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Renewable Energy, Macroeconomic Stability and the Sustainable Development of the Logistics Sector: Evidence from the Visegrad Countries

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Abstract

This article analyses the impact of renewable energy sources (*RES*s) and macroeconomic stability on the sustainable development of the logistics sector in countries in the Visegrad Group (V4) from 2008 to 2023. The study is based on indicators that describe three dimensions of logistics development: economic (ED_L), social ($SocD_L$), and environmental ($EnvD_L$), as well as the indicator of renewable energy sources (*RE*) and macroeconomic stabilisation (*M*). Lagged regression analyses and SUR models are used to capture both the current and delayed effects of energy and economic policies. The results show that the development of renewable energy has the greatest and most stable impact on logistics development, particularly in Hungary and Slovakia, where it supports the dynamic growth of environmental and social indicators. In Poland, the effect of renewable energy sources is more variable and manifests itself with a delay, reflecting the costs of the energy transition. Macroeconomic stability plays a smaller but still important role, improving investment predictability and the sector's resilience to crises, although its impact is varied and often manifests over a longer period. This study's innovation is the simultaneous inclusion of energy and macroeconomic perspectives in logistics analysis, demonstrating that sustainable development of the sector is only possible by simultaneously strengthening both of these pillars.

Keywords: renewable energy; macroeconomic stability; sustainable development; logistics sector

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1. Introduction

The modern economy is at a crucial stage of energy transformation, the significance of which extends far beyond ecological and environmental issues. The growing importance of renewable energy sources (*RES*s) is directly related to the need to build a stable foundation for economic development and implement sustainable development principles across sectors. The implementation of renewable energy sources, including hydrogen, biomass, hydropower, geothermal, wind, solar thermal, and solar PV, can decrease or eliminate the reliance on fossil fuels. One area particularly impacted by this transformation is the logistics sector, which accounts for a significant portion of global greenhouse gas emissions and underpins the functioning of modern supply chains [1,2].

The dynamic development of logistics today requires not only innovative technological solutions and process digitisation, but also integration with national energy and macroeconomic policies [3,4]. On the one hand, this requires investment in clean energy sources

and low-emission infrastructure and, on the other, maintaining economic stability, which creates predictable conditions for the sector's development. In this context, renewable energy sources and macroeconomic stabilisation are becoming key factors in determining the competitiveness and resilience of logistics to crises and market fluctuations.

The analysis carried out for the countries of the Visegrad Group (V4) reveals differences in the pace and scope of the implementation of the green transformation in logistics. On the one hand, the Czech Republic and Hungary are characterised by higher levels of stability and sustainability, while on the other, Poland and Slovakia are catching up, experiencing particularly dynamic economic and social development. At the same time, research findings indicate that the importance of renewable energy sources in the sector's development is greater and more stable than the impact of macroeconomic stabilisation, which is more often characterised by volatility and delayed impact.

The aim of the present study is to present the interrelationship between the development of renewable energy sources, macroeconomic stability, and the sustainable development of the logistics sector in the countries in the Visegrad Group. In particular, it analyses how renewable energy and economic stabilisation jointly impact the economic, social, and environmental dimensions of logistics. The empirical research results allow for the formulation of conclusions that are important from both a public policy and business practice perspective, indicating directions for building a competitive and low-emission logistics sector in Central Europe. The novelty of the study is the simultaneous consideration of the impact of renewable energy sources and macroeconomic stability on the sustainable development of logistics in the countries of the Visegrad Group, using a dynamic approach and regression analyses to capture the current and delayed effects of economic and energy policies.

2. Literature Review

2.1. Renewable Energy and the Development of the Logistics Sector

The development of modern logistics is increasingly related to the need for energy transformation [1]. Global supply chains are responsible for a significant portion of greenhouse gas emissions, and fossil-fuel-based road, maritime, and air transport has remained among the largest sources of pollution for years. In this context, renewable energy is becoming not only an alternative, but also a strategic factor in determining the future of the logistics sector [2–4].

Consumers and business partners are increasingly paying attention to the carbon footprint of products, which means that logistics companies must adapt their operational strategies [5,6]. Renewable energy sources play a key role in this process, as they allow the combination of economic efficiency and the requirements of sustainable development [1]. Currently, Poland and the Czech Republic still rely heavily on coal, resulting in high CO_2 emissions, although Poland is also developing wind and solar energy. Hungary is gradually increasing the share of renewable energy, especially solar, with a significant share of nuclear power, while coal use is limited. Slovakia relies primarily on nuclear and hydropower, with a small share of wind and solar, resulting in relatively low emissions compared to Poland. In general, Poland and the Czech Republic have a high share of fossil fuels, while Hungary and Slovakia rely more on nuclear and renewable energy, resulting in lower emissions from their energy systems.

One of the most important directions of change is the electrification of the transport fleet. A growing number of companies are investing in trucks, delivery vehicles, and last-mile solutions powered by electricity or hydrogen, which helps to reduce dependence on crude oil, stabilise costs, and lower emissions [7,8]. In Scandinavian countries and Western Europe, a dynamic expansion of solar and wind energy can already be observed [9].

Renewable energy sources are also transforming logistics infrastructure. Warehouses and distribution centres are increasingly equipped with photovoltaic panels, wind turbines, and energy recovery systems, making them energy self-sufficient and even capable of supplying surplus energy back into the grid. Integrated energy management systems enable consumption optimisation, storage of excess production, and balancing of demand during peak hours [10–12].

Such an approach not only reduces operating costs but also enhances resilience to energy price fluctuations and potential supply disruptions. The importance of energy stability for the continuity of supply chains becomes particularly evident during global crises [13].

Digitalisation and automation are supporting the use of renewable energy in logistics. Modern analytical platforms enable emissions monitoring, route optimisation, and integration of energy consumption data. Artificial intelligence-based solutions allow for prediction of energy demand and dynamic adaptation of operational processes [12].

Equally important are energy storage systems that enable a more complete use of renewable sources, especially in the case of solar and wind energy, which are characterised by variable production. Investments in batteries and hydrogen technologies are becoming an essential element of the next-generation logistics infrastructure [1,10].

Although the potential for renewable energy in logistics is enormous, the transformation process also presents many challenges. The highest investment costs remain the most significant, particularly in the electrification of truck fleets and the construction of hydrogen infrastructure [14]. Many companies also fear the limited availability of technology and the insufficient number of charging and refuelling points for alternative fuels [15].

Another barrier is the lack of uniform international regulations and the varying pace of implementation of solutions between countries. For global logistics operators, this means adapting to various standards, increasing operational complexity [16]. Despite the challenges, the benefits of implementing renewable energy sources in logistics cannot be overstated. First, the carbon footprint is significantly reduced, improving the reputation of the brand and increasing appeal to the customer [5]. Second, companies gain greater energy independence and cost stability [12]. Third, the implementation of technological innovations strengthens competitiveness on the global market [16].

Furthermore, the energy transition in logistics drives the development of new business models, such as electric fleet sharing, green transport corridors, and energy partnerships between companies. These innovations enable the logistics sector to play an important role in building a low-carbon economy [16,17].

The role of international cooperation and public support cannot be overlooked either. EU programmes, energy transition funds, and tax incentives can accelerate the pace of change and facilitate the investment of logistics companies in innovation [18,19].

Renewable energy is becoming a driving force for the transformation of logistics, merging ecological, economic, and technological aspects [1]. Its use in transportation, warehouses, and distribution centres allows not only reduced emissions, but also the construction of more flexible and resilient supply chains [16]. Although the transformation process presents challenges, the long-term benefits make green energy a cornerstone of the development of the logistics sector in the 21st century.

2.2. Renewable Energy, Macroeconomic Stability, and Sustainable Development of the Sector

The modern economy is facing a fundamental transformation of energy, one that is not limited solely to its ecological dimension. Renewable energy is increasingly seen as a key factor influencing macroeconomic stability and the foundation in sustainable development

for individual economic sectors [20–22]. Its importance is growing in the face of global energy crises, fluctuating commodity prices, and ongoing climate change [22].

Traditional energy sources, oil, gas, and coal, have determined energy policy and shaped macroeconomic conditions for development for decades. However, their limited availability, geographical concentration and susceptibility to political conflicts and market speculation mean that the use of fossil fuels increases the risk of instability [23].

Renewable energy sources (RESs) allow independence from fuel imports and ensure greater predictability [24]. Photovoltaic installations, wind farms, and hydroelectric power plants are not exposed to fluctuations in global commodity markets. In the long term, they stabilise energy costs, translating directly into inflation, industrial competitiveness, and business conditions [12,25]. Renewable energy is the foundation for transformation in many sectors. Industry, transport, agriculture, and logistics are under pressure to reduce greenhouse gas emissions and improve energy efficiency. Implementing green technologies not only mitigates negative environmental impacts but also builds a competitive advantage [26]. For businesses, the use of renewable energy means lower long-term costs, greater resilience to crises, and better access to financing. A growing number of financial institutions are making loans and investments conditional on environmental, social, and governance (ESG) indicators. As a result, renewable energy is becoming a prerequisite for sustainable development in the private sector [27,28].

Investments in renewable energy sources are pro-development. First, they generate new jobs, both in equipment manufacturing and in installation and maintenance services [29]. Second, they stimulate technological innovation, which is then applied in other sectors of the economy [28]. Third, they reduce external costs related to health and environmental protection, which burden state budgets [25]. Furthermore, the development of renewable energy sources promotes energy decentralisation. Local communities and local governments, using renewable sources, can produce energy for their own needs and sell surpluses to the grid. This increases resilience to shocks and supports balanced regional development [30]. The challenges and advantages of renewable energy sources are presented in the figure below (Figure 1).

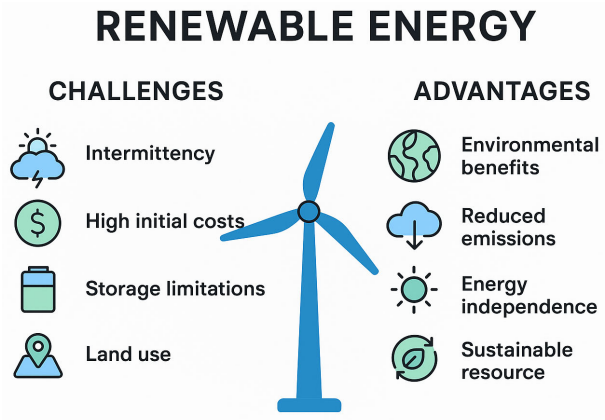


Figure 1. The challenges and advantages of renewable energy resources.

Macroeconomic stability means a balance between economic growth, inflation, employment, and external balances [31], as shown in the figure below (Figure 2).

Energy crises often disrupt this balance: rising fuel prices lead to inflationary pressures, while import dependence worsens the trade balance [13]. The development of renewable energy sources helps mitigate these risks by reducing the impact of external factors on the economy [30]. The situation in Europe after 2022 is a prime example, when rising gas and oil prices highlighted the strong link between macroeconomic stability and energy

policy. Countries that invested quicker in renewable energy sources adapted better to the crisis, maintaining lower inflation and greater predictability for businesses [32,33]. In a world of global competition, access to affordable and stable energy is becoming one of the most important factors in determining competitiveness. Countries and regions investing in renewable energy sources gain an advantage in costs, attract foreign investment, and build the image of innovative economies [28,31]. Trade regulations are equally important; a growing number of countries are introducing mechanisms that take into account the carbon footprint of imports. This means that companies operating based on renewable energy sources gain access to new markets, while those relying on fossil fuels may be burdened with additional costs [23,32]. However, the energy transition is not without challenges. The biggest challenge remains the upfront costs of investing in renewable energy infrastructure and modernising transmission grids [28]. In many countries, the volatility of wind and solar energy production is also a problem, which requires the development of storage technologies [34]. Sustainable development is not only about economic growth but also about caring for the environment and social well-being. Renewable energy fits this concept because it combines ecological, economic, and social dimensions [35]. This is illustrated in the figure below (Figure 3).

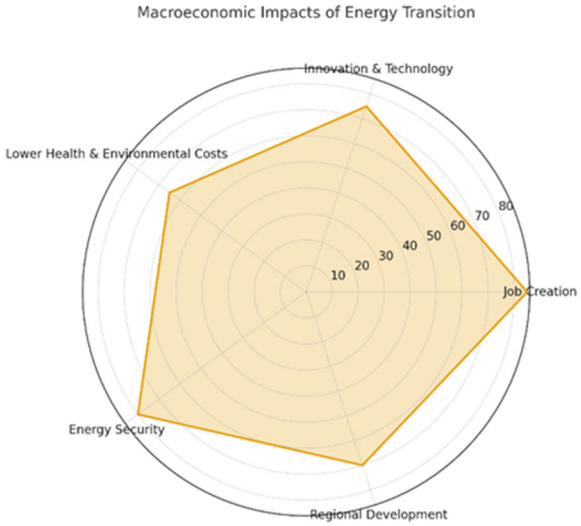


Figure 2. Macroeconomic Impacts of Energy Transition.

At the micro level, it allows companies to reduce costs and build a positive image. At the macro level, it stabilises the economy, increases energy security, and supports the transformation toward a low-emission economy [10,11,26]. Globally, it contributes to the achievement of the goals of the 2030 Agenda and the Paris Agreement [36]. In the coming decades, the share of renewable energy in the energy mix will increase steadily. Rapid technological progress is reducing the costs of photovoltaic installations and wind farms, while the development of hydrogen technologies and energy storage solutions addresses the problem of production instability [37,38]. The future belongs to hybrid systems, which combine various energy sources and enable flexible management. Investments in digitalisation, artificial intelligence and the Internet of Things will also play a crucial role, allowing optimisation of consumption and grid balance [34,37,39]. Renewable energy is becoming a key element in the building of macroeconomic stability and the foundation for sustainable development. It offers ecological, social, and economic benefits while simultaneously mitigating the risks associated with traditional fossil fuels [26,27,40]. Although the transformation process requires significant investments and well thought out public policies, the long-term benefits are invaluable [35]. Countries and sectors that prioritise

renewable energy sources will gain an advantage in the global economy while contributing to a more stable and equitable world [41,42].

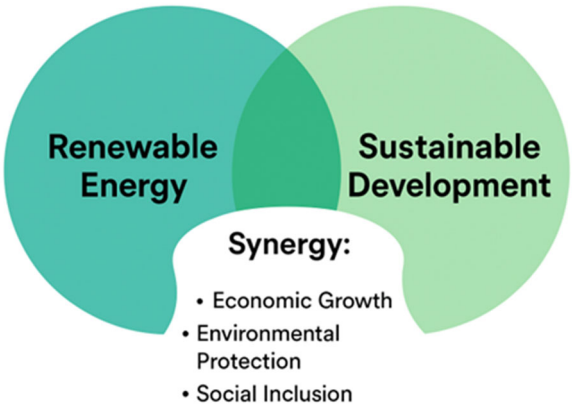


Figure 3. Synergy of renewable energy sources and sustainable development.

3. Research Methodology

3.1. Research Goal

The countries of the Visegrad Group (V4)—the Czech Republic, Hungary, Poland, and Slovakia—are an interesting research area due to their varying levels of economic development, distinct energy sector structures, and implementation rates of sustainable development policies.

All four countries pursue common climate goals and EU regulations, but their initial conditions and economic and political priorities significantly differ.

Poland remains the most fossil-fuel-dependent, especially on coal, which hinders its energy transition. At the same time, renewable energy has expanded rapidly there in recent years [43]. In Slovakia and the Czech Republic, nuclear energy has a stronger presence in the energy mix. This supports their energy security but also reduces the pace at which renewable energy can expand [44]. On the other hand, Hungary is implementing a policy of gradual decarbonisation, improving energy efficiency and developing green technologies [44].

These differences concern not only the structure of the economy and the energy mix, but also the level of macroeconomic stability, innovation, and the ability to adapt socially and environmentally to the challenges of transformation.

Literature and research in this area indicate that these discrepancies significantly impact the region. They affect the pace of climate action, how EU rules are applied, and the region's progress toward the Sustainable Development Goals [43–45].

This study aims to determine the strength and direction of the impact of renewable energy index (*RE*) and macroeconomic stabilisation index (*M*) on the sustainable development index of the logistics sector (SD_L) in the Visegrad Group countries between 2008 and 2023, taking into account the delayed effects of policies and differences between countries. The rationale for this objective is:

1. The discrepancies identified in the literature between the V4 countries regarding energy transition and achievements in renewable energy sources.
2. The growing importance of macroeconomic stability determines investment, efficiency, and resilience to shocks.
3. The lack of existing analyses that simultaneously incorporate all three components: renewable energy sources, macroeconomic stabilisation, and the logistics sector and its three dimensions (economic, social, and environmental).

4. The political and economic importance of such research in the context of the challenges of EU climate policies, regulations, and the region's development needs.

3.2. Hypothesis

The study used data from the Eurostat database, covering enterprises belonging to Section H—Transport and Storage (according to the NACE Rev. 2 classification). This section covers activities related to transporting goods and people by various modes of transport (road, rail, water, and air). It also includes support services for transportation, such as warehousing, logistics, and cargo handling, which are key elements of the functioning of the economy and the flow of goods on a national and international scale.

The study was conducted in six stages.

Creation and analysis of the sustainable development index of the logistics sector (SD_L) in the Visegrad Group countries for the years 2008–2023 and its pillars: economic (ED_L), social ($SocD_L$), and environmental ($EnvD_L$). Estimating basic descriptive statistics: maximum value, minimum value, mean value, standard deviation, and median. Presentation of trend lines.

The analytical indicators that constitute the SD_L pillars are presented in Table 1.

To create SD_L, the following formula was used:

$$SD_L = \frac{1}{n}\sum_{j=1}^{n} \left(ED_{L\mathrm{i}} + SocD_{L\mathrm{i}} + EnvD_{L\mathrm{i}}\right) \quad (1)$$

where

SD_L—synthetic indicator of sustainable development of logistics sector in the i-year;
ED_L—synthetic indicator of economic development of logistics sector in the i-year;
$SocD_L$—synthetic indicator of social development of logistics sector in the i-year;
$EnvD_L$—synthetic indicator of environmental development of logistics sector in the i-year;
n—the number of metrics.

The analytical indicators were transformed using the following formulas (in order to standardise their measurement scales):

- for the stimulants:

$$S_{ij} = \frac{x_{ij}}{\max_i\{x_{ij}\}},\ S_{ij} \in [0;1] \quad (2)$$

- for the destimulants:

$$D_{ij} = \frac{\min_i\{x_{ij}\}}{x_{ij}},\ D_{ij} \in [0;1] \quad (3)$$

where

- S_{ij}/D_{ij}—stands for the normalised value of the j-th variable in the i-th year;
- x_{ij}—the value of the j-th variable in the i-th year;
- $\min_i\{x_{ij}\}$—is the lowest value of the j-th variable in the i-th year;
- $\max_i\{x_{ij}\}$—the highest value of the j-th variable in the i-th year.

Creation and analysis of the renewable energy index (RE) in the Visegrad Group countries in 2008–2023. Estimation of basic descriptive statistics: maximum value, minimum value, mean value, standard deviation, and median. Presentation of trend lines.

The RE in the Visegrad Group countries in 2008–2023 was composed of six analytical indicators, which are presented in Table 2.

Table 1. Analytical indicators of the pillars of the SD_L.

Synthetic Indicator	Type of Indicator (Stimulant/Destimulant)	Analytical Indicator
Economic development of the logistics sector (ED_L)	Stimulant	Enterprises [number]
		Turnover or gross premiums written [million euro]
		Production value [million euro]
		Value added at factor cost [million euro]
		Gross operating surplus [million euro]
		Total purchases of goods and services [million euro]
		Gross investment in tangible goods [million euro]
		Gross operating surplus/turnover (gross operating rate) [percentage]
		Share of gross operating surplus in value added [percentage]
		Investment rate (investment/value added at factors cost) [percentage]
	Destimulant	Share of personnel costs in production [percentage]
		Average personnel costs (personnel costs per employee) [thousand euro]
Social development of the logistics sector ($SocD_L$)	Stimulant	Wages and Salaries [million euro]
		Social security costs [million euro]
		Employees [number]
		Turnover per person employed [thousand euro]
		Apparent labour productivity (gross value added per person employed) [thousand euro]
		Wage-adjusted labour productivity (apparent labour productivity by average personnel costs) [percentage]
		Gross value added per employee [thousand euro]
		Growth rate of employment [percentage]
		Persons employed per enterprise [number]
		Investment per person employed [thousand euro]
	Destimulant	Personnel costs [million euro]
		Share of personnel costs in total purchases of goods and services [percentage]
Environmental development of the logistics sector (Env_L)	Destimulant	Carbon dioxide [tonne]
		Methane [tonne]
		Nitrous oxide [tonne]
		Sulphur oxides [tonne]
		Carbon monoxide [tonne]
		Nitrogen oxides [tonne]
		Ammonia [tonne]

Table 2. Analytical indicators of renewable energy index in the Visegrad Group countries.

Synthetic Indicator	Type of Indicator (Stimulant/Destimulant)	Analytical Indicator
Renewable energy (*RE*)	Stimulant	Overall share of energy from renewable sources [percentage]
	Stimulant	Share of energy from renewable sources in final energy consumption [percentage]
	Stimulant	Share of renewable energy sources in energy consumption in transport [percentage]
	Stimulant	Share of renewable energy in electricity consumption [percentage]
	Stimulant	Energy productivity (GDP/primary energy consumption) [EUR/kg oe]
	Destimulant	Greenhouse gas emissions from transport (tonne)

The *RE* was created using the formula:

$$RE = RES_i + FECRES_i + TRES_i + ELRES_i + EP_i + GGT_i \quad (4)$$

where

- *RE*—renewable energy index, 2008–2023
- RES_i—overall share of energy from renewable sources, 2008–2023;
- $FECRES_i$—share of energy from renewable sources in final energy consumption, 2008–2023;
- $TRES_i$—share of renewable energy sources in energy consumption in transport, 2008–2023;
- $ELRES_i$—share of renewable energy in electricity consumption, 2008–2023;
- EP_i—energy productivity, 2008–2023;
- GGT_i—greenhouse gas emissions from transport, 2008–2023.

The analytical indicators were transformed using the same formulas used to create the SD_L pillars.

1. Calculation and analysis of the macroeconomic stabilisation index (*M*) in the Visegrad Group countries in 2008–2023. Estimation of basic descriptive statistics: maximum value, minimum value, mean value, standard deviation, and median. Presentation of trend lines.

M was calculated using the following formula [46]:

$$M = [(\Delta GDP \cdot U) + (U \cdot HICP) + (HICP \cdot G) + (G \cdot CA) + (CA \cdot \Delta GDP)] \cdot 0.475 \quad (5)$$

where

- *M*—macroeconomic stabilisation;
- $\Delta\, GDP$ − Δgross demestic product;
- *HICP*—Harmonised Index of Consumer Prices;
- *U*—unemployment rate;
- *G*—government debt;
- *CA*—current account balance to gross domestic product.

Conducting a correlation analysis between the indicators of logistics sector development (SD_L), renewable energy (RE), and macroeconomic stabilisation (M) in the Visegrad Group countries in 2008–2023. Calculation of Pearson's R, Spearman's Rho, Gamma and Kendall rank correlation coefficients. The choice of these methods enables a comprehensive analysis of relationships of various natures. The Pearson coefficient measures the classic, linear relationship between quantitative variables with a near-normal distribution. The Spearman coefficient allows for the examination of monotonic, even nonlinear, relationships using ranks, making it robust to outliers and not requiring the fulfilment of normality assumptions.

The Kendall coefficient serves a complementary function to the Spearman coefficient—it measures the consistency of ranks between variables, making it more reliable when the number of observations is small or data are ranked. The Gamma coefficient, on the other hand, is used to analyse relationships between ordinal variables, enabling the assessment of the direction and strength of relationships in ranking systems, for example, between a country's logistics position and its macroeconomic stability.

The use of four complementary coefficients allows for a more comprehensive picture of the interdependencies between the indicators being studied—both linearly and nonlinearly, for continuous and ordinal variables. Thanks to this, the obtained results are characterised by greater reliability, comparability and resistance to statistical distortions.

The ranges of correlation strength were assumed at the following level [47]:

- $|rxy| = 0$—no correlation;
- $0 < |rxy| \leq 0.19$—very weak;
- $0.20 \leq |rxy| \leq 0.39$—weak;
- $0.40 \leq |rxy| \leq 0.59$—moderate;
- $0.60 \leq |rxy| \leq 0.79$—strong;
- $0.80 \leq |rxy| \leq 1.00$—very strong.

2. Estimation of linear regression models using the least squares method. Estimation of the impact of renewable energy (RE) and macroeconomic stabilisation (M) on the sustainable development of the logistics sector (SD_L) in the Visegrad Group countries in the years 2008–2023. The models take into account both the current values of variables and their lags ($_{t-1}$, $_{t-2}$, $_{t-3}$).

The regression equation takes the form:

$$\begin{aligned} SD_L = \propto_0 + \propto_1 \cdot RE &+ \propto_2 \cdot RE_{(t-1)} \\ &+ \propto_3 \cdot RE_{(t-2)} + \propto_4 \cdot RE_{(t-3)} \propto_5 \cdot M + \propto_6 \cdot M_{(t-1)} + \propto_7 \cdot M_{(t-2)} \\ &+ \propto_8 \cdot M_{(t-3)} + \varepsilon_i \end{aligned} \quad (6)$$

3. Estimation of multi-equation regression models using the Seemingly Unrelated Regression (SUR) method for the Visegrad Group countries in the years 2008–2023. The interrelationships of three dimensions of sustainable development of the logistics sector (SD_L)—economic (ED_L), social ($SocD_L$), and environmental ($EnvD_L$)—were analysed in the context of the impact of renewable energy index (RE) and macroeconomic stabilisation index (M). The models take into account both the current values of variables and their time lags ($_{t-1}$, $_{t-2}$), which allows for capturing the dynamic effects of energy and macroeconomic policies.

The equations took the form:

$$
\begin{aligned}
ED_L = \propto_0 + \propto_1 & \cdot SocD_L + \propto_2 \cdot SocD_{L(t-1)} + \propto_3 \\
& \cdot SocD_{(t-2)} + \propto_4 \cdot EnvD_L + \propto_5 \cdot EnvD_{L(t-1)} + \propto_6 \cdot EnvD_{L(t-2)} + \propto_7 \cdot RE + \propto_8 \cdot RE_{(t-1)} \\
& + \propto_9 \cdot RE_{(t-2)} + \propto_{10} \cdot M + \propto_{11} \cdot M_{(t-1)} + \propto_{12} \cdot M_{(t-2)} + \varepsilon_i \\
SocD_L = \propto_0 + \propto_1 & \cdot ED_L + \propto_2 \cdot ED_{L(t-1)} + \propto_3 \\
& \cdot ED_{(t-2)} + \propto_4 \cdot EnvD_L + \propto_5 \cdot EnvD_{L(t-1)} + \propto_6 \cdot EnvD_{L(t-2)} + \propto_7 \cdot RE + \propto_8 \cdot RE_{(t-1)} \\
& + \propto_9 \cdot RE_{(t-2)} + \propto_{10} \cdot M + \propto_{11} \cdot M_{(t-1)} + \propto_{12} \cdot M_{(t-2)} + \varepsilon_i \\
EnvD_L = \propto_0 + \propto_1 & \cdot ED_L + \propto_2 \cdot ED_{L(t-1)} + \propto_3 \\
& \cdot ED_{(t-2)} + \propto_4 \cdot SocD_L + \propto_5 \cdot SocD_{L(t-1)} + \propto_6 \cdot SocD_{L(t-2)} + \propto_7 \cdot RE + \propto_8 \cdot RE_{(t-1)} \\
& + \propto_9 \cdot RE_{(t-2)} + \propto_{10} \cdot M + \propto_{11} \cdot M_{(t-1)} + \propto_{12} \cdot M_{(t-2)} + \varepsilon_i
\end{aligned}
\tag{7}
$$

To comprehensively and reliably verify the main hypothesis, indicators were developed and analysed, correlation analysis was conducted, and models were created and estimated using the OLS and SUR models.

The study considers both the immediate and delayed impact of *RE* and *M* on SD_L in the Visegrad Group countries and the multidimensional nature of sustainable development (ED_L, $SocD_L$, $EnvD_L$).

This study is important from both a scientific and a practical perspective. It allows for a better understanding of how the development of renewable energy sources and macroeconomic stabilisation influence the sustainable development of the logistics sector in the Visegrad Group countries. The analysis results:

- can support decision-makers in planning energy and economic policies, identifying actions that will improve logistics' economic, social, and environmental efficiency in the short and long term;
- considers the specific characteristics of individual countries, enabling better adaptation of development strategies to local conditions;
- can be a valuable source of knowledge for science, business, and public administration (in the context of the challenges related to EU climate policy and the needs of the region's energy and economic transformation).

4. Results

Table 3 shows the sustainable development index for the logistics sector (SD_L) in the Visegrad Group from 2008 to 2023, together with its economic dimensions (ED_L), social dimensions ($SocD_L$), and environmental dimensions ($EnvD_L$). These indicators were analysed for basic descriptive statistics.

The data indicate that the Czech Republic and Hungary achieve higher indicator values than Poland and Slovakia, indicating a more stable and balanced development in these countries.

The Czech Republic was characterised by high indicator values in all three dimensions from the beginning, with relatively low variability throughout the period, indicating a stable development of the logistics sector. Hungary also achieved relatively high indicator levels, with significant growth in $SocD_L$ and $EnvD_L$, although the growth dynamics in these dimensions were somewhat less predictable than in the Czech Republic.

Slovakia recorded the lowest indicator values in 2008 (taking into account all countries studied). The ED_L in this country showed significant variability in subsequent years, ranging from very low to relatively high. At the beginning of the study period, Poland was characterised by a relatively low level of development, particularly in ED_L, but in subsequent years, a steady increase was observed, primarily in ED_L and $SocD_L$.

Table 3. The Sustainable Development Index for the Logistics Sector (SD_L) in the Visegrad Group, 2008–2023.

Year	Sustainable Development of the Logistics Sector (SD_L)															
	Czechia				Hungary				Poland				Slovakia			
	ED_L	$SocD_L$	$EnvD_L$	SD_L	ED_L	$SocD_L$	$EnvD_L$	SD_L	ED_L	$SocD_L$	$EnvD_L$	SD_L	ED_L	$SocD_L$	$EnvD_L$	SD_L
2008	0.87	0.70	0.54	0.70	0.70	0.77	0.57	0.68	0.48	0.65	0.72	0.61	0.48	0.54	0.40	0.47
2009	0.77	0.59	0.63	0.66	0.67	0.63	0.61	0.63	0.42	0.60	0.75	0.59	0.40	0.57	0.45	0.47
2010	0.81	0.62	0.66	0.70	0.69	0.67	0.66	0.67	0.45	0.69	0.70	0.61	0.56	0.64	0.45	0.55
2011	0.87	0.69	0.70	0.75	0.72	0.73	0.65	0.70	0.52	0.71	0.71	0.65	0.66	0.63	0.48	0.59
2012	0.85	0.68	0.73	0.75	0.70	0.71	0.79	0.73	0.48	0.70	0.75	0.65	0.70	0.62	0.52	0.61
2013	0.85	0.73	0.76	0.78	0.77	0.74	0.77	0.76	0.50	0.71	0.79	0.67	0.74	0.66	0.59	0.66
2014	0.84	0.77	0.76	0.79	0.83	0.86	0.71	0.80	0.53	0.76	0.81	0.70	0.73	0.62	0.92	0.76
2015	0.88	0.83	0.75	0.82	0.87	0.89	0.68	0.81	0.54	0.78	0.79	0.70	0.72	0.67	0.69	0.69
2016	0.86	0.84	0.73	0.81	0.83	0.82	0.71	0.79	0.54	0.77	0.74	0.69	0.64	0.61	0.65	0.63
2017	0.85	0.84	0.72	0.80	0.85	0.82	0.68	0.79	0.57	0.79	0.85	0.74	0.65	0.65	0.68	0.66
2018	0.91	0.86	0.77	0.85	0.87	0.86	0.69	0.80	0.66	0.90	0.84	0.80	0.67	0.67	0.74	0.69
2019	0.91	0.85	0.81	0.86	0.90	0.85	0.73	0.83	0.67	0.85	0.46	0.66	0.67	0.66	0.75	0.70
2020	0.86	0.74	0.96	0.85	0.66	0.67	0.98	0.77	0.67	0.84	0.50	0.67	0.64	0.62	0.93	0.73
2021	0.89	0.88	0.84	0.87	0.87	0.85	0.89	0.87	0.69	0.90	0.43	0.67	0.74	0.67	0.76	0.72
2022	0.90	0.89	0.85	0.88	0.88	0.86	0.74	0.83	0.71	0.92	0.51	0.71	0.75	0.68	0.80	0.74
2023	0.91	0.91	0.83	0.88	0.89	0.87	0.74	0.83	0.73	0.94	0.50	0.72	0.77	0.69	0.79	0.75
Basic descriptive statistics																
Max	0.91	0.91	0.96	0.88	0.90	0.89	0.98	0.87	0.73	0.94	0.85	0.80	0.77	0.69	0.93	0.76
Min	0.77	0.59	0.54	0.66	0.66	0.63	0.57	0.63	0.42	0.60	0.43	0.59	0.40	0.54	0.40	0.47
Mean	0.86	0.78	0.75	0.80	0.79	0.79	0.72	0.77	0.57	0.78	0.68	0.68	0.66	0.64	0.66	0.65
SD	0.04	0.10	0.09	0.07	0.09	0.08	0.10	0.07	0.10	0.10	0.14	0.05	0.10	0.04	0.16	0.09
Median	0.87	0.80	0.75	0.81	0.83	0.82	0.71	0.79	0.54	0.78	0.73	0.67	0.67	0.64	0.68	0.68

Descriptive statistics confirm these observations. During the period under review, the Czech Republic achieved the highest average SD_L value (0.80) (with low variability, indicating stable and sustainable sector development). Hungary achieved an average of 0.77, significantly improving $SocD_L$ and $EnvD_L$. Poland recorded an average value of 0.66 (which may indicate a relatively stable development, with a significant growth of ED_L and $SocD_L$). Slovakia, on the other hand, achieved the lowest average SD_L value (0.65). Taking into account the countries studied, it is characterised by a relatively lower level of sustainable development in the sector, with progress observed mainly in $EnvD_L$ between 2018 and 2023.

Chart 1 presents trend analysis. It confirms that the Czech Republic and Hungary are experiencing strong and stable growth in all areas. Of all countries studied, Poland has experienced the fastest ED_L and $SocD_L$ (the trend fit in these areas is exceptionally high, R^2 above 0.9). At the same time, $EnvD_L$ shows a negative trend and a low fit to the trend line (R^2 = 0.3897), indicating a persistent problem in this dimension. In Slovakia, the highest growth dynamics were observed in $EnvD_L$, suggesting that it is coming to an end in this dimension, while SD_L is growing more slowly but steadily (R^2 = 0.738).

In summary, the logistics sector of the Visegrad Group is evolving toward greater sustainability, but the pace and balance of this process vary. It is worth emphasising that:

- Poland and Slovakia should invest in sustainable logistics and ecoinnovations,
- the Czech Republic and Hungary should develop strategies to maintain stability and further modernise the sector (particularly through digitalisation and process automation);
- in the Visegrad Group, strengthening synergies between the economic, social, and environmental dimensions is crucial, enabling the logistics sector to meet the challenges of the energy transition and the increasing regulatory requirements of the European Union.

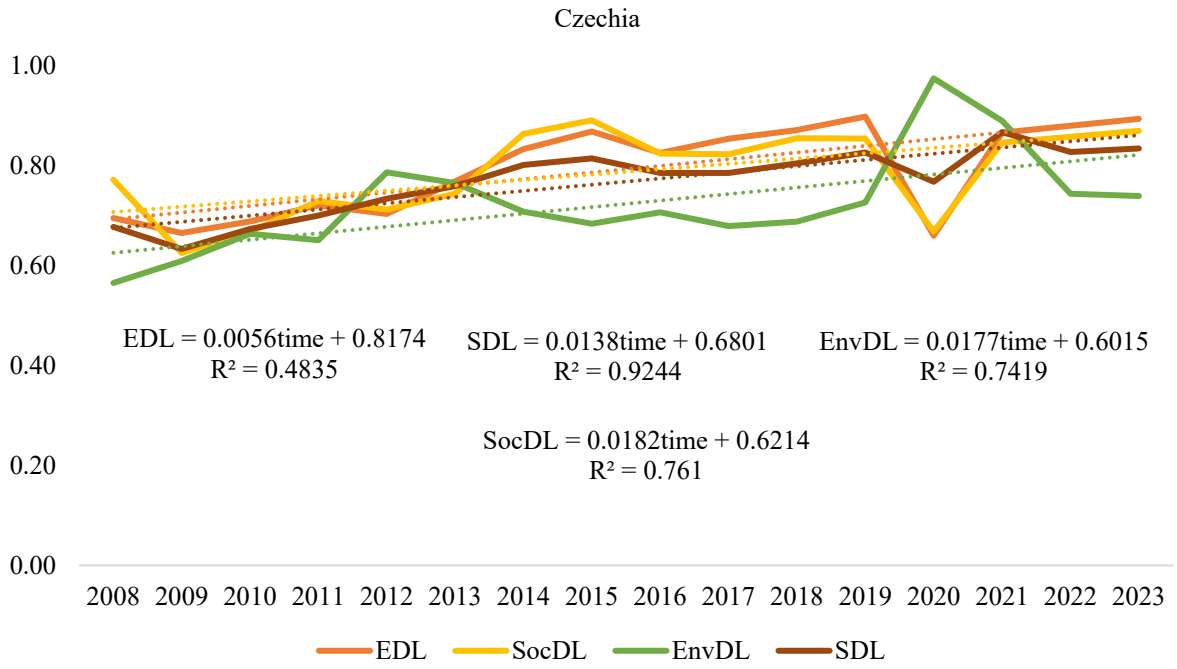
Table 4 presents the renewable energy index (*RE*) for the Visegrad Group from 2008 to 2023. This indicator was analysed for basic descriptive statistics.

The data show a significant increase in *RE* in all countries, although the pace and dynamics of the change vary.

At the beginning of the study period, the Czech Republic had a low *RE* level (0.38 in 2008), while the other countries recorded values above 0.50. In the following years, the Czech Republic recorded a rapid increase in the index, reaching 0.93 in 2023. In 2008, the *RE* in Poland was 0.51; in subsequent years, the index systematically increased, reaching 0.98 in 2023. Hungary was characterised by a slower but stable growth rate, from 0.51 in 2008 to 0.94 in 2023. From 2008 to 2023, Slovakia had the highest *RE* level (approximately 0.80 in 2014 and 0.99 in 2023).

Descriptive statistics indicate that the average share of *RE* was highest in Slovakia (0.80), followed by the Czech Republic (0.74), Poland (0.73), and Hungary (0.70).

Chart 2 presents trend analysis. It confirms the above observations. During the period analysed, the Czech Republic recorded the highest *RE* growth rate (0.0302 per year, R^2 = 0.8815). It can be concluded that it has undergone the greatest energy transformation. Poland and Slovakia also record strong and well-adjusted growth trends (0.0244 and 0.0270, respectively, with R^2 above 0.86). On the other hand, Hungary achieved the lowest growth rate (0.019 per year), but the trend remains stable and well adjusted (R^2 = 0.8047).


Czechia
1.00
0.80
0.60
0.40
0.20
0.00
EDL = 0.0056time + 0.8174
R² = 0.4835
SDL = 0.0138time + 0.6801
R² = 0.9244
EnvDL = 0.0177time + 0.6015
R² = 0.7419
SocDL = 0.0182time + 0.6214
R² = 0.761
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
EDL
SocDL
EnvDL
SDL

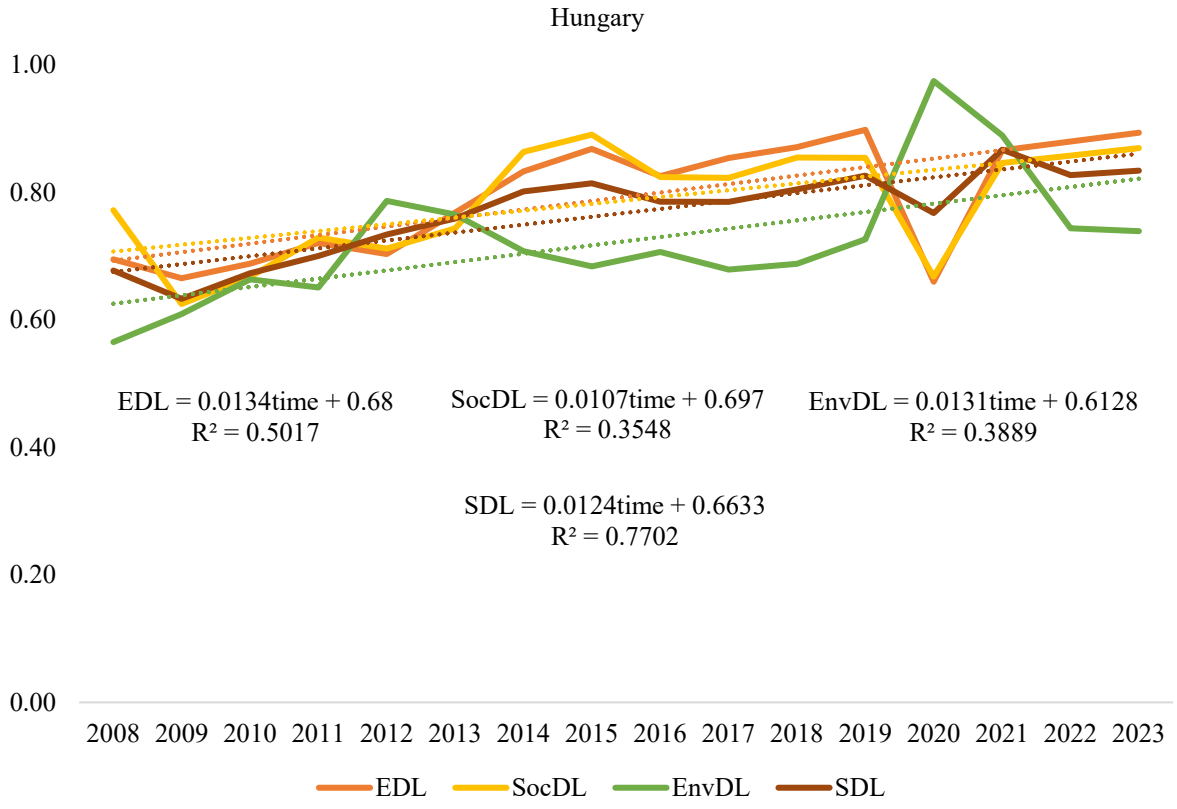

Hungary
1.00
0.80
0.60
0.40
0.20
0.00
EDL = 0.0134time + 0.68
R² = 0.5017
SocDL = 0.0107time + 0.697
R² = 0.3548
EnvDL = 0.0131time + 0.6128
R² = 0.3889
SDL = 0.0124time + 0.6633
R² = 0.7702
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
EDL
SocDL
EnvDL
SDL

Chart 1. *Cont.*

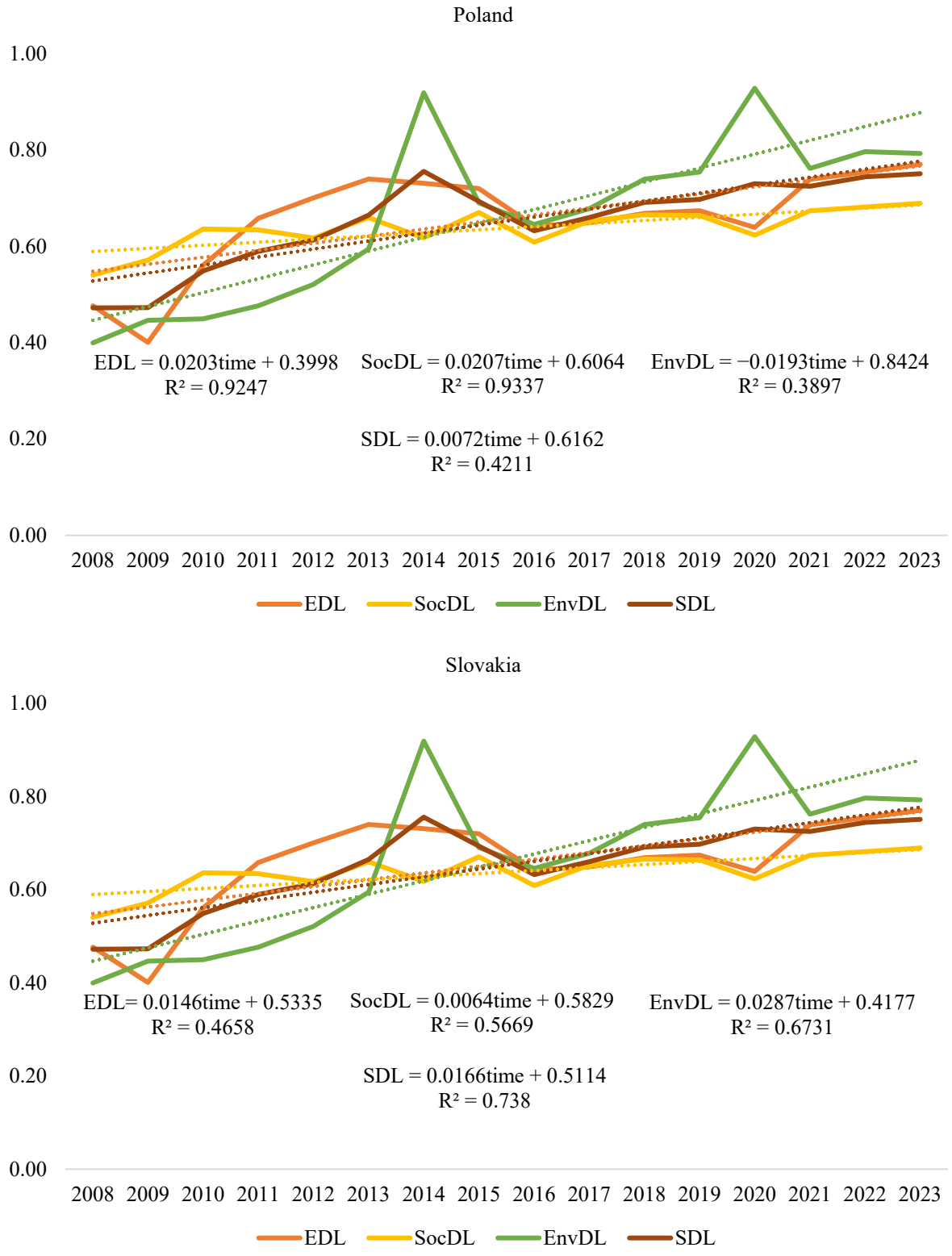


Chart 1. The trend analysis of the Sustainable Development Index for the Logistics Sector (SD_L) in the Visegrad Group, 2008–2023.

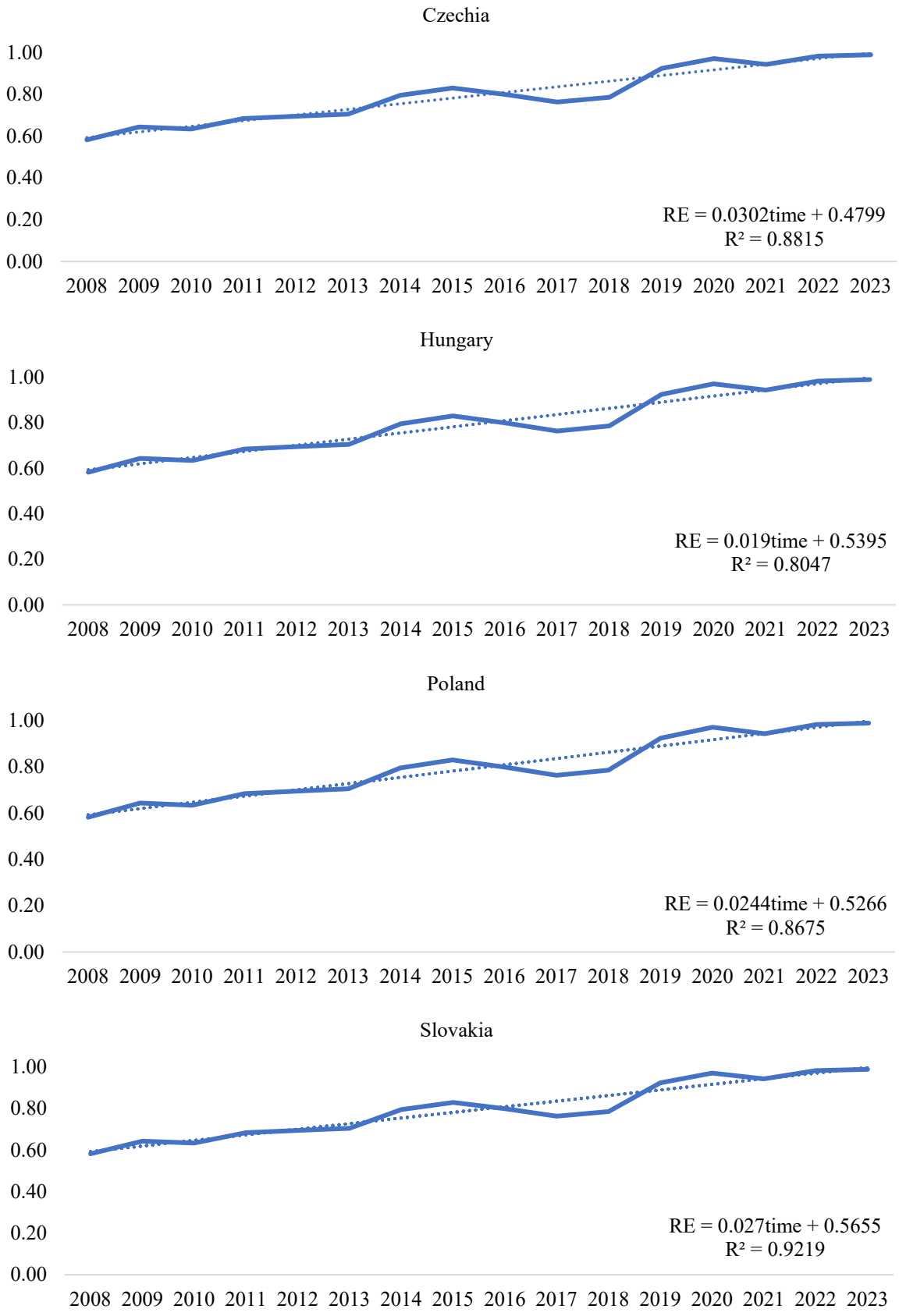


Chart 2. The trend analysis of the renewable energy index (*RE*) for the Visegrad Group, 2008–2023.

Table 4. Renewable energy index (*RE*) in the Visegrad Group, 2008–2023.

Year	Renewable Energy (*RE*)			
	Czechia	**Hungary**	**Poland**	**Slovakia**
2008	0.38	0.51	0.51	0.58
2009	0.55	0.59	0.58	0.64
2010	0.58	0.62	0.62	0.63
2011	0.55	0.64	0.66	0.68
2012	0.69	0.67	0.69	0.69
2013	0.72	0.70	0.70	0.70
2014	0.77	0.69	0.72	0.80
2015	0.77	0.69	0.72	0.83
2016	0.77	0.70	0.67	0.80
2017	0.77	0.68	0.66	0.76
2018	0.78	0.68	0.78	0.79
2019	0.84	0.71	0.83	0.92
2020	0.92	0.80	0.88	0.97
2021	0.87	0.76	0.83	0.94
2022	0.89	0.84	0.90	0.98
2023	0.93	0.94	0.98	0.99
Basic descriptive statistics				
Max	0.93	0.94	0.98	0.99
Min	0.38	0.51	0.51	0.58
Mean	0.74	0.70	0.73	0.80
SD	0.15	0.10	0.12	0.13
Median	0.77	0.69	0.71	0.79

In summary, *RE* grows in all four countries, although the pace of this process varies:

- The Czech Republic and Poland—the fastest growth,
- Slovakia—a leader in terms of high and relatively stable *RE* levels,
- Hungary—accelerating *RE* activities,
- the Visegrad Group—increased energy security, reduced dependence on fossil fuels, and better adapted to the climate requirements of the European Union.

Table 5 presents the macroeconomic stabilisation index (*M*) in the Visegrad group from 2008 to 2023. This indicator was analysed for basic descriptive statistics.

Data show that these indicators are lower and more volatile than SD_L and *RE*.

The values range from 0.27 (Slovakia, 2009) to 0.64 (Hungary, 2017). At the beginning of the period under review, all countries recorded low values (below 0.45) related to the global financial crisis. In the following years, there was improvement, particularly noticeable around 2014–2017, when all countries achieved relatively highest stabilisation levels. Since 2019, declines have been observed again and after 2020 (the COVID-19 pandemic), the indicator values in most countries decreased significantly.

The highest mean of *M* was in the Czech Republic (0.49), just ahead of Hungary (0.48), Poland (0.46), and Slovakia (0.43).

Chart 3 presents trend analysis. It suggests different developments. The Czech Republic and Hungary have a very low trend line fit (R^2 0.0692 and 0.0185, respectively),

indicating that there is no clear trend—the values are rather unstable. An upward trend is observed in Poland (0.0133 per year, R^2 = 0.6247). It indicates a gradual improvement in macroeconomic stability in the long term. In Slovakia, the trend is positive, but poorly fitted (R^2 = 0.0858), indicating significant fluctuations.

Table 5. Macroeconomic stabilisation index (*M*) in the Visegrad Group, 2008–2023.

Year	Macroeconomic Stabilisation (*M*)			
	Czechia	**Hungary**	**Poland**	**Slovakia**
2008	0.42	0.33	0.37	0.39
2009	0.40	0.28	0.32	0.27
2010	0.45	0.44	0.38	0.38
2011	0.43	0.46	0.38	0.36
2012	0.43	0.44	0.36	0.34
2013	0.45	0.53	0.40	0.46
2014	0.53	0.63	0.48	0.54
2015	0.57	0.58	0.46	0.54
2016	0.56	0.59	0.51	0.46
2017	0.62	0.64	0.53	0.45
2018	0.60	0.59	0.55	0.49
2019	0.57	0.55	0.53	0.48
2020	0.48	0.45	0.50	0.41
2021	0.54	0.49	0.58	0.51
2022	0.43	0.39	0.52	0.38
2023	0.36	0.28	0.44	0.34
Basic descriptive statistics				
Max	0.62	0.64	0.58	0.54
Min	0.36	0.28	0.32	0.27
Mean	0.49	0.48	0.46	0.43
SD	0.08	0.11	0.08	0.08
Median	0.46	0.47	0.47	0.43

In summary, *M* in the countries studied is relatively low and prone to fluctuations, especially in crises like the pandemic.

In addition, it is necessary to:

- The Czech Republic and Hungary—strengthen their ability to manage disruptions,
- Slovakia—introduce structural measures to decrease economic vulnerability,
- Poland—promote further opportunities for sustainable long-term growth,
- The Visegrad Group—harmonise short-term stabilisation efforts with long-term economic development.

Table 6 presents the analysis of the correlation between the Sustainable Development Index (SD_L) and the Renewable Energy Index (*RE*), and the Macroeconomic Stabilisation Index (*M*) in the Visegrad Group from 2008 to 2023.

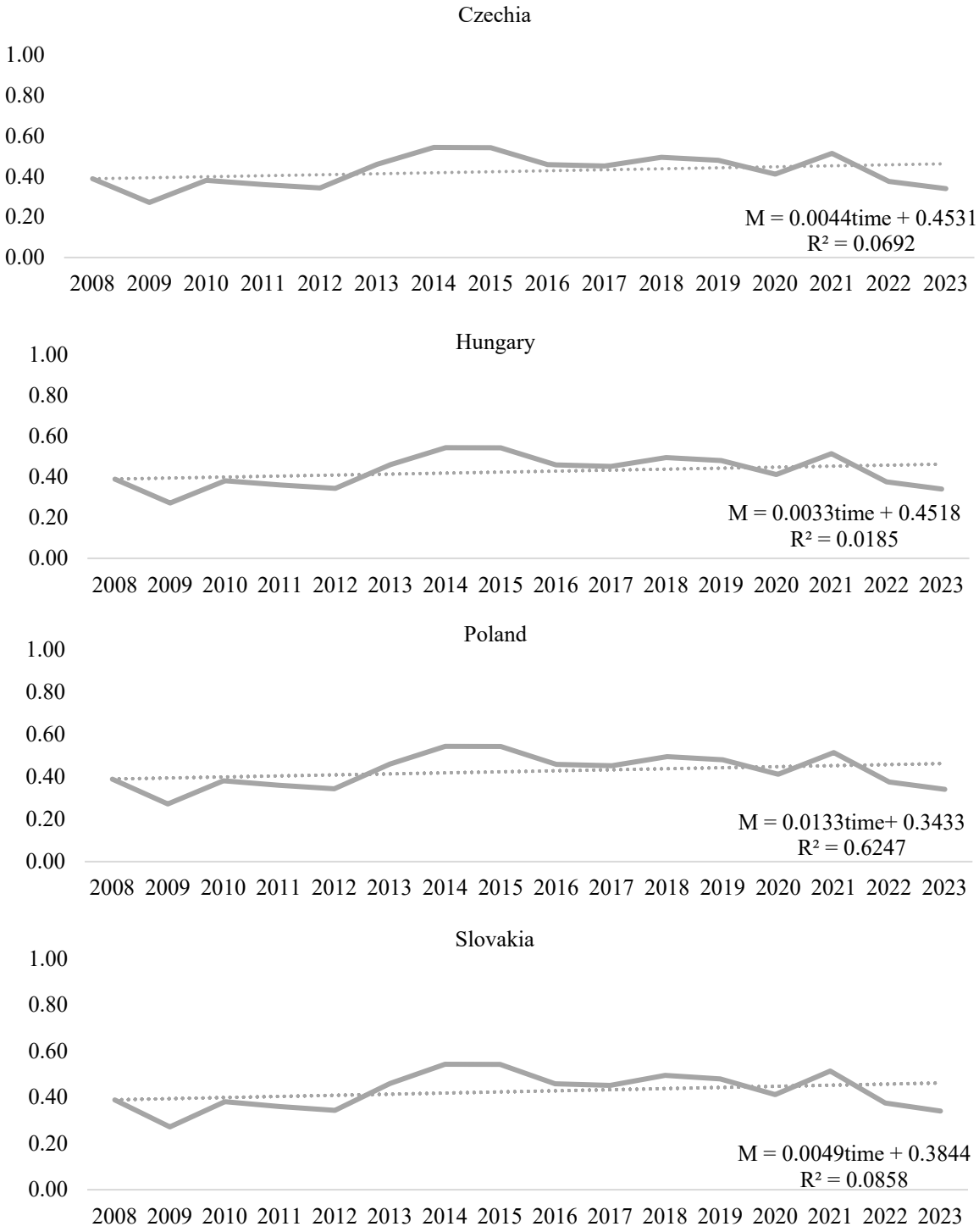


Chart 3. The trend analysis of macroeconomic stabilisation index (*M*) for the Visegrad Group, 2008–2023.

Varying correlations were observed, depending on the country and the correlation measure used (all positive).

For SD_L and *RE*, all countries recorded high or moderate correlations (Pearson 0.524–0.915; Spearman 0.585–0.941; Gamma 0.467–0.817; Kendall 0.467–0.817), indicating strong and consistent relationships, linear and monotonic.

Table 6. Correlation for the Visegrad Group (SD_L/RE, SD_L/M), 2008–2023.

Correlation for the Visegrad Group, 2008–2023								
Correlation Coefficient	**Czechia**		**Hungary**		**Poland**		**Slovakia**	
	SD_L/RE	SD_L/M	SD_L/RE	SD_L/M	SD_L/RE	SD_L/M	SD_L/RE	SD_L/M
Pearson's R	0.915	0.359	0.724	0.438	0.524	0.703	0.862	0.554
Spearman's Rho	0.941	0.244	0.809	0.297	0.585	0.694	0.885	0.412
Gamma	0.817	0.217	0.650	0.200	0.467	0.517	0.800	0.317
Kendall rank	0.817	0.217	0.650	0.200	0.467	0.517	0.800	0.317

In SD_L and M, the correlations were lower (Pearson 0.359–0.703; Spearman 0.244–0.694; Gamma 0.200–0.517; Kendall 0.200–0.517), suggesting a weaker relationship between these variables.

The strongest relationship was observed in the Czech Republic for SD_L and RE (Spearman 0.941), while the weakest relationship was observed in Hungary and Poland for SD_L and M (Gamma and Kendall 0.200, lack of significance).

Overall, the results indicate that the relationships for SD_L and RE are significantly stronger than those for SD_L and M, with their strength varying between the Visegrad groups.

Table 7 shows the estimation of linear regression models using the least squares method. The impact of the Renewable Energy Index (RE) and the macroeconomic stabilisation index (M) on the Sustainable Development of the Logistics Sector (SD_L) in the Visegrad Group was estimated from 2008 to 2023.

The models consider both the current values of the variables and their lags ($t-1$, $t-2$, $t-3$), allowing the temporal effects of energy and macroeconomic policies to be captured.

The models presented meet standard linear regression assumptions. Parameter linearity, lack of perfect multicollinearity, zero expected error, lack of homoscedasticity, lack of autocorrelation of residuals (both first- and second-order), and normality of the residual distribution were confirmed. The test statistics (White, LM, Jarque–Bera) and the p-values indicate that none of the assumptions were violated, ensuring the reliability of the estimate results.

Table 7. The OLS estimation, dependent variable SD_L, explanatory variable: RE and M (with $_{t-1, t-2, t-3}$).

Czechia				
Model 1: OLS, using observations 2008–2023 (T = 16)				
Dependent variable: SD_L				
	Coefficient	Std. error	p-value	R-squared
const	0.486	0.030	<0.0001	0.957
$RE_{(t-1)}$	0.396	0.033	<0.0001	
M	−0.168	0.074	0.044	
$M_{(t-1)}$	0.231	0.089	0.025	

Table 7. *Cont.*

Assumptions of OLS				
Assumption	Test/Indicator	Result/Statistic	*p*-value	Assessment of fulfilment
1. Linearity in parameters	Model specification	Linear model (*const* + $RE_{(t-1)}$ + M + $M_{(t-1)}$)	-	Fulfilled
2. No perfect multicollinearity	Estimation possible	All SE finite, model stable	-	Fulfilled
3. Expected value of error = 0	Constant term in the model	Constant present	-	Fulfilled
4. Homoscedasticity	White's test	LM = 9.567; df = 9	0.387	Fulfilled
5. No autocorrelation of residuals (1st order)	LM test; DW	LMF = 0.023; p = 0.884; DW = 2.05	0.884	Fulfilled
6. No autocorrelation of residuals (2nd order)	LM test	LMF = 2.379	0.148	Fulfilled
7. Normality of residuals ǀ	Test Chi^2 (Jarque–Bera typ)	$\chi^2(2)$ = 0.193	0.908	Fulfilled
Hungary				
Model 1: OLS, using observations 2008–2023 (T = 16)				
Dependent variable: SD_L				
	Coefficient	Std. error	*p*-value	R-squared
const	0.270	0.075	0.0031	0.777
RE	0.511	0.088	<0.0001	
M	0.292	0.076	0.0021	
Assumptions of OLS				
Assumption	Test/Indicator	Result/Statistic	*p*-value	Assessment of fulfilment
1. Linearity in parameters	Model specification	Linear model (*const* + *RE* + *M*)	-	Fulfilled
2. No perfect multicollinearity	Estimation possible	All SE finite, model stable	-	Fulfilled
3. Expected value of error = 0	Constant term in the model	Constant present	-	Fulfilled
4. Homoscedasticity	White's test	LM = 7.100; df = 5	0.213	Fulfilled
5. No autocorrelation of residuals (1st order)	LM test; DW	LMF = 0.219; p = 0.648; DW = 2.067	0.648	Fulfilled
6. No autocorrelation of residuals (2nd order)	LM test	LMF = 0.203	0.819	Fulfilled
7. Normality of residuals ǀ	Test Chi^2 (Jarque–Bera typ)	$\chi^2(2)$ = 1.614	0.446	Fulfilled

Table 7. *Cont.*

Poland				
Model 1: OLS, using observations 2008–2023 (T = 16)				
Dependent variable: SD_L				
	Coefficient	Std. error	*p*-value	R-squared
const	0.532	0.072	<0.0001	0.7
RE	0.475	0.192	0.0353	
$RE_{(t-1)}$	−0.968	0.291	0.0089	
$RE_{(t-2)}$	0.506	0.215	0.043	
M	0.313	0.156	0.0752	
Assumptions of OLS				
Assumption	Test/Indicator	Result/Statistic	*p*-value	Assessment of fulfilment
1. Linearity in parameters	Model specification	Linear model (*const* + *RE* + $RE_{(t-1)}$ + $RE_{(t-2)}$ + *M*)	-	Fulfilled
2. No perfect multicollinearity	Estimation possible	All SE finite, model stable	-	Fulfilled
3. Expected value of error = 0	Constant term in the model	Constant present	-	Fulfilled
4. Homoscedasticity	White's test	LM = 13.060; df = 8	0.11	Fulfilled
5. No autocorrelation of residuals (1st order)	LM test; DW	LMF = 0.090; p = 0.771; DW = 1.79	0.771	Fulfilled
6. No autocorrelation of residuals (2nd order)	LM test	LMF = 0.114	0.894	Fulfilled
7. Normality of residuals ׀	Test Chi^2 (Jarque–Bera typ)	$\chi^2(2)$ = 0.749	0.688	Fulfilled
Slovakia				
Model 1: OLS, using observations 2008–2023 (T = 16)				
Dependent variable: SD_L				
	Coefficient	Std. error	*p*-value	R-squared
const	0.232	0.070	0.0128	0.889
$RE_{(t-1)}$	0.519	0.153	0.0115	
$RE_{(t-2)}$	−0.434	0.197	0.0638	
$RE_{(t-3)}$	0.501	0.142	0.0096	
M	0.407	0.101	0.0049	
$M_{(t-2)}$	−0.417	0.121	0.0105	

Table 7. *Cont.*

Assumptions of OLS				
Assumption	Test/Indicator	Result/Statistic	*p*-value	Assessment of fulfilment
1. Linearity in parameters	Model specification	Linear model (*const* + $RE_{(t-1)}$ + $RE_{(t-2)}$ + $RE_{(t-3)}$ + M + $M_{(t-2)}$)	-	Fulfilled
2. No perfect multicollinearity	Estimation possible	All SE finite, model stable	-	Fulfilled
3. Expected value of error = 0	Constant term in the model	Constant present	-	Fulfilled
4. Homoscedasticity	White's test	LM = 11.1802; df = 10	0.344	Fulfilled
5. No autocorrelation of residuals (1st order)	LM test; DW	LMF = 0.528; p = 0.495; DW = 2.328	0.495	Fulfilled
6. No autocorrelation of residuals (2nd order)	LM test	LMF = 1.259	0.361	Fulfilled
7. Normality of residuals	Test Chi^2 (Jarque–Bera typ)	$\chi^2(2)$ = 1.041	0.594	Fulfilled

Analysis of the regression coefficients indicates a significant impact of both *RE* and *M* on SD_L in all countries studied, although some of their effects appear with delay, and the influence of the variables can be positive or negative. The coefficient of determination (R^2) confirms the good fit of the models to the data.

In all countries analysed, the impact of *RE* and *M* on SD_L is clearly differentiated in terms of the strength and nature of the effect.

In the case of *RE*, the strongest positive impact is observed in Hungary, where *RE* significantly and clearly strengthens SD_L, and in Slovakia, where $RE_{(t-1)}$ plays the most significant role. In the Czech Republic, the effect is also positive, but somewhat weaker and occurs only in a delayed form, suggesting that the economy needs time to adapt to investments in renewable energy sources. Poland, on the other hand, is characterised by high volatility: the *RE* impact is positive, but in the subsequent period a very strong negative effect appears, only to become positive again with a longer delay. This pattern indicates the transition costs of the energy transition and the delayed adaptation of the logistics sector.

In terms of *M*, the most favourable current results are achieved in Slovakia, where the coefficient for *M* is the highest among the studied countries, and in Poland, where the effect is positive, although weaker. *M* also has a positive and relatively strong effect in Hungary. In the Czech Republic, the impact of *M* is negative, but a positive effect appears in the subsequent period. This reverse pattern may suggest that stabilisation measures limit the sector's flexibility in the short term but improve its equilibrium in the long term. At the same time, it is important to emphasise that the Czech Republic has the lowest current impact of *M* on SD_L (M = <0.168), which means that immediate stabilisation measures can initially hinder the development of logistics. However, the strongest negative lagged effect is revealed, $M_{(t-2)}$ = 0.417-indicating that excessive or prolonged macroeconomic stabilisation dampens the dynamics of the logistics sector after some time.

In summary, the data indicate that the development of *RE* and *M* is crucial for SD_L. Their effects can manifest in the current period and with a certain time lag. *RE* typically has the highest impact on SD_L, especially in the current period or with the first lag. The coefficients for *RE* are positive and statistically significant in most models, suggesting that

RE development strongly supports SD_L. Overall, *RE* has the most significant and stable impact on the SD_L, while *M* has a smaller and more variable impact over time, depending on the lags and the model's specificity.

Table 8 presents the estimation of multi-equation regression models using the Seemingly Unrelated Regression (SUR) method for the Visegrad Group from 2008 to 2023. The interrelationships of three dimensions of sustainable development of the logistics sector (SD_L), economic (ED_L), social ($SocD_L$) and environmental ($EnvD_L$), were analysed in the context of the impact of renewable energy sources (*RE*) and macroeconomic stabilisation (*M*). The models consider both the current values of variables and their time lags ($t-1$, $t-2$), which allows capturing the dynamic effects of energy and macroeconomic policies.

Table 8. The SUR estimation, dependent variables: ED_L, $SocD_L$, $EnvD_L$, explanatory variable: depending on the model, ED_L, $SocD_L$, $EnvD_L$ (with$_{t-1}$, $_{t-2}$) and *RE*, *M* (with $_{t-1}$, $_{t-2}$).

Czechia				
Model 2: SUR, using observations 2008–2023 (T = 16)				
Equation (1)				
Dependent variable: ED_L				
	Coefficient	Std. error	*p*-value	R-squared
const	−0.675	0.031	0.0021	0.999
$SocD_L$	0.987	0.009	7.61×10^{-5}	
$SocD_{L(t-1)}$	1.157	0.044	0.0015	
$SocD_{L(t-2)}$	0.310	0.014	0.0019	
$EnvD_L$	1.283	0.023	0.0003	
$EnvD_{L(t-1)}$	1.019	0.036	0.0013	
RE	−1.320	0.035	0.0007	
$RE_{(t-1)}$	−0.747	0.017	0.0005	
$RE_{(t-2)}$	−0.477	0.014	0.0009	
M	0.244	0.012	0.0024	
$M_{(t-1)}$	−0.312	0.015	2.30×10^{-3}	
$M_{(t-2)}$	−0.363	0.018	0.0026	
Equation (2)				
Dependent variable: $SocD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	−0.303	0.042	0.0002	0.998
ED_L	1.099	0.052	1.42×10^{-7}	
$EnvD_L$	−0.801	0.032	4.56×10^{-8}	
$EnvD_{L(t-2)}$	0.207	0.026	0.0001	
RE	0.446	0.035	4.53×10^{-6}	
$RE_{(t-1)}$	0.292	0.033	5.17×10^{-5}	
M	0.091	0.018	1.40×10^{-3}	

Table 8. *Cont.*

Equation (3)				
Dependent variable: $EnvD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	−0.158	0.071	0.0684	0.992
ED_L	1.218	0.096	1.45×10^{-5}	
$SocD_L$	−1.193	0.06	1.07×10^{-6}	
$SocD_{L(t-2)}$	−0.111	0.034	0.0172	
RE	0.572	0.049	2.38×10^{-5}	
$RE_{(t-1)}$	0.445	0.051	0.0001	
$RE_{(t-2)}$	0.140	0.041	1.44×10^{-2}	
M	0.061	0.027	0.0657	
Cross-equation VCV for residuals				
	3.30×10^{-7}	(−0.574)	(−0.272)	
	-1.42×10^{-6}	1.84×10^{-5}	(−0.729)	
	-9.86×10^{-7}	1.98×10^{-5}	3.99×10^{-5}	
Tests				
Breusch–Pagan test for diagonal covariance matrix				
Chi-square (3) = 13.0843 [0.0045]				
log determinant = −37.1825				
Hansen–Sargan over-identification test				
Chi-square (1) = 20.5239 [0.0022]				
Hungary				
Model 2: SUR, using observations 2008–2023 (T = 16)				
Equation (1)				
Dependent variable: ED_L				
	Coefficient	Std. error	*p*-value	R-squared
const	0.064	0.056	0.291	0.976
$SocD_L$	1.166	0.083	2.27×10^{-6}	
$SocD_{L(t-1)}$	−0.326	0.093	0.0097	
$SocD_{L(t-2)}$	0.393	0.082	0.0019	
$RE_{(t-1)}$	−0.832	0.221	0.007	
$RE_{(t-2)}$	0.695	0.208	0.0123	
M	−0.248	0.066	0.007	

Table 8. *Cont.*

Equation (2)				
Dependent variable: $SocD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	0.052	0.024	0.0841	0.996
ED_L	0.761	0.03	1.89×10^{-6}	
$ED_{L(t-1)}$	0.346	0.055	1.40×10^{-3}	
$ED_{L(t-2)}$	−0.471	0.034	3.41×10^{-5}	
RE	−0.680	0.115	2.00×10^{-3}	
$RE_{(t-1)}$	1.691	0.143	7.58×10^{-5}	
$RE_{(t-2)}$	−0.832	0.094	3.00×10^{-4}	
M	−0.133	0.037	1.63×10^{-2}	
$M_{(t-1)}$	0.327	0.045	8.00×10^{-4}	
Equation (3)				
Dependent variable: $EnvD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	1.080	0.07	4.67×10^{-6}	0.974
ED_L	−1.449	0.206	4.00×10^{-4}	
$SocD_L$	0.536	0.226	5.51×10^{-2}	
$SocD_{L(t-1)}$	−0.999	0.081	1.68×10^{-5}	
$SocD_{L(t-2)}$	−0.326	0.096	1.49×10^{-2}	
RE	0.740	0.107	5.00×10^{-4}	
$RE_{(t-2)}$	0.511	0.188	3.45×10^{-2}	
$M_{(t-2)}$	1.128	0.100	2.88×10^{-5}	
Cross-equation VCV for residuals				
	0.000156	(−0.022)	(−0.078)	
	-1.25×10^{-6}	2.02×10^{-5}	(0.020)	
	-1.38×10^{-5}	1.25×10^{-6}	0.000198	
Tests				
Breusch–Pagan test for diagonal covariance matrix				
Chi-square (3) = 0.0982414 [0.9920]				
log determinant = −28.1063				
Hansen–Sargan over-identification test				
Chi-square (1) = 20.4017 [0.0156]				
Poland				
Model 2: SUR, using observations 2008–2023 (T = 16)				

Table 8. *Cont.*

Equation (1)				
Dependent variable: ED_L				
	Coefficient	Std. error	*p*-value	R-squared
const	−0.263	0.045	0.0021	0.997
$SocD_L$	0.986	0.071	3.36×10^{-5}	
$SocD_{L(t-1)}$	0.461	0.053	0.0003	
$EnvD_{L(t-1)}$	−0.169	0.017	0.0002	
$EnvD_{L(t-2)}$	0.110	0.023	0.0048	
$RE_{(t-2)}$	−0.221	0.039	0.0023	
M	0.130	0.037	0.017	
$M_{(t-1)}$	−0.252	0.066	0.0127	
$M_{(t-2)}$	−0.11	0.043	0.0507	
Equation (2)				
Dependent variable: $SocD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	0.353	0.004	0.0001	0.999
$ED_{L(t-1)}$	−0.595	0.009	3.00×10^{-4}	
$ED_{L(t-2)}$	−0.298	0.007	5.00×10^{-4}	
$EnvD_L$	0.053	0.003	3.20×10^{-3}	
$EnvD_{L(t-1)}$	−0.047	0.003	3.10×10^{-3}	
$EnvD_{L(t-2)}$	−0.212	0.002	6.50×10^{-5}	
RE	0.608	0.005	8.07×10^{-5}	
$RE_{(t-1)}$	0.182	0.008	2.10×10^{-3}	
$RE_{(t-2)}$	−0.223	0.009	1.60×10^{-3}	
M	0.461	0.005	1.00×10^{-4}	
$M_{(t-1)}$	0.563	0.007	2.00×10^{-4}	
$M_{(t-2)}$	0.403	0.006	2.00×10^{-4}	
Equation (3)				
Dependent variable: $EnvD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	−0.565	0.186	2.90×10^{-2}	0.969
ED_L	−2.397	0.511	5.40×10^{-3}	
$ED_{L(t-1)}$	−2.542	0.535	5.10×10^{-3}	
$ED_{L(t-2)}$	−2.171	0.358	1.80×10^{-3}	
$SocD_L$	3.165	0.401	5.00×10^{-4}	
$SocD_{L(t-1)}$	1.355	0.392	1.81×10^{-2}	
$SocD_{L(t-2)}$	3.898	0.405	2.00×10^{-4}	
$RE_{(t-1)}$	−0.794	0.26	2.83×10^{-2}	
$M_{(t-2)}$	−1.532	0.318	4.80×10^{-3}	

Table 8. *Cont.*

Cross-equation VCV for residuals				
	2.61×10^{-5}	(0.915)	(0.603)	
	2.61×10^{-6}	3.11×10^{-7}	(0.238)	
	8.12×10^{-5}	3.51×10^{-6}	0.000696	
Tests				
Breusch–Pagan test for diagonal covariance matrix				
Chi-square (3) = 17.5929 [0.0005]]				
log determinant = −37.9004				
Hansen–Sargan over-identification test				
Chi-square (1) = 18.1794 [0.0331]				
Slovakia				
Model 2: SUR using observations 2008–2023 (T = 16)				
Equation (1)				
Dependent variable: ED_L				
	Coefficient	Std. error	*p*-value	R-squared
const	1.785	0.044	3.22×10^{-5}	0.997
$SocD_{L(t-2)}$	2.817	0.058	1.91×10^{-5}	
$EnvD_L$	1.147	0.030	4.09×10^{-5}	
$EnvD_{L(t-1)}$	2.203	0.055	3.40×10^{-5}	
$EnvD_{L(t-2)}$	1.979	0.052	4.09×10^{-5}	
RE	−1.477	0.041	4.63×10^{-5}	
$RE_{(t-1)}$	−3.238	0.087	4.26×10^{-5}	
$RE_{(t-2)}$	−0.147	0.022	6.80×10^{-3}	
M	−1.792	0.049	4.53×10^{-5}	
$M_{(t-1)}$	−2.514	0.065	3.83×10^{-5}	
$M_{(t-2)}$	−1.465	0.027	1.44×10^{-5}	
Equation (2)				
Dependent variable: $SocD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	0.710	0.062	2.61×10^{-5}	0.840
ED_L	−0.739	0.159	$3.50 \times 10^{+1}$	
$ED_{L(t-2)}$	0.686	0.116	1.10×10^{-3}	
$EnvD_L$	−0.366	0.053	5.00×10^{-4}	
$EnvD_{L(t-2)}$	−0.264	0.043	9.00×10^{-4}	
RE	0.405	0.071	1.30×10^{-3}	
$RE_{(t-2)}$	0.538	0.081	6.00×10^{-4}	
$M_{(t-2)}$	−0.719	0.142	2.30×10^{-3}	

Table 8. *Cont.*

Equation (3)				
Dependent variable: $EnvD_L$				
	Coefficient	Std. error	*p*-value	R-squared
const	0.881	0.323	2.32×10^{-2}	0.806
ED_L	−2.219	0.645	7.40×10^{-3}	
$ED_{L(t-2)}$	2.176	0.418	6.00×10^{-4}	
$RE_{(t-1)}$	1.514	0.302	7.00×10^{-4}	
$M_{(t-2)}$	−2.895	0.653	1.60×10^{-3}	
Cross-equation VCV for residuals				
	8.92×10^{-6}	(−0.952)	(−0.481)	
	-2.92×10^{-5}	0.000106	(0.476)	
	-9.03×10^{-5}	0.000308	0.003954	
Tests				
Breusch–Pagan test for diagonal covariance matrix				
Chi-square(3) = 19.1134 [0.0003]				
log determinant = −28.9615				
Hansen–Sargan over-identification test				
Chi-square(1) = 17.3313 [0.0438]				

Analysis of the regression coefficients indicates significant associations between all dimensions of SD_L in each of the countries studied, with the nature and strength of the effects varying between countries.

All models have a high R^2 and meet standard SUR assumptions. All OLS and SUR models used in the analysis met standard estimation assumptions, confirming their statistical validity and inferential reliability. Diagnostic tests for individual countries revealed no issues with residual autocorrelation (Durbin–Watson test, LM) or heteroscedasticity (White test), meaning that the variance of the random component is constant and the relationships between variables are not distorted by model errors. Furthermore, the Jarque–Bera test confirmed the normal distribution of residuals, which increases the reliability of the parameter significance tests used.

In the SUR multi-equation models, the Breusch–Pagan test results indicate significant interdependencies between the equations for the individual dimensions of sustainability in the logistics sector (SD_L, ED_L, $SocD_L$, $EnvD_L$). This indicates that the use of the SUR method was justified and statistically valid, as it allows for the interdependence of errors between the equations and thus increases the efficiency of parameter estimation.

High values of the coefficient of determination R^2 (0.7–0.96) confirm that the models explain the variability of the examined SD_L indicators very well, while the lack of violations of the basic regression assumptions indicates the stability and reliability of the obtained results.

In the Czech Republic, ED_L positively affects $SocD_L$ and $EnvD_L$, while *RE* reduces ED_L, and *M* has a positive effect in the current period but a negative effect in subsequent periods. In $SocD_L$, ED_L strongly supports social development, $EnvD_L$ has a negative effect, and *RE* and *M* have positive effects. In $EnvD_L$, ED_L has a positive effect, $SocD_L$ has a negative effect, *RE* has a significantly positive effect in the current and lagged periods, and *M* has a weakly positive effect.

In Hungary, ED_L positively affects $SocD_L$, while *RE* has a mixed effect on ED_L, negative with a one-period delay but positive after two periods, and M has a negative effect in the current period. In $SocD_L$, ED_L supports $SocD_L$ and $SocD_{L(t-1)}$, *RE* has a time-varying effect (negative in the current period, positive with lag) and *M* has both a negative and positive effect in subsequent periods. In $EnvD_L$, ED_L has a negative effect, $SocD_L$ has a mixed effect (negative in the lagged period), and *RE* and *M* have a positive effect in the lagged periods.

In Poland, ED_L has a mixed effect on $SocD_L$ and $EnvD_L$. In $SocD_L$, ED_L negatively affects lagged periods, while in $EnvD_L$, ED_L significantly limits environmental development. *RE* has a predominantly positive effect on $SocD_L$, although it may have a negative effect in lagged periods, while on ED_L and $EnvD_L$, the effects are mixed or negative in some lags. *M* supports ED_L, $SocD_L$, and $EnvD_L$ in most periods, although the impact may become apparent with a delay.

In Slovakia, ED_L positively influences $SocD_L$ in the lagged period but has a negative impact in the current period. $EnvD_L$ supports ED_L and is also reinforced by *RE* in the lagged period, while *M* has a mainly negative impact on ED_L and $EnvD_L$ in the short and medium term. In $SocD_L$, *RE* has a positive impact in current and lagged periods, while the impact of ED_L and *M* is revealed in lags, and $EnvD_L$ has a negative impact.

Analysis of SUR models for the Visegrad Group indicates that ED_L strongly supports $SocD_L$ and $EnvD_L$, although its environmental impact can be limited in some countries. *RE* positively impacts $SocD_L$ and $EnvD_L$ (these effects often manifest with a delay). *M* operates differently over time—in some cases, it supports all dimensions of SD_L, while in others, it can limit them (especially in the short term). The results obtained stress the importance of acknowledging the temporal dimensions of *RE* and *M*. At the same time, they indicate the need for strategic planning of energy and macroeconomic policies to support sustainable development of logistics effectively.

The countries in the Visegrad group are developing their logistics sectors towards greater sustainability, although the pace and balance of this process vary. An increase in the use of renewable energy sources is visible across the region, strengthening energy security and supporting climate change in line with EU policy. The greatest challenge remains the weak and volatile macroeconomic stability that limits development predictability. In general, the Visegrad Group has the potential to become a major hub for green and innovative logistics in Europe, provided that economic, energy, and environmental policies are better coordinated.

5. Discussion

The discussion of the results shows that both renewable energy sources and macroeconomic stability play a significant role in shaping sustainable development in countries of the logistics sector in the Visegrad Group, although their impact is not uniform over time or between countries. The results of the model estimation indicate that increasing the share of renewable energy in the energy mix promotes the development of sustainable logistics, which is consistent with previous studies that highlight the importance of the green transition in reducing transport emissions and improving the energy efficiency of entire supply chains [10,15,17,19]. This is particularly important in Poland and the Czech Republic, where the logistics sector is a key element of the economy and is strongly linked to international trade networks. The cited studies consistently indicate that integrating energy, digital, and organisational solutions lead to reduced emissions, improved transport efficiency, and increased economic competitiveness. The results obtained in this study are therefore consistent with a broader body of research confirming the importance of green transformation and logistics innovation as key drivers of development in European countries.

Macroeconomic stability is shown to be the second pillar of sector development, ensuring predictable investment conditions and fostering the modernisation of transport infrastructure and the implementation of innovative logistics solutions. In countries with higher stability, such as the Czech Republic, the correlation between macroeconomic stability and sustainable logistics development is stronger, suggesting that economic policy can enhance or weaken the potential effects of the energy transition. However, the countries with differences among the Visegrad Group indicate the need to consider local conditions. Hungary and Slovakia are characterised by a more variable impact of renewable energy sources on the logistics sector, which may be a consequence of lower investments in transport and energy infrastructure or a lower level of energy diversification. Poland, on the other hand, as the region's largest economy, reveals a strong dependence of the logistics sector on energy policy, making it particularly sensitive to the pace of the transition towards green energy.

The regression results also emphasise that the simultaneous impact of macroeconomic stability and the development of renewable energy sources is crucial for the sustainable development of logistics. This means that actions focused solely on one of these areas may not yield the expected results. For example, the dynamic development of renewable energy in the absence of macroeconomic stability can lead to investment barriers and delays in the implementation of green technologies in logistics.

Interpreting these results within the broader context of the literature reveals their consistency with previous research indicating the synergistic nature of the energy transition and economic stability [23,24,31]. At the same time, the study brings a new perspective by focusing on the logistics sector, which so far has been mainly in terms of cost efficiency or digitalisation, and less often in the context of the impact of macroeconomic and energy factors on its sustainable development.

6. Conclusions

Research clearly establishes that the development of renewable energy sources and the maintenance of macroeconomic stability are key factors that contribute to sustainable development in countries of the logistics sector of the Visegrad Group. The results of empirical analyses indicate that these two elements are mutually strengthening: the expansion of renewable energy alone is insufficient without a stable economic environment, and macroeconomic stability without investments in green energy does not translate into a lasting transformation of logistics.

Based on the results obtained, several policy conclusions can be drawn. First, the countries in the Visegrad Group should continue and accelerate investments in renewable energy sources, treating them not only as a tool for energy transformation but also as a foundation for modernising the logistics sector. Second, it is necessary to strengthen macroeconomic stability through predictable fiscal and monetary policies, which will increase the attractiveness of investments in green transport infrastructure. Third, due to the variability in performance across countries, policies should be tailored to the specific characteristics of national economies: In Poland, policy supporting technological innovation in logistics should focus primarily on the green transformation of the sector and reducing its negative environmental impact. In the Czech Republic, the priority should be strengthening the integration of renewable energy sources with the logistics infrastructure and accelerating the adoption of renewable energy solutions. Both countries should develop the digitalization and automation of logistics processes, but with different emphasis—Poland towards emission reduction, and the Czech Republic towards energy efficiency and systemic innovation. Hungary and Slovakia should focus on increasing regulatory stability and intensifying investment in renewable energy sources.

This current study expands on previous analyses by focusing on the impact of renewable energy and macroeconomic stability on the sustainable development of the logistics sector in the Visegrad Group countries. It demonstrates the synergistic effects of these factors, taking into account national differences, allowing for the formulation of practical recommendations for policymakers and logistics companies. This research offers a new perspective by integrating energy, economic, and technological aspects in the context of green logistics transformation.

The practical implications of the research are particularly important for logistics companies. The results indicate that companies operating in a stable and environmentally friendly economic environment have greater opportunities to implement innovations in low-emission transport, process automation, and supply chain digitisation. This means that cooperation between the private sector and the state—through public–private partnerships, investment support programmes, and joint research and development projects—can significantly accelerate the transformation of logistics toward sustainable development.

The countries of the Visegrad Group face the challenge of simultaneously strengthening macroeconomic stability and developing the renewable energy sector. Only their complementary impact will allow us to create lasting foundations for green and competitive logistics, capable of meeting the requirements of European climate policy and growing market expectations.

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