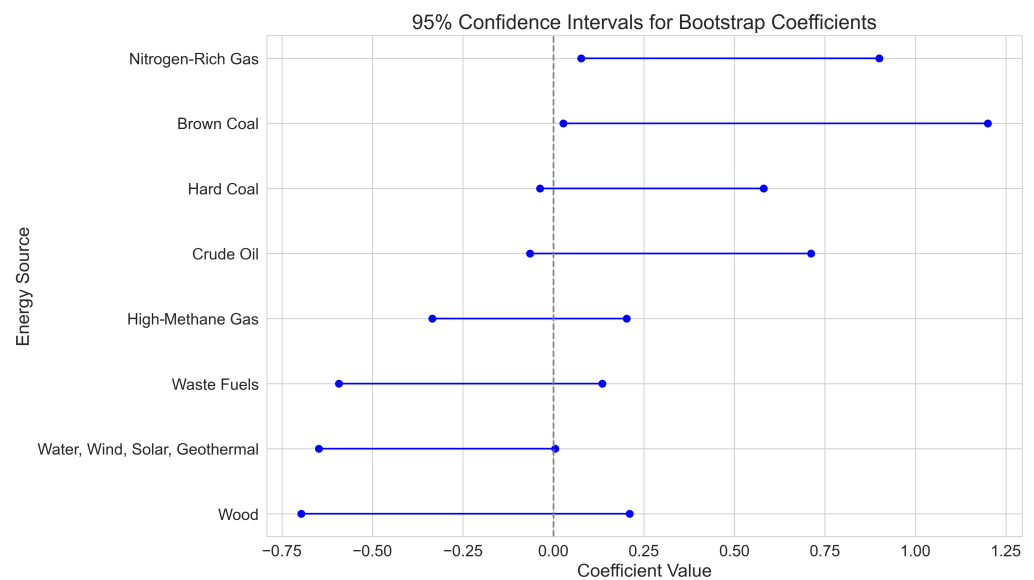


Figure 6. The 95% confidence intervals of bootstrapped regression coefficients for PM2.5 across energy sources.

Although bootstrapping significantly improved statistical robustness, standard regression methods still have limitations, particularly in addressing endogeneity. To mitigate this issue, an instrumental variable (IV) regression was performed using the 2SLS approach. Hard Coal consumption was identified as the endogenous variable, and an exogenous policy shock was selected as the instrumental variable. Correlation analysis confirmed a strong association between the instrument and the endogenous regressor while ensuring no direct correlation with the regression error term. Rank testing verified that the instrument provided sufficient variation for estimation. Features highly correlated with Hard Coal were removed, including Brown Coal and Nitrogen-Rich Gas (positively) and Water, Wind, Solar, and Geothermal (negatively). Additionally, High-Methane Gas, which showed a moderate positive correlation, was also excluded. The policy shock for 2017 and 2018 was set to 0 due to the absence of significant political impacts on coal energy. The average Electricity Prices for households in Poland between 2015 and 2020 were 0.5017, 0.4987, 0.5046, 0.5055, 0.4862, and 0.5374 PLN/kWh, respectively [43]. Although not an energy source per se, they were included as a potential additional factor. The IV-2SLS regression for the PM2.5 country average showed an adjusted R^2 of 0.9983 and an F-statistic of 40.97 using a robust covariance estimator, with Hard Coal as the endogenous variable and policy shock as the instrument.

The IV-2SLS regression results are shown in Table 1. Crude Oil has a moderate positive effect ($\beta = 0.0007$, $p < 0.01$), while Wood shows a small negative coefficient ($\beta = -0.0003$, $p < 0.01$). Waste Fuels exhibit a minimal effect ($\beta = 3.978 \times 10^{-5}$, $p < 0.01$), and Electricity Price is positively associated with PM2.5 ($\beta = 23.649$, $p = 0.0112$). However, Hard Coal

stands out as the most detrimental factor, with a positive effect on PM_{2.5} ($\beta = 2.034 \times 10^{-5}$, $p < 0.01$). Despite its lower coefficient compared to Crude Oil, Hard Coal's higher statistical significance ($T\text{-stat} = 10.19$) and precise estimation showed an important effect on air quality.

Table 1. IV-2SLS parameter estimates.

Variable	β Estimate	Std. Error	$T\text{-Stat}$	$p\text{-Value}$
Hard Coal	2.03×10^{-5}	1.99×10^{-6}	10.19	0.0000
Crude Oil	0.0007	7.34×10^{-5}	9.62	0.0000
Waste Fuels	3.98×10^{-5}	1.22×10^{-5}	3.27	0.0011
Electricity Price	23.649	9.32	2.54	0.0112
Wood	−0.0003	3.61×10^{-5}	−8.16	0.0000

Figure 7 presents the average concentrations of PM_{2.5} and PM₁₀ across individual Voivodeships in Poland from 2015 to 2020. A general downward trend in pollutant levels is observed in all regions, with the exception of 2017 and 2018, where some Voivodeships exhibit deviations from this trend.

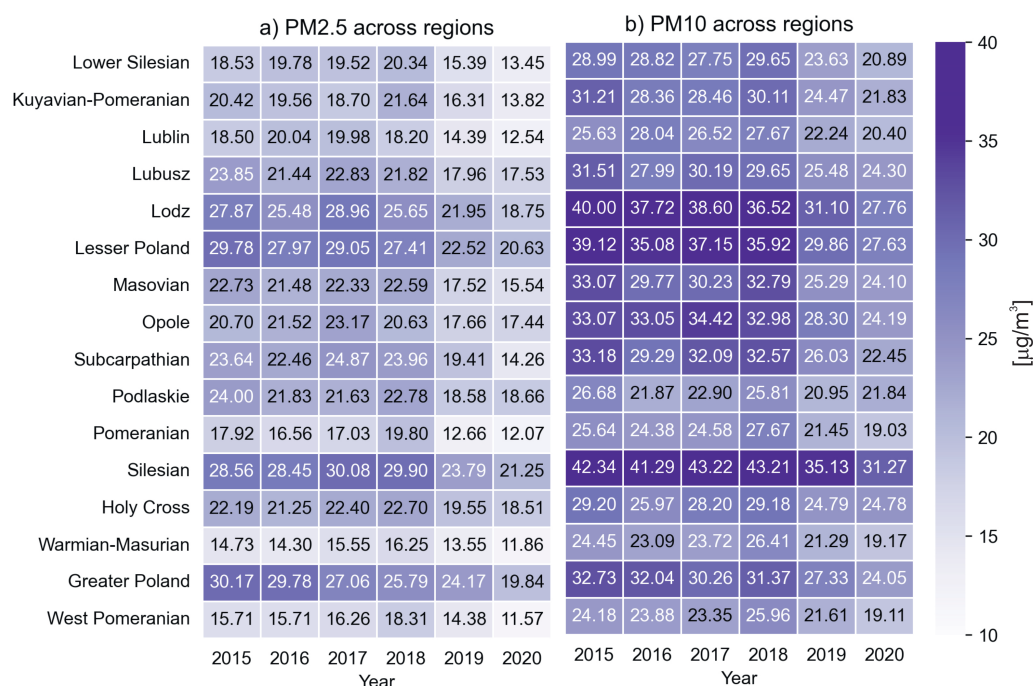


Figure 7. Heatmap of average PM concentrations in Polish Voivodeships (2015–2020): (a) PM_{2.5}, (b) PM₁₀.

Notably, according to the European Stage 2 air quality standard, the annual PM_{2.5} concentration limit of $20 \mu\text{g}/\text{m}^3$ was met by almost all Voivodeships, except for Lesser Poland ($20.63 \mu\text{g}/\text{m}^3$) and Silesian ($21.25 \mu\text{g}/\text{m}^3$). Voivodeships with PM_{2.5} concentrations near the regulatory limit (between 17 and $20 \mu\text{g}/\text{m}^3$) include Lubusz, Lodz, Opole, Podlaskie, Holy Cross, and Greater Poland. The regions with the lowest average PM_{2.5} concentrations were West Pomeranian ($11.57 \mu\text{g}/\text{m}^3$) and Warmian–Masurian ($11.86 \mu\text{g}/\text{m}^3$).

For PM₁₀, the annual concentration limit of $40 \mu\text{g}/\text{m}^3$ was met in all Voivodeships. The highest recorded annual PM₁₀ concentrations in 2020 were observed in Silesian ($31.27 \mu\text{g}/\text{m}^3$), Lodz ($27.76 \mu\text{g}/\text{m}^3$), and Lesser Poland ($27.63 \mu\text{g}/\text{m}^3$). A systematic decline in PM₁₀ concentrations is also evident, with an anomaly in 2018. The lowest PM₁₀

concentrations in 2020 were recorded in Pomeranian ($19.03 \mu\text{g}/\text{m}^3$), West Pomeranian ($19.17 \mu\text{g}/\text{m}^3$), and Warmian–Masurian ($19.17 \mu\text{g}/\text{m}^3$).

Overall, the highest PM₁₀ concentrations during the study period were observed in Silesian in 2017 and 2018, reaching $43.22 \mu\text{g}/\text{m}^3$ and $43.21 \mu\text{g}/\text{m}^3$, respectively. Certain Voivodeships consistently maintained PM_{2.5} and PM₁₀ levels within annual regulatory limits throughout the study period—specifically, Pomeranian, Warmian–Masurian, and West Pomeranian. In contrast, the Voivodeships that exceeded the annual PM₁₀ standard at least once during the study period were Lodz and Silesian.

Figure 8 shows the ratio between PM_{2.5} and PM₁₀, which serves as a useful indicator for identifying the general relationship between air pollution and its sources.

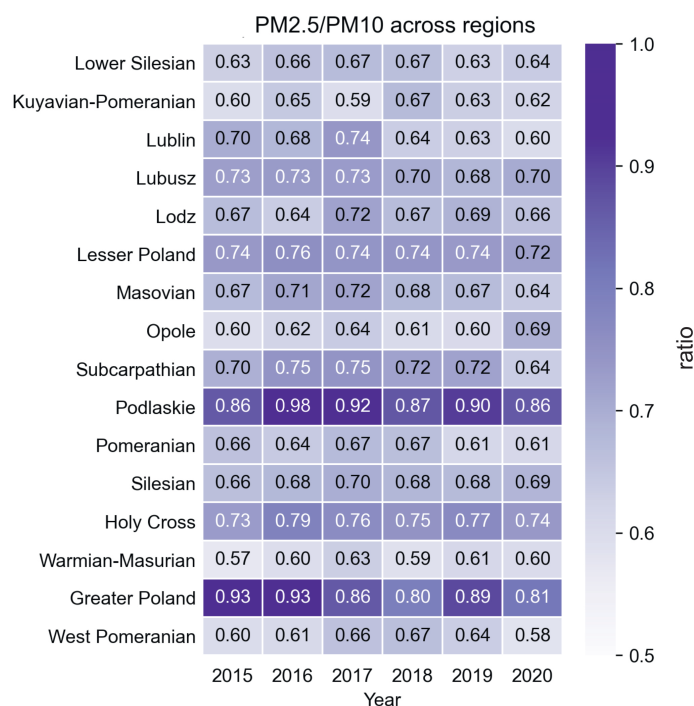


Figure 8. Heatmap of PM_{2.5}/PM₁₀ ratio in Polish Voivodeships (2015–2020).

Ratios around 0.9 or higher are observed in Podlaskie (0.98 in 2016) and Greater Poland (0.93 in 2015 and 2016), indicating a strong anthropogenic origin of pollution, primarily associated with fuel combustion, residential heating, and similar sources. Ratios around 0.7 also suggest an anthropogenic origin, linked to industrial emissions, secondary particulate matter, or agricultural activities. Such values are observed in Holy Cross, Subcarpathian, Silesian, Lesser Poland (where the ratio remains relatively stable over the years), and Lubusz.

Natural sources of particulate matter are predominant in Warmian–Masurian, West Pomeranian, and Opole.

Spatial autocorrelation (Global Moran's I) for PM_{2.5}, PM₁₀, and the PM_{2.5}/PM₁₀ ratio is shown in Table 2. The spatial autocorrelation of PM_{2.5} generally exhibited low Moran's I values across all years, ranging from 0.050 in 2015 to 0.153 in 2020. Statistical significance was observed only in 2017 ($p = 0.031$), while other years showed non-significant spatial patterns. In contrast, PM₁₀ concentrations demonstrated consistent and significant spatial autocorrelation, with Moran's I values between 0.320 and 0.402 and p -values remaining below 0.05 for all years. The PM_{2.5}/PM₁₀ ratio exhibited negative Moran's I values, suggesting a lack of spatial clustering or a tendency toward spatial dispersion. None of the ratio values were statistically significant, with p -values exceeding 0.14 across all years.

Table 2. Spatial autocorrelation (Global Moran's I) for PM2.5, PM10, and PM2.5/PM10 ratio.

Year	2015	2016	2017	2018	2019	2020
PM2.5						
Moran's I Index	0.050	0.114	0.264	0.135	0.150	0.153
Z-Score	0.761	1.211	2.162	1.353	1.408	1.417
p-Value	0.447	0.226	0.031	0.176	0.159	0.156
PM10						
Moran's I Index	0.320	0.337	0.402	0.324	0.400	0.366
Z-Score	2.565	2.728	3.167	2.796	3.199	2.940
p-Value	0.010	0.006	0.002	0.005	0.001	0.003
PM2.5/PM10 Ratio						
Moran's I Index	−0.236	−0.227	−0.116	−0.272	−0.257	−0.254
Z-Score	−1.200	−1.131	−0.348	−1.459	−1.329	−1.296
p-Value	0.230	0.258	0.728	0.145	0.184	0.195

4. Discussion

Results from the bootstrapped regression analysis suggest that fossil fuel-based energy sources are consistently associated with increased PM2.5 concentrations, whereas renewable or alternative sources may have a mitigating effect or exhibit greater uncertainty in their influence. The results suggest a strong association between fossil fuel consumption and increased PM2.5 concentrations, reinforcing the well-documented impact of coal, oil, and gas combustion on air pollution. Hard Coal, Brown Coal, Nitrogen-Rich Gas, and Crude Oil show positive coefficient estimates, indicating that higher usage of these energy sources may correspond with elevated levels of PM2.5. This aligns with existing research on the emission profiles of these fuels, which are known to release particulate pollutants and precursors such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x) [44]. The relatively narrow confidence intervals for Hard Coal suggest its contribution to PM2.5 levels is relatively stable across different samples, whereas the wider distributions observed for Nitrogen-Rich Gas, Brown Coal, and Wood indicate greater variability, possibly due to differences in combustion conditions, fuel quality, or regional factors influencing emissions. High-Methane Gas does not appear to have a direct impact on PM pollution levels, making it a good choice as a transition energy source when considering PM pollution.

Water, Wind, Solar, Geothermal, Wood, and Waste Fuels exhibit predominantly negative or near-zero coefficients, suggesting that increased reliance on these energy sources is either associated with reductions in PM2.5 levels or has no significant impact. The negative coefficients observed for renewable sources could be indicative of indirect effects, such as the displacement of polluting energy sources, improved energy efficiency, or differences in energy system infrastructure. However, the broad confidence intervals for most of these sources highlight potential uncertainties, emphasizing the need for further investigation into their specific contributions to air quality. The broad confidence intervals suggest uncertainty, but most of the estimates fall predominantly on the side of negative correlations. While energy from Water, Wind, and Solar lacks a clear mechanism to increase PM levels, energy from Wood and Waste requires further examination. Although Wood combustion may have a relatively positive effect in winter by replacing more polluting fuels, its overall impact may not contribute to a net reduction in PM emissions.

The presence of bimodal distributions in sources like High-Methane Gas, Hard Coal, and Waste Fuels suggests the possibility of non-linear relationships or the influence of unobserved variables, such as differences in regional policies, technological efficiency, or varying emission control measures. The slight right-skewness in the Crude Oil coefficient distribution may reflect occasional high-emission scenarios, possibly linked to industrial processes or transportation sectors with high variability in emission intensities. It may be

associated with the summer period (where in general PM levels are within the limits) and transportation impact, as shown in studies conducted in Krakow [28].

The results highlight the impact of some fossil fuel combustion on air pollution while suggesting that High-Methane Gas could serve as a good transitional energy source, possibly due to its combustion mechanisms. At the same time, renewable and alternative energy sources show potential for reducing or not increasing PM2.5 levels. The findings reveal certain trends but come with limitations and should be seen as a starting point for further research. The variability in coefficient estimates suggests that additional factors—such as combustion technology, regulatory frameworks, and regional energy mixes—should be explored in future studies. Without further research to narrow uncertainty intervals, these results cannot be directly used for policy decisions.

The boxplot confirms that fossil fuels are generally associated with increased PM2.5 pollution, while renewable and alternative sources tend to have either neutral or negative effects. High-Methane Gas does not appear to have a direct impact on PM concentrations, likely due to its combustion characteristics. Methane-rich fuels facilitate more homogeneous combustion, which enhances fuel–air mixing and promotes complete combustion, significantly reducing the formation of PM [45]. However, while High-Methane Gas itself is associated with lower particulate emissions, combustion technology plays a crucial role in determining actual pollution levels. Poor air–fuel mixing or inefficient combustion conditions could still lead to increased emissions in some cases [46], but under typical operational conditions, High-Methane Gas seems to be a reasonable transition fuel. The variability in coefficient estimates underscores the complex relationship with air quality and highlights the need for further research using higher time-resolution data on energy sources.

The results from the IV-2SLS regression show a relationship between energy sources and PM2.5 concentration. Increased Wood use appears to reduce pollution, which may be surprising; it is likely due to its role in household heating, possibly replacing more polluting sources. Waste Fuels have a small positive effect. The use of Hard Coal (highly correlated with Brown Coal and High-Nitrogen Gas) in air pollution highlights its central role in increasing PM2.5 levels, which is in line with studies about air pollution—especially during the winter season [13]. The inclusion of the policy shock as an instrument helps mitigate endogeneity concerns, strengthening the causal interpretation; however, there is a need to increase the number of observations.

Analyzing the annual average values of PM10 and PM2.5, the Silesian Voivodeship exhibits the highest air pollution levels. This region is characterized by its strong industrial profile, including Hard Coal mining, numerous power plants, and combined heat and power (CHP) stations. It is also one of the most urbanized areas in Poland. The second and third most polluted regions are the Lodz and Lesser Poland Voivodeships, both directly bordering Silesia. In the Lodz Voivodeship, one of the largest Brown Coal power plants in Poland is located, while in Lesser Poland, a coal-fired power plant and a CHP station are situated in the Krakow district area. All three of these Voivodeships are major industrial centers. Their topography—featuring cities located in valleys—exacerbates air quality issues, particularly during the heating season when emissions from household heating peak.

In contrast, the best air quality is observed in northern Poland. Voivodeships bordering the Baltic Sea showed the lowest PM10 and PM2.5 levels. The Warmian–Masurian Voivodeship contains the Elblag CHP plant (25 MW), powered by biomass, while the West Pomeranian Voivodeship is home to the Szczecin CHP plant (76 MW), also biomass-fueled [47]. Several factors contribute to the improved air quality in these regions, including favorable terrain characteristics, strong ventilation, and extensive forested and green areas.

The four Voivodeships with the highest forest coverage in 2022 were [48] as follows:

- Lubusz—49.4%.
- Subcarpathian—38.2%.
- Pomeranian—35.8%.
- West Pomeranian—35.8%.

Conversely, the regions with the lowest forest coverage were as follows:

- Kuyavian–Pomeranian—11.8%.
- Lodz—21.4%,
- Masovian and Lublin—23.4%.

The PM_{2.5}/PM₁₀ ratio was highest in the Greater Poland and Podlaskie Voivodeships, exceeding 0.9. This indicates a strong anthropogenic influence, mainly from direct industrial emissions. During the study period, two coal-fired power plants were operating in Greater Poland: Poznan-Karolin (313 MW, Hard Coal) and Patnow I (now decommissioned, Brown Coal) [47]. The Podlaskie Voivodeship has the Bialystok CHP plant (204 MW), primarily fueled by Brown Coal and near its border, the Ostroleka B power plant (690 MW) is fueled by Hard Coal.

No direct correlation can be established between power plant operations and the PM_{2.5}/PM₁₀ ratio, as the largest power plants and CHP stations are found in other Voivodeships. For instance, the Koziencice power plant (4072 MW) in the Masovian Voivodeship has a PM_{2.5}/PM₁₀ ratio below 0.7. Similarly, the Belchatow power plant in Lodz (5072 MW) exhibits a ratio comparable to Masovia. Even Silesia, with the highest number of power plants and CHP stations, maintains a similar ratio of 0.7.

Interestingly, in the Warmian–Masurian Voivodeship, where no major power plants or CHP stations are located, the lowest PM_{2.5}/PM₁₀ ratio was recorded. This suggests that suspended particulate matter in this region is predominantly of natural origin, and overall concentrations of both PM₁₀ and PM_{2.5} remain low. The northern location, high lake density, and extensive green areas further contribute to favorable air quality conditions.

The spatial patterns of PM_{2.5} and PM₁₀ show clear differences in pollution distribution. PM₁₀ exhibited strong spatial dependence, with high and significant Moran's I values, suggesting more regional sources, such as industry and major natural influences. PM_{2.5} showed weaker and mostly non-significant autocorrelation, likely due to more local sources, such as traffic, and weather conditions that disperse fine particles unevenly. The negative Moran's I values for the PM_{2.5}/PM₁₀ ratio indicate that the origin of particulate matter varies significantly between regions. This may be linked to differences in industry, geography, and land use. These results highlight the need for localized air quality measures tailored to particle size, as PM_{2.5} does not fully follow the regional patterns of PM₁₀. Transboundary emissions from neighboring countries and regions are also a potential factor that should be investigated in further studies.

5. Conclusions

Energy sources in Poland are diverse, with a dominant share of coal-related sources like Hard Coal and Brown Coal. Over the years, a noticeable increase in the contribution of renewable energy sources has been observed along with a general decline in PM₁₀ and PM_{2.5} concentrations. However, the ratio of PM_{2.5} to PM₁₀ has remained relatively stable across different Voivodeships. The data were averaged annually to enable a comparison between energy sources and air pollution. While this approach introduces some distortion, it helps reveal general trends. In Poland, particulate pollution during the warmer summer months remains within regulatory limits and is not a major concern. The real issue arises in winter, primarily due to household heating with coal [2,28]. This study does not specifically address seasonal variations, which limits its ability to capture the full impact of winter pollution.

Based on national-scale averaged data, the strongest negative correlation with PM₁₀ and PM_{2.5} concentrations is observed for Wind, Solar, and Geothermal energy, as well as for Waste Fuels. In contrast, the highest positive correlation is found for Brown Coal and Nitrogen-Rich Gas. Regression coefficient analysis using bootstrapping confirms that fossil fuels generally exhibit positive regression coefficients, while renewable energy sources show negative coefficients except for High-Methane Gas, which shows no clear impact. Confidence intervals that do not cross zero are found for Nitrogen-Rich Gas and Brown Coal (both positive), as well as for Wind, Solar, and Geothermal energy (negative). Despite the inherent uncertainty in regression analysis, a prevailing negative influence of coal-based energy (both Hard and Brown Coal) is evident, while Waste Fuels, Wood, and renewable energy sources such as Solar, Geothermal, and Wind have a generally positive or not significant negative impact on air quality. High-Methane Gas appears to be a suitable transition fuel from the perspective of PM pollution, as it shows no significant impact on particulate matter levels. However, more research is needed, as a confidence interval from -0.3 to 0.25 was observed in bootstrapped regression analysis. Further research should also consider factors beyond PM.

IV-2SLS results show that Hard Coal has a positive effect on PM_{2.5} levels. It is highly correlated with Brown Coal and Nitrogen-Rich Gas, while negatively correlated with Water, Wind, Solar, and Geothermal energy. Waste fuels showed potential to increase PM_{2.5} but with more uncertainty, likely due to their mixed composition of biomass, plastics, and industrial residues. Wood has a negative association with PM_{2.5}, possibly due to seasonal effects or replacing more polluting fuels. Electricity Prices also matter, suggesting an indirect link between energy costs and pollution levels.

A clear spatial differentiation in air pollution levels is observed across Polish Voivodeships. The lowest concentrations of PM₁₀ and PM_{2.5} occur in northern Poland, particularly in Voivodeships along the Baltic coast, with the best air quality recorded in the Warmian–Masurian Voivodeship. These regions lack large energy plants and benefit from high forest coverage and extensive recreational areas.

The worst air quality is found in the Silesian, Lesser Poland, and Lodz Voivodeships, where significant concentrations of industrial facilities and coal-based power plants are present. However, an analysis of the PM_{2.5}/PM₁₀ ratio suggests that power plant location alone does not directly determine air quality. Instead, multiple additional factors contribute to pollution levels, including increased road traffic, the presence of other industrial hubs, forest coverage, and urbanization levels. Notably, while the PM_{2.5}/PM₁₀ ratio has remained relatively stable in most regions over the years, northern Voivodeships exhibit ratios close to values indicating predominantly natural sources of particulate matter.

On a national scale, the PM_{2.5}/PM₁₀ ratio serves as a useful indicator of whether the dominant pollution sources are anthropogenic or natural. However, further research is required to disentangle specific anthropogenic contributions. Additionally, an analysis of regional pollution levels suggests that mesoscale terrain features are not insignificant. Voivodeships in central and northern Poland, where lowlands dominate, tend to have slightly lower pollution levels, whereas those in the south, characterized by mountainous and upland terrain with cities often located in valleys, exhibit higher concentrations. The concentration of industrial facilities and energy farms in the south further intensifies this effect. Air quality policies should consider the different spatial patterns of PM_{2.5} and PM₁₀, as indicated by Moran's I . PM₁₀ shows strong spatial dependence, requiring regional-scale interventions, while PM_{2.5} exhibits weaker or no spatial autocorrelation, suggesting a need for more localized control measures. Future studies should also account for transboundary pollution to show the full picture of spatial dependencies.

Coal has been the dominant energy source in Poland for years, but its use has been gradually declining. A similar long-term decrease in PM_{2.5} concentrations may be observed across Voivodeships. While the energy mix seems to affect air pollution in regions with significant energy production, geographical factors may also play a key role. Brown Coal and Nitrogen-Rich Gas seem to be linked to higher pollution levels, while renewable energy sources may help improve air quality. Pollution levels vary by region, with the cleanest air in northern Poland and the highest pollution in industrialized southern Voivodeships. However, the annual analysis does not capture seasonal variations, which are important since PM pollution exceeding regulatory limits is mainly observed in winter due to household heating. The PM_{2.5}/PM₁₀ ratio suggests both natural and human-made pollution sources, highlighting the need for targeted air quality policies.

6. Limitation and Recommendation

This study highlights potential relationships between energy sources and PM concentrations, providing a basis for preliminary policy recommendations on air quality and energy transitions. However, due to the nature of energy source reporting, which follows an annual schema, data aggregation was necessary. As a result, the analysis may not fully capture variations in emissions and pollution dispersion. While bootstrapping improved statistical robustness, the wide confidence intervals indicate a high degree of uncertainty. To draw more precise conclusions and support effective policymaking, further research incorporating higher spatial and temporal resolution data, along with advanced atmospheric modeling, is recommended. Without further research to narrow uncertainty intervals, these results cannot be directly used for policy decisions.

The following are recommendations for future research and policy development:

- Targeted research near potential emission sources to better understand local pollution patterns and validate correlations with energy production.
- Better coordination between emission and air quality reporting schemes to align energy source data with high-resolution temporal PM measurements.
- Cross-border pollution analyses to assess transboundary effects and their impact on national and regional air quality.
- Simultaneous analysis of geographical factors alongside atmospheric particle tracing to better understand pollution transport and accumulation.
- Enhanced atmospheric modeling incorporating meteorological data and real-time emission tracking for more accurate pollution dispersion predictions.
- The integration of seasonal variations into policy frameworks, recognizing that PM pollution exceeds Polish regulatory limits, mainly in winter.
- The refinement of statistical methods, including narrowing uncertainty intervals, to improve the reliability of findings for policy decisions.
- The consideration of socioeconomic factors, such as energy pricing and household heating choices.

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Data Availability Statement: Publicly available datasets from the Chief Inspectorate For Environmental Protection database and Poland's Data Portal were analyzed in this study. These data can be found here: (<http://powietrze.gios.gov.pl/pjp/home>, accessed on 11 February 2025) and here: (https://dane.gov.pl/pl/dataset/2767/resource/38951,bilans-energii-pierwotnej_peny-bilans-w-latach-2005-2020, accessed on 11 February 2025). API documentation is available here: (<http://powietrze.gios.gov.pl/pjp/content/api>, accessed on 11 February 2025) and here: (<https://api.dane.gov.pl/doc>, accessed on 11 February 2025). Data about energy plants are from the InStrat Foun-

dition, available here: (<https://energy.instrat.pl/system-elektroenergetyczny/baza-elektrowni/>, accessed on 11 February 2025).

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CHP	combined heat and power
ESE	extreme smog episode
EU	European Union
IQR	interquartile range
KDE	Kernel Density Estimation
PLN	Polish Zloty
PM	particulate matter
PONE	Low-Emission Reduction Program in Krakow
STL	Seasonal and Trend Decomposition with Loess method

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