

SECTORIAL TRANSITION TO RENEWABLE ENERGY SOURCES: THE CASE OF SLOVAKIA

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This paper investigates the determinants of renewable energy use across nine manufacturing sectors in Slovakia during the period 2004–2024, with particular attention to the Russia-Ukraine war. Using sector-level panel data, the study examines how relative energy prices, sectoral economic activity, and a war-period shock are associated with the share of renewable energy in final energy consumption. The results reveal substantial and persistent heterogeneity in renewable energy use across manufacturing industries. The paper, pulp and printing sector and the wood and wood products sector exhibit considerably higher renewable energy shares than other manufacturing sectors, reflecting the importance of sector-specific production characteristics and biomass availability. By contrast, neither relative energy prices, sectoral value added, nor the war period are statistically significantly associated with renewable energy shares. These findings remain robust across alternative panel-data specifications. The results suggest that renewable energy use in Slovak manufacturing is shaped primarily by structural and technological characteristics of individual industries rather than by short-term economic incentives or recent geopolitical developments. The study highlights the importance of sector-specific approaches to industrial transition and demonstrates that aggregate analyses may conceal substantial differences in renewable energy adoption across manufacturing sectors.

Keywords: renewable energy adoption, manufacturing sectors, Slovakia, geopolitical shock

Introduction

Energy is a fundamental input to economic activity, enabling the transformation of resources into goods and services and underpinning production, economic growth, and household consumption (Stern, 2011; Eyuboglu et al., 2025). From a systems perspective, energy encompasses multiple sources, carriers, and technologies that convert energy inputs into usable forms of energy. Primary energy sources include fossil fuels, nuclear energy, and renewable sources (such as biomass, wind, solar, and hydropower), while common energy carriers comprise electricity, refined petroleum products, gaseous energy carriers, heat, or hydrogen (IEA, 2023). These sources and carriers differ in their availability, cost structures, and environmental impacts (Al Mubarak et al., 2024). Concerns over greenhouse gas emissions, energy security, the depletion of finite natural resources, and long-term environmental protection have driven global efforts to transition from fossil fuel-based energy systems toward renewable energy sources (Kaberger, 2018; Hassan et al., 2024; Ozkan et al., 2025). This transition represents not merely a technological substitution, but a structural transformation of economic production and consumption patterns, with far-reaching implications for productivity, competitiveness, societal well-being, material use, trade, and environmental sustainability (Grayson, 2017; Vezzoni, 2023).

Promoting renewable energy has been a central pillar of international climate policy since the Kyoto Protocol in 1997 (Luo et al., 2025) and has gained further prominence following the Paris Agreement in 2015, which seeks to limit global warming by committing countries to reduce greenhouse gas emissions and expand the use of low-carbon energy sources, including renewables (Akrofi et al., 2022; Berrich et al., 2024). At the EU level, global climate objectives are complemented by initiatives such as the European Green Deal and the Fit for 55 policy package, which set targets to reduce greenhouse gas emissions by 55% by 2030 and achieve carbon neutrality by 2050. Decarbonizing the energy system is central, with policies (Renewable Energy Directive) emphasizing secure and affordable energy supplies,

the integration of energy markets, and the prioritization of renewable power and energy efficiency, and supporting the accelerated deployment of wind, solar, and other renewable technologies across sectors (Marquez-Sobrinho et al., 2023; Salim et al., 2026). In addition, the REPowerEU plan was introduced to speed up the clean energy transition, reduce dependence on imported fossil fuels – particularly in response to geopolitical risks – and expand renewable energy generation so that the share of renewables in the EU's overall energy consumption reaches 42.5% by 2030, alongside energy-saving measures and infrastructure modernization (Vezzoni, 2023; EC, 2025).

The transition to renewable energy has emerged as both a challenge and an opportunity for national economies. However, a larger share of renewable energy in overall energy production and consumption does not necessarily indicate the replacement of fossil fuels, but may instead reflect an expansion of total energy demand (York and Bell, 2019). Growth in renewable energy capacity is uneven and influenced by country-specific factors, including the size and structure of the economy, production technologies, resource availability, and regulatory frameworks (Khezri et al., 2022; Hoa et al., 2023; Kunsakaja and Pazeraite, 2025; Xue et al., 2025). Economic development, technological capabilities, employment in advanced technology sectors, and policy strength have been identified as significant drivers of renewable energy deployment, whereas labor market characteristics (unemployment) can slow progress. Additional determinants, such as geographical endowments, economic freedom, and political structures, further shape renewable portfolios, highlighting the importance of both economic and institutional factors (Tu et al., 2022; Kor et al., 2025). Past energy mixes, domestic resources, and sectoral characteristics also play a role, suggesting that path dependence and legacy energy infrastructure can persistently influence renewable adoption (Papiez et al., 2018). These factors, however, can be complemented or disrupted by exogenous shocks that accelerate or constrain the renewable energy transition. A prominent example is the geopolitical shock in energy markets caused by the Russian invasion of Ukraine in 2022, which exposed Europe's high dependency on imported fossil fuels from Russia and underscored the strategic importance of energy security (Kuzemko

et al., 2022). This crisis prompted measures to facilitate renewable energy generation in the EU, improve energy efficiency, and diversify supplies, notably under initiatives such as the REPowerEU plan (Maliszewska-Nienartowicz, 2024; Ah-Voun et al., 2024; Yang et al., 2025; EC, 2025).

Some scholars argue that the war has acted as a catalyst for renewable energy expansion, spurring countries to implement measures supporting the accelerated development of wind, solar, and other renewable technologies, thereby reinforcing long-term energy transition goals (IEA, 2022; Maliszewska-Nienartowicz, 2024; Yang et al., 2025; Beck et al., 2025). Renewable energy firms also showed relatively strong stock performance during the early phases of the conflict, reflecting investor expectations that renewable capacity could provide resilience amid geopolitical disruption (Liao, 2023). The war was accompanied by a series of EU sanctions targeting Russian energy (including import bans on coal, seaborne crude oil, and liquefied natural gas), as well as finance and key economic sectors (European Council, 2025), which further raised questions about energy security and incentivized the search for alternative and domestically produced energy sources. However, another strand of the literature notes that crises can generate complex and sometimes contradictory dynamics. In the short term, several EU member states temporarily reactivated coal-fired power plants and increased the use of liquefied natural gas, reflecting a security-first approach that, in some cases, appeared to conflict with climate objectives (Patrahau et al., 2022; Knodt et al., 2024; Shoukat et al., 2024). These responses suggest that under stress, energy systems may prioritize reliability over decarbonization, potentially slowing the transition toward low-carbon energy sources (Knodt et al., 2024). Moreover, studies of national energy policy persistence indicate that not all EU member states responded to the crisis by significantly accelerating renewable deployment; some maintained their existing energy mixes with limited new renewable integration, illustrating policy lock-in effects and structural inertia – a pattern also observed in Slovakia (Misik and Oravcova, 2024).

Slovakia is a small, open economy that is almost entirely dependent on imported fossil fuels, with the vast majority of its natural gas and crude oil supplies historically originating from Russia. Nuclear power, which dominates electricity generation, similarly relies on imported fuel from Russia, while hydropower represents the main domestic renewable contribution. As documented by Misik and Oravcova (2024), Slovakia has exhibited a high degree of policy persistence in the aftermath of the Russia-Ukraine war, driven by fixed energy infrastructure and long-term supply arrangements. Consequently, the country largely maintained established energy priorities rather than pursuing a decisive shift toward renewable energy sources. This persistence was reflected in Slovakia's negotiation of exemptions from EU sanctions on Russian gas and crude oil and in the absence of particularly ambitious renewable energy targets. The Slovak National Energy and Climate Plan initially set a 19.2% share of renewables in gross final energy consumption by 2030, a target that, according to EU guidance, would need to be increased, with the updated proposal reaching 25% (EnergiePortal, 2024).

Despite EU-level pressure and broader regional trends toward renewable energy sources, Slovakia's aggregate energy mix exhibited only gradual change in the immediate post-war period, with renewable energy deployment progressing at a modest pace. National-level outcomes were largely formed by the response of the energy sector itself, whose operational structures, production technologies, and fuel composition constrained the uptake of renewables. Building on these insights, the present analysis moves beyond aggregate national indicators and shifts the focus to manufacturing sectors, examining how the share of renewable energy in sectoral final energy consumption evolved over time and whether the Russia-Ukraine war coincided with changes in sector-specific energy use patterns.

The aim of this paper is to examine the role of renewable energy in sectoral energy use in Slovakia and to assess whether a major geopolitical shock, namely the Russian invasion of Ukraine, altered energy consumption patterns across manufacturing industries. While macro-level responses suggest a relatively slow expansion of renewable energy in Slovakia amid heightened volatility in global energy markets, it remains unclear how these dynamics translated into adjustments in the sectoral energy mix and the relative importance of renewable energy sources. This distinction is particularly important in manufacturing, where energy use, fuel substitutability, and the capacity to integrate renewable energy vary substantially across industries due to differences in production processes, cost structures, resource endowments, and technological constraints. Focusing on nine manufacturing sectors that combine energy use with potential for renewable energy integration, the analysis employs sector-level panel data for the period 2004–2024 to capture both structural developments and the effects of the recent crisis. The empirical analysis relates the sectoral share of renewable energy in final energy consumption to relative energy prices, sectoral value added, and a war-period indicator, while explicitly accounting for persistent differences across manufacturing industries through panel-data specifications. In doing so, the paper contributes to the literature on energy transition by complementing national-level analyses of renewable energy adoption (e.g., comparative EU studies – Gajdzik et al., 2024; Dinca et al., 2025) with a more granular sector-based perspective and by highlighting the importance of sectoral heterogeneity in shaping industrial energy transitions. The study also relates to sector-level analyses conducted for other countries (Hamed et al., 2023; Jose and Patra, 2025).

Material and Methods

To assess how economic conditions, relative energy prices, sectoral heterogeneity, and external shocks influence the composition of energy sources consumed by major manufacturing sectors in Slovakia, panel regression models were estimated. The analysis focuses on the share of renewable energy in total final energy consumption by sector and relates it to the relative price of renewable and non-renewable energy sources, sectoral economic activity, and a geopolitical shock represented by the Russia-Ukraine war. Given the substantial differences in production technologies, energy use patterns, and resource availability across manufacturing industries, the empirical framework accounts for unobserved sector-specific effects and persistent heterogeneity between sectors.

Data and variables

The analysis is based on annual sector-level panel data for Slovakia covering the period 2004–2024. The sectoral scope is restricted to nine manufacturing sectors: manufacturing of metals (iron, steel, non-ferrous metals); chemicals and petrochemicals; non-metallic minerals; manufacturing of machinery; transport equipment; textile and leather; food, beverages and tobacco; wood and wood products; and paper, pulp and printing.

The share of renewable energy in total final energy consumption within sector i and year t , REN_{it} , is the dependent variable, allowing the analysis to focus on changes in the composition of energy use rather than on absolute energy demand. Data on final energy consumption by sector and energy product were drawn from Eurostat energy balances and are expressed in gigawatt-hours (GWh). Final energy consumption refers to energy delivered to end users; final energy consumption in industry refers to energy supplied from all parts of the economy and used directly by industrial

sectors. The energy product category “Renewables and biofuels” was used to determine the share of renewable energy in total final energy consumption.

Data on the explanatory variables were obtained from both national and European statistical sources. Energy price variables are measured at the national level, vary over time but are common across sectors, and capture economic incentives for fuel substitution between renewable and other energy sources. The analysis employs the relative price of wood to natural gas, where wood prices serve as a proxy for renewable energy costs and natural gas prices represent other (fossil) energy alternatives. Wood (firewood) was selected because this kind of biomass constitutes the dominant renewable energy source for Slovak manufacturing and may serve as a substitute for fossil energy inputs. The choice was also motivated by the availability of consistent price data. Wood prices were obtained from the National Forest Centre and complemented by data from the Statistical Office of the Slovak Republic, originally expressed in Eur/m³. Natural gas prices for non-household consumers (band I3) in the first semester of each year were obtained from Eurostat and expressed in Eur/kWh. To ensure unit consistency, wood prices were converted to Eur/kWh using an average energy-content factor of 2,000 kWh/m³ of firewood (derived from OravaKrb, n.d.; Drevari.sk, n.d.). The relative energy price variable was subsequently calculated as a ratio of wood to natural gas prices and entered into the model in logarithmic form, $\ln(P_{wood,t}/P_{gas,t})$. The logarithmic transformation facilitates an elasticity-like interpretation of the estimated coefficient and reflects the assumption that energy use decisions respond to proportional rather than absolute changes in relative prices.

Sectoral economic activity is proxied by gross value added of sector i in year t , obtained from the Statistical Office of the Slovak Republic and expressed in mil. Eur at constant prices. To allow for elasticity-type interpretation, the natural logarithm of value added was used, $\ln(VA_{it})$.

To account for the potential effects of the Russia-Ukraine war and the associated energy crisis, a war-period dummy variable was included. The variable captures common changes in the economic and energy environment during the crisis period, including heightened energy security concerns, market disruptions, and policy responses. The binary variable W_t takes the value of 1 for the years 2022–2024 and 0 otherwise.

Empirical specification

To account for structural differences between manufacturing sectors, including differences in production technologies, energy use patterns, fuel mix, and the availability of biomass resources, the empirical analysis incorporates sector-level effects. These effects control for unobserved heterogeneity across industries that may influence renewable energy shares but cannot be directly measured.

As an initial benchmark, a pooled ordinary least squares (OLS) model was considered. However, because manufacturing sectors are likely to differ systematically in ways that are not fully captured by the observed explanatory variables, panel-data specifications were subsequently employed. The main specification is a random-effects (RE) panel model in which renewable energy shares are estimated as a function of relative energy prices, economic activity, and a geopolitical shock:

$$REN_{it} = \alpha + \beta_1 \ln\left(\frac{P_{wood,t}}{P_{gas,t}}\right) + \beta_2 \ln(VA_{it}) + \gamma W_t + \mu_i + \varepsilon_{it}$$

where: REN_{it} – denotes the share of renewable energy in total final energy consumption within sector i and year t ; $P_{wood,t}/P_{gas,t}$ – denotes the relative energy price of renewable and non-renewable energy

sources in year t ; VA_{it} – denotes value added of sector i in year t ; W_t – is the war dummy variable with the value of 0 for t relating to the years 2004–2021 and 1 for t relating to the years 2022–2024; μ_i – denotes a sector-specific random effect capturing unobserved time-invariant differences across manufacturing industries; ε_{it} – represents the error term

The random-effects specification accounts for unobserved sectoral heterogeneity while allowing both within-sector and between-sector variation to contribute to parameter estimation

Model selection was based on panel-data specification tests. The Breusch-Pagan Lagrange Multiplier test confirmed the presence of significant sector-level effects, rejecting the pooled OLS specification ($\chi^2 = 1,706.8$, $p < 0.001$). The analysis therefore proceeded with panel estimators. Subsequently, the Hausman test did not reject the consistency of the random-effects estimator ($\chi^2 = 0.863$; $p = 0.834$); hence, the random-effects model was selected as the baseline specification.

To assess the robustness of the results to alternative approaches for controlling unobserved sectoral heterogeneity, two additional specifications were estimated. First, a fixed-effects (FE) model was employed, controlling for time-invariant sector characteristics through a within-sector transformation of the data. Second, a least squares dummy variable (LSDV) model was estimated by including sector-specific dummy variables, thereby allowing explicit estimation of differences in intercepts across industries. For all specifications, standard errors were clustered at the sector level using the CR2 small-sample correction. This approach provides more reliable inference in settings with a small number of clusters (nine manufacturing sectors), where conventional standard errors may underestimate sampling uncertainty and lead to unreliable statistical inference.

Results and Discussion

To provide context for the subsequent analysis of selected manufacturing industries, we first examine energy consumption in the industrial sector as a whole in Slovakia over the period 2004–2024. Energy consumption is defined as final energy use, referring to energy sources and carriers delivered to and used by industry for its own energy purposes. This includes both process and non-process uses such as manufacturing and processing activities, space heating and cooling, lighting, and motive power. It excludes the use of energy products for non-energy purposes, such as the use of natural gas as a feedstock in chemical processes (for example, in the production of fertilizers), which is not consumed as energy.

Total industrial energy use is an aggregate indicator and is further decomposed into three mutually exclusive sub-categories: renewables and biofuels, other primary sources – including solid fossil fuels, manufactured gases, natural gas, oil and petroleum products, and non-renewable waste – and secondary energy, comprising electricity and heat. This classification allows for a clear assessment of both overall trends in industrial energy demand and changes in the composition of energy sources and carriers over time. In particular, it provides a benchmark against which developments in the selected manufacturing sectors can later be evaluated, and it facilitates an assessment of the evolution of renewable energy use during periods of economic disruption and geopolitical shocks.

Overall industrial energy consumption (Figure 1) accounts for approximately one third of final energy consumption in the Slovak economy (entire economy including households). In the observation period 2004–2024 it ranged between 33,300 GWh and 42,600 GWh, and can be divided into three

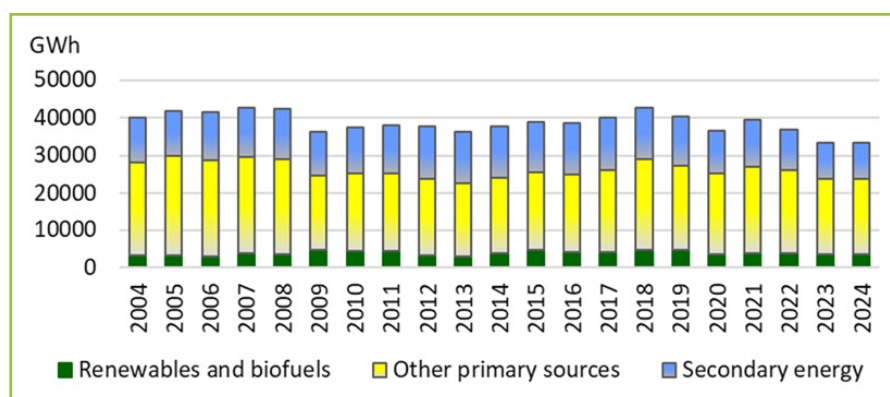


Figure 1 Final consumption of energy in the Slovak industry sector

Source: Eurostat

phases. From 2004 to 2008, energy use remained relatively high and stable, reflecting steady industrial activity prior to the global financial crisis. During 2009–2014, a decline mirrored the economic slowdown, followed by partial recovery in 2014–2018. In the period 2019–2024, total consumption fluctuated moderately, with a notable drop in 2020 and a further decrease in 2023–2024, likely associated with the Covid-19 pandemic and the Russia-Ukraine war.

Energy use from renewables remained modest, ranging from 2,800 GWh to 4,700 GWh, accounting for a small but persistent share of total industrial energy consumption. Under Slovak conditions, renewable energy sources include primary solid biofuels (biomass), biogases and ambient heat (heat pumps). Early adoption in 2004–2008 was stable (average 3,300 GWh). Consumption increased slightly during 2009–2011, possibly reflecting early EU-driven renewable energy policies, including the adoption

of the Renewable Energy Directive in 2009. From 2012 onward, renewable use fluctuated (higher values can be observed in 2015–2019, when EU renewable energy policy frameworks were evolving, including the revised Renewable Energy Directive adopted in 2018), with the war period showing no substantial increase, suggesting that the crisis was not associated with a pronounced acceleration of renewable integration at the aggregate industrial level.

Fossil fuels remained the dominant energy source. After 2018, their use gradually declined (with the exception of an increase in 2021), reflecting both efficiency improvements and production reductions. Secondary energy consumption from delivered electricity and heat showed a moderate upward trend in the early years, consistent with electrification and increased heat demand in industrial processes. After 2015, secondary energy fluctuated, with a notable decrease in 2020–2024, possibly

due to efficiency improvements, production adjustments, and energy price effects associated with the crisis period.

Table 1 shows detailed consumption of different energy sources and carriers in the first and the last observation period, i.e. 2004 and 2024.

The inspection of energy consumption across the nine studied manufacturing sectors in Slovakia reveals substantial variation in both final energy use and the adoption of renewable energy sources (Table 2). Over the entire period under review, total energy consumption is highest in metal manufacturing, reaching an average value above 14,000 GWh, although it shows a decreasing trend over time. A notable divergence across sectors emerges in the share of renewables and biofuels: the paper, pulp and printing sector together with the wood and wood products manufacturing sector stand out with consistently high shares of renewable energy, ranging from 39% (in 2006) to 69% (in 2018) in the paper industry and from 37% (in 2021) to 66% (in 2012 and 2015) in the wood manufacturing industry. This pattern is consistent with the higher availability of biomass residues and other renewable by-products in these sectors, enabling a more integrated and cost-effective transition to renewables compared to other sectors. In contrast, the remaining sectors demonstrate minimal renewable energy adoption, with renewables comprising only a fraction of total energy consumption. These sectors rely predominantly on fossil fuels and secondary energy sources (electricity and heat), with renewables often constituting less than 1% of energy use.

Temporal patterns indicate a general decline in total energy consumption in several sectors after the mid-2010s. Manufacturing of metals, of textiles and manufacturing of paper, pulp and printing belong to this group, as well as manufacturing of non-metallic minerals where the decline is only marginal. On the other hand, manufacturing of transport equipment, chemicals and petrochemicals, and machinery do not show a decrease in their energy consumption. However, except for the paper and wood industry, renewables adoption shows only modest increases over time, highlighting sector-specific barriers to renewable integration. In the early 2020s, only the chemical sector and the manufacturing of non-metallic minerals showed an increase in renewable energy consumption. These findings highlight the importance of considering sectoral heterogeneity in renewable energy transitions.

Table 1 Composition of energy sources and carriers in energy consumption of the Slovak industry sector

Energy source	2004		2024	
	GWh	share	GWh	share
Total	0,084	100.00%	33,437	100.00%
Solid fossil fuels	6,371	15.89%	2,271	6.79%
Manufactured gases	4,961	12.38%	3,966	11.86%
Natural gas	9,942	24.80%	8,739	26.13%
Oil and petroleum products	3,511	8.76%	3,610	10.80%
Non-renewable waste	231	0.58%	1,750	5.23%
Electricity	10,724	26.75%	9,153	27.37%
Heat	1,153	2.88%	417	1.25%
Renewables and biofuels	3,191	7.96%	3,530	10.56%
Ambient heat (heat pumps)	0	0.00%	32	0.10%
Primary solid biofuels	3,189	7.96%	3,474	10.39%
Biogases	2	0.00%	24	0.07%

Data source: Eurostat

Table 2 Renewable sources in final energy consumption of sectors in the Slovak economy

Sector		2004	2010	2020	2021	2022	2023	2024
Manufacturing of metals	GWh	51.4	31.1	66.1	89.2	34.2	10.8	0
	share	0.33%	0.21%	0.57%	0.65%	0.29%	0.11%	0.00%
Chemicals and petrochemicals	GWh	0	4.2	0.6	1.4	2.2	0.8	17.5
	share	0.00%	0.11%	0.01%	0.02%	0.04%	0.02%	0.34%
Non-metallic minerals	GWh	0.3	0	1.7	1.7	11.9	26.4	35.0
	share	0.01%	0.00%	0.03%	0.03%	0.23%	0.62%	0.76%
Transport equipment	GWh	0.3	0	1.7	1.7	1.4	1.7	1.1
	share	0.03%	0.00%	0.09%	0.08%	0.07%	0.08%	0.06%
Machinery manufacturing	GWh	64.2	86.7	56.4	49.2	98.9	64.2	39.7
	share	3.93%	4.22%	2.3%	1.97%	3.97%	2.83%	1.73%
Food, beverages and tobacco	GWh	14.7	0.6	76.7	71.9	53.6	60.8	75.0
	share	0.63%	0.04%	4.46%	4.24%	2.86%	2.87%	3.65%
Textile and leather	GWh	0	1.1	0.8	0.3	0.3	0.3	0
	share	0.00%	0.23%	0.37%	0.12%	0.10%	0.12%	0.00%
Wood and wood products	GWh	275.8	450.3	243.1	180.3	264.2	450.3	444.4
	share	44.95%	62.86%	44.61%	37.09%	48.41%	63.46%	60.96%
Paper, pulp and printing	GWh	2,714.7	3,688.8	2,896.4	3,235.6	3,220.3	2,744.2	2,692.2
	share	47.82%	59.80%	62.89%	64.33%	66.18%	64.31%	67.55%

Data source: Eurostat

To determine whether differences in renewable energy use are associated with economic conditions, relative energy prices, or broader external shocks, panel regression models are employed. Table 3 presents the results of the baseline random-effects specification and two robustness checks based on alternative approaches to controlling for sectoral heterogeneity. Across all specifications, the estimated coefficients of the main explanatory variables remain similar in sign and magnitude, indicating that the main conclusions are not sensitive to the choice of panel estimator.

The baseline random-effects model shows that the relative price of wood compared with natural gas does not have a statistically significant effect

on the renewable energy share in manufacturing sectors. The coefficient of $\ln(P_{wood}/P_{gas})$ is negative, suggesting that an increase in the relative price of biomass energy is associated with a lower renewable energy share; however, the effect is small and statistically insignificant. This indicates that short-term changes in relative energy prices were not strongly associated with renewable energy adoption in Slovak manufacturing.

Sectoral economic activity, measured by value added, has a negative coefficient in the baseline model. The estimate suggests that sectors with higher value added tend to exhibit lower renewable energy shares, although this relationship is not statistically significant when using the CR2 small-

Table 3 Determinants of renewable energy share in Slovak manufacturing sectors

Variable	RE model	FE model	LSDV model
$\ln(P_{wood}/P_{gas})$	-0.0117 (0.0524)	-0.0118 (0.0525)	-0.0118 (0.0525)
$\ln VA$	-0.0268 (0.0264)	-0.0257 (0.0265)	-0.0257 (0.0265)
W (war period)	0.0124 (0.0225)	0.0123 (0.0225)	0.0123 (0.0225)
Constant	0.3025 (0.2556)	—	0.1859 (0.2172)
D_metals	—	—	-0.0253 (0.0151)
D_chemicals	—	—	-0.0361 (0.0240)
D_nonmetals	—	—	-0.0357 (0.0241)
D_machinery	—	—	0.0484 (0.0331)
D_textiles	—	—	-0.0263 (0.0153)
D_transport	—	—	0.0069 (0.0203)
D_paper	—	—	0.5492*** (0.0209)
D_wood	—	—	0.5001*** (0.0306)
Observations	189	189	189
R ²	0.0537	0.0531	0.9706

Source: own calculations

Robust standard errors reported in parentheses; significance codes: *** $p < 0.001$; the reference sector in the LSDV model is food, beverages and tobacco

sample correction. This may indicate that larger industrial sectors rely more strongly on established energy systems and production technologies, which can limit substitution toward renewable sources.

The war-period dummy variable has a positive but statistically insignificant coefficient. The estimated effect suggests a small increase in renewable energy shares during the 2022–2024 period; however, no statistically significant structural change in sectoral energy use patterns was identified. Therefore, the Russia-Ukraine war does not appear to have substantially accelerated renewable energy adoption within the analyzed manufacturing sectors over the observed period.

The robustness checks support the baseline findings. The fixed-effects specification produces nearly identical estimates for the main variables, suggesting that the results are not driven by unobserved time-invariant sector characteristics. Similarly, the least-squares dummy variable specification yields comparable estimates after explicitly controlling for sector-specific intercept differences. The LSDV specification additionally highlights substantial structural differences between industries. Compared with the reference category of food, beverages and tobacco, the paper, pulp and printing sector and the wood and wood products sector exhibit substantially higher renewable energy shares. These differences remain statistically significant after controlling for the other explanatory variables and applying sector-clustered robust standard errors (CR2), confirming that sector-specific production characteristics and biomass availability play an important role in shaping renewable energy use across manufacturing industries. The substantially higher explanatory power of the LSDV model (R^2) reflects the inclusion of sector-specific intercepts, which capture persistent structural differences between industries rather than additional explanatory power from the observed economic variables.

Overall, the findings reveal that renewable energy use in Slovak manufacturing is shaped primarily by structural and sector-specific characteristics rather than by short-term changes in relative energy prices or recent geopolitical developments. The lack of a statistically significant association between renewable energy shares and relative wood-to-gas prices, as well as the limited effect of the Russia-Ukraine war period, indicates that changes in the industrial energy mix have been gradual and likely constrained by existing production processes, energy requirements, and sector-specific conditions. The substantial differences identified between industries, particularly the higher renewable energy shares in the paper, pulp and printing and wood and wood products sectors, highlight the importance of biomass availability and production characteristics in enabling renewable energy integration. These findings suggest that policies supporting renewable energy adoption in manufacturing should account for the heterogeneous technological opportunities and constraints across industries rather than relying only on general market-based incentives.

Conclusion

This study examined the determinants of renewable energy use across key manufacturing sectors in Slovakia over the period 2004–2024, with particular attention to the potential impact of the Russia-Ukraine war. Using sector-level panel regression models, the analysis revealed substantial heterogeneity in renewable energy adoption across industries. The paper, pulp and printing sector and the wood and wood products sector consistently exhibited the highest renewable energy shares, reflecting the importance of biomass availability and sector-specific production characteristics. In contrast, metals, chemicals, non-metallic minerals, transport equipment, and textiles showed considerably lower renewable energy shares, indicating greater dependence

on conventional energy sources. These differences highlight the importance of structural conditions in shaping the ability of manufacturing sectors to integrate renewable energy.

The empirical analysis does not identify statistically significant effects of relative energy prices, sectoral economic activity, or the Russia-Ukraine war period on renewable energy shares in manufacturing energy consumption when using the CR2 small-sample correction. The estimated coefficients remain stable across the random-effects baseline model and the fixed-effects and sector-dummy robustness specifications, indicating that the findings are not sensitive to alternative approaches for controlling sectoral heterogeneity. The lack of a significant association between renewable energy shares and the relative price of wood and natural gas suggests that short term market incentives played a limited role in changing the sectoral energy mix. Similarly, the energy market disruptions and increased energy security concerns following the Russian invasion of Ukraine were not associated with a measurable shift towards renewable energy within the analyzed manufacturing sectors.

The findings suggest that renewable energy adoption in Slovak manufacturing may be influenced primarily by long-term structural and technological factors rather than by short-term economic fluctuations or recent geopolitical shocks. Industries characterized by established production processes, specific energy requirements, and limited availability of renewable substitutes may face greater constraints in transitioning away from conventional energy sources. These results complement broader evidence showing substantial heterogeneity in renewable energy adoption across industrial sectors. Previous studies show that sectoral characteristics, energy intensity, and institutional conditions often influence renewable energy uptake more strongly than market prices alone (Tu et al., 2022; Gajdzik et al., 2024), and that public perception of renewables adoption also influences industrial and policy actions (Gatto et al., 2024). In addition, geopolitical shocks may encourage energy system adjustments and resilience strategies, but their effects differ across sectors and national contexts (Maliszewska-Nienartowicz, 2024).

Several limitations of the analysis should be acknowledged. First, energy prices are measured at the national level and therefore do not capture sector-specific contracts, long-term pricing arrangements, or differences in effective energy costs faced by individual sectors. In addition, the analysis considers the relative price of renewable and non-renewable energy proxied by only two energy carriers, wood and natural gas, which may not fully reflect the broader range of energy sources and price signals influencing industrial energy decisions. Second, the war-period dummy captures an average effect for the period 2022–2024 and does not distinguish between different transmission channels through which the Russia-Ukraine war may have influenced energy use, such as supply disruptions, policy responses, changes in energy security considerations, or broader market adjustments. Moreover, this period may also reflect the influence of other contemporaneous economic, regulatory, and market developments, including post-pandemic adjustments, making it difficult to isolate the effect of the war itself. Third, the analysis does not explicitly address potential endogeneity between renewable energy adoption and sectoral characteristics, as investment decisions, technological changes, and firm-level strategies may influence both renewable energy use and economic activity. Finally, the use of renewable energy shares as the dependent variable focuses on changes in the composition of energy consumption rather than changes in absolute energy use and sector-level aggregation may conceal differences among firms within the same sector. Despite these limitations, the applied methodology provides a suitable framework for examining sectoral heterogeneity in renewable energy

adoption and assessing whether changes in economic activity, relative energy prices, and the recent energy crisis coincided with shifts in the sectoral energy mix in Slovakia. The approach also provides a useful starting point for future research that could further explore the determinants of industrial renewable energy adoption using more detailed sectoral or firm-level data.

The findings provide several policy implications for promoting renewable energy use in the Slovak manufacturing sectors. The substantial heterogeneity identified across industries suggests that a uniform policy approach may be less effective than measures tailored to the technological and operational characteristics of individual sectors. Industries with persistently low renewable energy shares may require targeted support to address sector-specific barriers related to production processes, infrastructure, and investment capacity, while sectors with greater availability of renewable inputs may have stronger potential for further integration of renewable energy sources. The limited role of relative energy prices in explaining renewable energy shares indicates that policies focused solely on short-term market incentives may be insufficient to accelerate industrial energy transitions. Instead, policy measures should support long-term structural adjustments, including energy efficiency improvements, modernization of production technologies, investments in renewable-ready infrastructure, and the development of sector-specific pathways for industrial decarbonization. The lack of a significant change in renewable energy shares during the Russia-Ukraine war period further suggests that temporary energy market disruptions alone may not have been sufficient to induce substantial changes in industrial energy use patterns, particularly in a context where Slovakia retained access to certain fossil fuel supplies through negotiated exemptions and alternative supply arrangements. Finally, the results emphasize the importance of monitoring renewable energy adoption at the sectoral level. Aggregate national indicators cannot adequately capture substantial differences between industries and provide limited guidance for targeted interventions. A more disaggregated approach can help identify sectors with the greatest potential for renewable energy integration and support policy design that reflects the specific opportunities and constraints faced by individual manufacturing industries.

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