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# Energy Security and Sustainable Development of the Energy Sector: Comparative Analysis of the Visegrad Group Countries

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## Abstract

A sustainable energy sector is crucial for a country's stable and environmentally friendly socioeconomic development. Economic security (ES), the basis for the functioning of the state, is one of the major factors affecting the development. The objective of this article is to examine how ES influenced the sustainable development of the energy sector in the Visegrad Group countries, i.e., Poland, Slovakia, Hungary, and Czechia, over the period spanning from 2008 to 2020. To evaluate a meaningful relationship between the indicators ($p < 0.05$), we used correlation coefficients, the ordinary least squares method, and the seemingly unrelated regression model. The findings indicate that ES impacts the sustainable development of the energy sector, where positive results can be achieved by implementing coordinated macroeconomic policies. Green energy sources and renewable energy are crucial in this process.

Keywords: energy sector, sustainable development, economic security

JEL: O13, O40

# Introduction

The current development of the energy sector includes three basic pillars: economic (E), social (S), and environmental (Env) (Misztal, Kowalska, and Fajczak-Kowalska 2022). It is crucial for global sustainable development goals (SDGs) and national security (Prasad et al. 2019). Therefore, proactive steps must be taken to drive energy transformation and integrate renewable energy sources (Cergibozan 2022).

Sustainable development (SD) depends on external, geopolitical, macrosocial, technological, and internal factors related to the financial and economic situation of the energy sector (Sebestyén 2021). SD has been the subject of several theoretical and empirical analyses (Komarnicka and Murawska 2021; Misztal, Kowalska, and Fajczak-Kowalska 2022). As a rule, progress in SD is positively correlated with socioeconomic development, access to new technological solutions, and society's ecological awareness (Halkos and Gkampoura 2020; Razmjoo et al. 2021; Wahab et al. 2021).

A novelty of our paper is the study of the impact of economic security (ES) on the sustainable energy sector, with the aim of identifying SD and ES indicators in the Visegrad Group countries, i.e., Poland, Slovakia, Hungary, and Czechia. Our research contributes to the theory of SD by proposing a conceptual framework that defines the relationship between SD and the energy sector.

The main objective of our research was to determine the impact of energy security on the SD of the energy sector of the Visegrad Group countries between 2008 and 2020. The basic research hypothesis is formulated as follows:

**Economic security positively influences the sustainable development of the energy sector, though the magnitude and pathways of this effect vary significantly across Visegrad countries due to differences in macroeconomic stability, energy policy, and innovation capacity.**

This assumption results from differences in sectoral development in those countries, varying levels of innovation, and different policies for the implementation of renewable energy sources. In addition, we wanted to answer the following research questions:

1. Does sustainable development in the studied countries demonstrate positive growth dynamics?
2. What are the dynamics of economic security?
3. Does the impact of economic security on the pillars of sustainable development differ across countries, or are there similarities among them?

In our analysis, we applied correlation coefficients (Pearson's r, Spearman's rho, Goodman-Kruskal's gamma, and Kendall's tau), the ordinary least squares (OLS) method, and the seemingly unrelated regression (SUR) model.

We verified the classical OLS assumptions, including:

- Absence of multicollinearity among independent variables (via Variance Inflation Factor, VIF)
- Homoskedasticity (Breusch-Pagan test)
- Normality of residuals (Jarque-Bera test)
- No autocorrelation (Durbin-Watson statistic)

We developed original analytical indicators for ES and SD designed to assess energy policy transformations towards SD by European Union institutions.

The study comprises six parts. Part Two describes the theoretical foundations of the study and presents SD in the energy sector and ES in the Visegrad Group countries. Part Three presents the research methodology, which involves econometric models. Part Four describes in detail the results of our research, while Part Five discusses the results. The closing part contains the final conclusions and directions for future research.

Data for the analysis were obtained from Eurostat, while calculations were performed using Statistica and Gretl software.

## Literature review

### Sustainable development of the energy sector: definition and determinants

SD comprises three basic components: economic, social, and environmental (Misztal Kowalska, and Fajczak-Kowalska 2022). For enterprises, it entails conducting business in a way that not only yields specific economic and financial results but also improves working conditions and quality of work while minimizing negative environmental impacts (Silvestre and Ţîrcă 2019; Bose and Khan 2022). It also ensures the fulfillment of objectives for both current and future stakeholders (Bogołębska, Feder-Sempach, and Stawasz-Grabowska 2019; Zhou et al. 2022; Wang, Chen, and Li 2022). It enables current development without compromising the potential for future growth (Colbert and Kurucz 2007), while also promoting shared value (Porter and Kramer 2007). The term "sustainable development of enterprises" is also defined as a process that reduces resource consumption while generating added value for customers and business partners (Giovannoni and Fabietti 2013; Silvestre and Ţîrcă 2019; Thacker et al. 2019).

In the energy sector, SD considers socioeconomic issues (Lu et al. 2019; Kamran, Fazal, and Mudassar 2020). Its main objective is to meet market demands, safeguard national energy security, and protect the natural environment (Valentine 2011; Gong 2022). This sector plays a key role in ensuring stable and sustainable economic growth, and a key manifestation of progress is a change in the country's energy balance towards renewable energy sources (Stern 2011; Zahoor, Khan, and Hou 2022).

SD in the energy sector is influenced by a variety of internal and external factors. Internal factors encompass financial and non-financial resources, economic performance, business development models, and strategic approaches. External factors include the macroeconomic situation, social and geopolitical conditions, market structure and the possibilities of implementing new technologies (Pieloch-Babiarz, Misztal, and Kowalska 2021; Kuzma and Sehnem 2022; Khan, Khurshid, and Cifuentes-Faura 2023). ES is also a factor that affects SD across all economic sectors.

## Economic security

ES is a key component of national security. It is a heterogeneous, complex, and multithreaded concept that largely shapes quality-of-life standards for entire social groups, individually, locally, and internationally (Koval et al. 2019; Likhonosova et al. 2023).

ES forms the foundation of the state and is closely linked to its economy and society. It encompasses various areas of economic life and involves the complicated structure of the economic system and its environment. However, it is mainly associated with the efficiency and capacity of the economy. ES comprises aspects such as economic prosperity, high living standards, and free access to commodity and financial markets (Cable 1995; Hobela and Melnyk 2021).

ES addresses the risks that could affect prosperity, unrestricted market access, financial stability, and the availability of natural resources while also safeguarding the state's position and continued development. It is associated with all the elements of the state, including its territory, society, and government. In territorial terms, ES means maintaining territorial cohesion as an important factor in controlling the economy. For society, it translates into stability, improved living conditions, and a better quality of life. In relation to the state and its government, ES combines the independence of both internal and foreign policy (Akimov et al. 2020; Armstrong and Urata 2021).

ES is often defined as involving three components: financial aspects, raw materials, and food (Dźwigoł et al. 2019; Lee, Xing, and Lee 2022; Štreimikienė et al. 2022). It is, therefore, the basis for the functioning of the state, ensuring sustainable economic growth, increasing employment and investment, balanced fiscal relations, and positive foreign trade. However, ES can only be built upon transparent and stable economic goals, as they are the cornerstone of the development programming process.

## Economic security and sustainable energy development in the Visegrad countries: an overview of previous research results

Energy security refers to the state of the economy that ensures current and future energy and fuel demands are met in a technically and economically viable manner while complying with environmental protection requirements. The continuity of electricity supply is an indispensable condition for the existence and continuous development of modern societies (Lee, Xing, and Lee 2022).

A country's energy security is influenced by numerous elements, including the availability of domestic energy resources, the origin and degree of diversification of supply sources, the amount of accumulated reserves, the level of development of renewable energy sources, the form of ownership of the supply system enterprises, and the energy sector as a whole (Alper and Oguz 2016; Ahmad et al. 2022; Marra and Colantonio 2022).

The energy sector's SD occurs within well-defined socioeconomic conditions. Energy security and its sustainable growth are essential components of overall ES. On the other hand, general ES influences decisions made within the energy sector (Siksnelyte et al. 2018; Hosseini 2020; Heffron et al. 2021; Starzyńska and Kuna-Marszałek 2023).

In the Visegrad Group countries, the energy sector is largely based on fossil fuels, although recently, there has been a gradual shift towards renewable energy sources. A key challenge for these countries is the need to make new investments in renewable energy sources, which requires substantial financial outlays. This highlights the importance of ensuring stable financial flows for investments in green technologies in the energy sector (Dorożyński and Kuna-Marszałek 2016; Kochanek 2021; Uğurlu 2022).

To the best of our knowledge, research on the interdependence between ES and SD in the energy sector is rudimentary and incomplete. Therefore, our study contributes to the development of knowledge in this area. This is especially important in the context of the current, dynamically changing geopolitical situation.

# Research methodology

The aim of this research was to examine how ES influences the stable development of the energy sector in the Visegrad Group nations (Poland, Slovakia, Hungary, and Czechia) from 2008 to 2020. We analyzed those countries due to their shared political transformation and accession to the European Union at the beginning of the 21st century. Moreover, their energy sectors are based on fossil fuels and require reforms to implement green solutions. The economies of these countries are diverse, characterized by different levels of investment and varying impacts of macroeconomic conditions on energy sector development. Socioeconomic and environmental protection policies are implemented in different ways in each country.

In this context, we formulated the main research hypothesis as follows:

Economic security positively influences the sustainable development of the energy sector, though the magnitude and pathways of this effect vary significantly across the Visegrad countries due to differences in macroeconomic stability, energy policies, and innovation capacity.

The analyses included various elements.

1. We created an index for the E, S, Env, and SD dimensions of the energy sector. The construction of this index involved a number of steps.
2. Collecting analytical indicators and grouping them into the three pillars of SD, including:
   - Economic Dimension (E):
     - Positive indicators: Gross operating surplus (million EUR), investment rate (%), total purchases of goods and services (million EUR), number of companies, gross premiums written (million EUR), production value (million euros), value added at factor cost (million EUR), and gross investment in tangible assets (million EUR).
     - Negative indicator: cost-level index for total activity (%).
   - Social Dimension (S):
     - Positive indicators: Workforce size, expenditure on employee training and courses, social security costs (million EUR), gross value added per employee (thousand EUR), total wages and salaries (million EUR), investment per employee (thousand EUR), employer's social charges as a percentage of total personnel costs (%), and apparent labor productivity.
     - Negative indicators: workplace accident rates, share of personnel costs in total production (%), and total personnel costs (million EUR).
   - Environmental Dimension (Env):
     - Negative indicators: ammonia emissions, hydrofluorocarbons ($CO_2$ equivalent), methane emissions, sulfur oxides ($SO_2$ equivalent), carbon monoxide, nitrous oxide, and carbon dioxide.
       a) Transformation of the explanatory variables into integrated variables using the following formulas:

For stimulants:

$$\mathrm{xsnorm}_{ij} = \sum_{i=1}^{n} \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}$$

For destimulants:

$$\mathrm{xdnorm}_{ij} = \sum_{i=1}^{n} \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (1)$$

where:
$xsnorm_{ij}; xdnorm_{ij}$ – standardized value of the j-th in year i;
$x_{ij}$ – diagnostic indicator for year i;

b) Application of the following equation to construct the SD:

$$SD = \left( \frac{1}{nE} \sum_{j=1}^{nE} xnormij + \frac{1}{nS} \sum_{j=1}^{nS} xnormij + \frac{1}{nEnv} \sum_{j=1}^{nEnv} xnormij \right)/3; SD \in \left[0; 1\right], \quad (2)$$

where:
$SD_i$ – aggregated variable for year i.
xnormij – normalized value of the *j*-th diagnostic indicator for country (or year) *i*,
nE, nS, nEnv – number of diagnostic indicators in the economic, social, and environmental dimensions.

3. We created ES indicators based on formula (1). We used the following stimulants: gross domestic pct at market prices, the external balance of goods and services, wages and salaries, GERD bsector of performance, and destimulants, including the unemployment rate and HICP.

4. To assess the strength and direction of the linear relationship between SD and ES, we used Pearson's r, Spearman's rho, Goodman–Kruskal's gamma, and Kendall's tau correlation coefficients.

5. We applied the OLS method to estimate the model, represented by the following equation:

$$SD = \widehat{\beta}_0 + \widehat{\beta}_1 \cdot ES + \varepsilon_i, \quad (3)$$

where:
$\beta_0$ – intercept term,
$\beta_1$ – the slope;
$\varepsilon_i$ – residual for the i-th observation;
i – observation index.

The OLS model was specified as a simple linear regression, without lagged independent variables, as the short time dimension of the panel (2008–2020) did not justify a dynamic specification.

6. We developed a structural equation model and estimated it using the SUR method. Although the SUR model assumes the homogeneity of regressors, it was applied here to capture contemporaneous correlations between the error terms of the sustainability dimensions (economic, social, and environmental). Mutual interdependencies among these dimensions may introduce some degree of endogeneity. While this approach provides useful approximations, it constitutes a limitation of the current study. Future research should consider the application of more advanced estimation techniques, such

as Three-Stage Least Squares (3SLS), Structural Equation Modeling (SEM), or Panel Vector Autoregression (PVAR), to fully address potential endogeneity issues.

$$\begin{cases} E = \widehat{\beta}_0 + \widehat{\beta}_1 ES_i + \widehat{\beta}_2 ES_{(t-1)i} + \widehat{\beta}_3 S + \widehat{\beta}_4 Env + e_i \\ S = \widehat{\beta}_0 + \widehat{\beta}_1 ES_i + \widehat{\beta}_2 ES_{(t-1)i} + \widehat{\beta}_3 E + \widehat{\beta}_4 Env + e_i \\ Env = \widehat{\beta}_0 + \widehat{\beta}_1 ES_i + \widehat{\beta}_2 ES_{(t-1)i} + \widehat{\beta}_3 E + \widehat{\beta}_4 S + e_i \end{cases} \quad (4)$$

# Results

The first stage of the study involved calculating synthetic indicators that described the degree of ES and the level of SD in the Visegrad Group countries between 2008 and 2020. Detailed data on the indicators discussed are presented in Table 1. All countries showed a positive trend for both indicators in the studied period, meaning that the policies implemented by energy companies for SD and ES were efficient and effective.

Poland exhibited the highest SD dynamics (SD = 0.0348 time + 0.2063; $R^2$ = 0.8924) while Hungary showed the lowest (SD = 0.0097 time + 0.4252; $R^2$ = 0.821). Slovakia recorded the highest average SD level (mean = 0.51; Sd = 0.09), while Czechia and Poland had the lowest (mean = 0.45; Sd = 0.07 in Czechia and Sd = 0.14 in Poland). The maximum level of SD was identified in Poland (0.73 in 2020), and the minimum was in Czechia (0.27 in 2008).

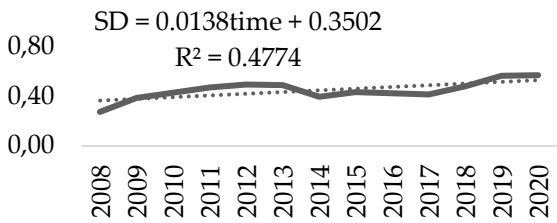
During this period, Poland experienced the highest dynamics of ES (ES = 0.0680 time – 0.0194; $R^2$ = 0.9576), while Slovakia had the lowest (ES = 0.0585 time + 0.0897; $R^2$ = 0.9341). Poland demonstrated the highest average ES level (mean = 0.60; Sd = 0.28), while Hungary had the lowest (mean = 0.46; Sd = 0.25). The maximum ES level was identified in Czechia (0.92, 2019), while the minimum level (0.12) was registered in both Poland (in 2009) and Slovakia (in 2008).

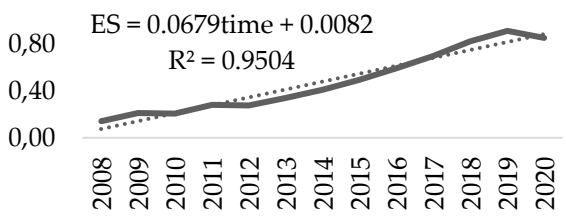
Table 1. The sustainable development and economic security indices of energy companies in the Visegrad Group, 2008–2020

| Energy Companies in the Visegrad Group | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Czechia | | | | | | | | | | | | | |
| Indicator | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
| SD | 0.27 | 0.38 | 0.43 | 0.47 | 0.49 | 0.49 | 0.40 | 0.43 | 0.42 | 0.41 | 0.48 | 0.56 | 0.57 |
| ES | 0.14 | 0.21 | 0.21 | 0.28 | 0.28 | 0.34 | 0.41 | 0.50 | 0.60 | 0.70 | 0.83 | 0.92 | 0.86 |

| Indicator | Descriptive statistics | | | | |
|---|---|---|---|---|---|
| | Mean | Sd | Median | Max | Min |
| SD | 0.45 | 0.07 | 0.43 | 0.57 | 0.27 |
| ES | 0.48 | 0.26 | 0.41 | 0.92 | 0.14 |

**Energy Companies in the Visegrad Group**

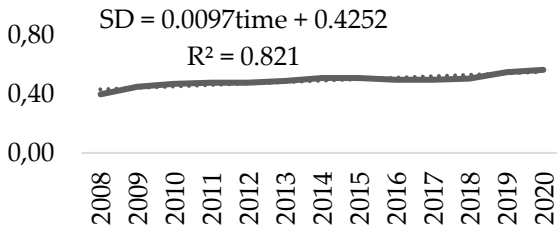


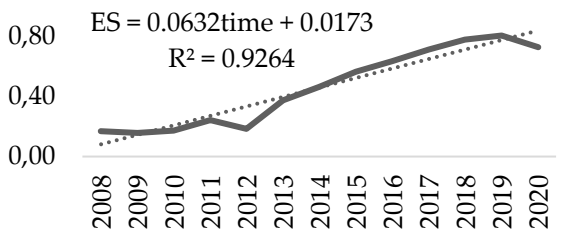




**Hungary**

| Indicator | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SD | 0.40 | 0.45 | 0.47 | 0.48 | 0.48 | 0.49 | 0.51 | 0.51 | 0.50 | 0.50 | 0.51 | 0.55 | 0.57 |
| ES | 0.17 | 0.16 | 0.17 | 0.24 | 0.18 | 0.37 | 0.46 | 0.57 | 0.63 | 0.71 | 0.78 | 0.80 | 0.73 |

| Indicator | Descriptive statistics | | | | |
|---|---|---|---|---|---|
| | Mean | Sd | Median | Max | Min |
| SD | 0.49 | 0.04 | 0.50 | 0.57 | 0.40 |
| ES | 0.46 | 0.25 | 0.46 | 0.80 | 0.16 |

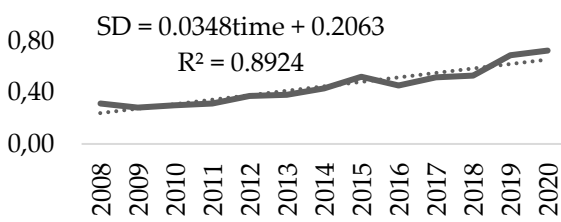


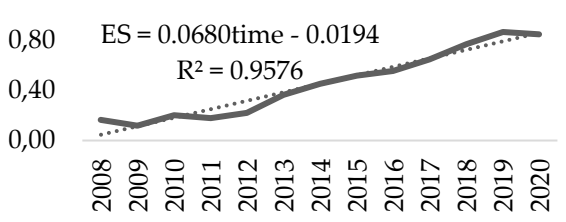




**Poland**

| Indicator | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SD | 0.31 | 0.28 | 0.30 | 0.32 | 0.37 | 0.38 | 0.43 | 0.52 | 0.45 | 0.52 | 0.53 | 0.69 | 0.73 |
| ES | 0.16 | 0.12 | 0.20 | 0.18 | 0.22 | 0.37 | 0.45 | 0.52 | 0.56 | 0.65 | 0.77 | 0.87 | 0.85 |

| Indicator | Descriptive statistics | | | | |
|---|---|---|---|---|---|
| | Mean | Sd | Median | Max | Min |
| SD | 0.45 | 0.14 | 0.43 | 0.73 | 0.28 |
| ES | 0.60 | 0.26 | 0.45 | 0.87 | 0.12 |



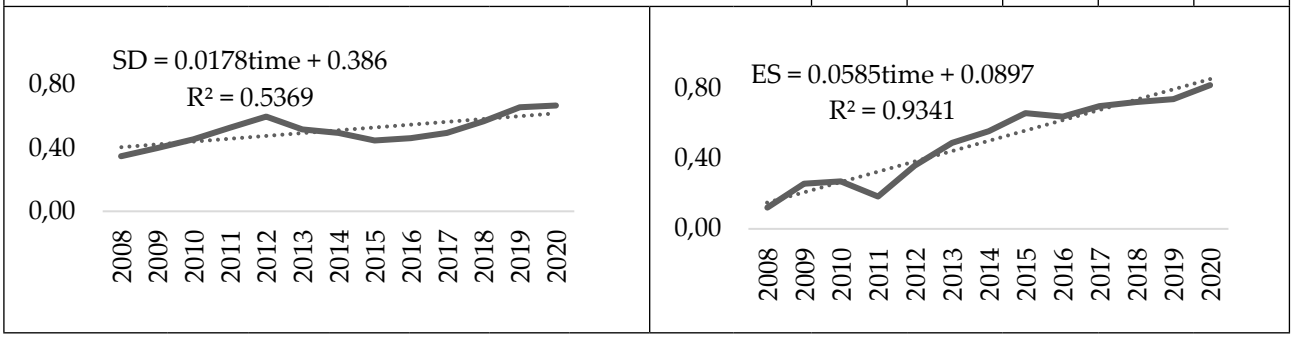




**Slovakia**

| Indicator | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| Energy Companies in the Visegrad Group | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SD | 0.35 | 0.40 | 0.45 | 0.53 | 0.60 | 0.52 | 0.50 | 0.45 | 0.46 | 0.49 | 0.57 | 0.66 | 0.67 |
| ES | 0.12 | 0.26 | 0.27 | 0.18 | 0.36 | 0.49 | 0.55 | 0.66 | 0.64 | 0.70 | 0.72 | 0.74 | 0.82 |

| Indicator | Descriptive statistics | | | | |
|---|---|---|---|---|---|
| | Mean | Sd | Median | Max | Min |
| SD | 0.51 | 0.09 | 0.50 | 0.67 | 0.35 |
| ES | 0.50 | 0.23 | 0.55 | 0.82 | 0.12 |




Source: own study based on Eurostat (n.d.).

Figure 1 presents the Pearson's r correlation coefficients between SD and ES in the Visegrad Group from 2008 to 2020. In all countries, the correlation coefficients between the variables were significant ($p < 0.05$). In all countries, the relationship between SD and ES was positive (the ES indicator of energy companies increased together with their SD indicator). The strength of the correlation coefficients varied across countries. The strongest correlation was observed in Poland (0.96; very strong), while the weakest was recorded in Slovakia (0.60; moderate).

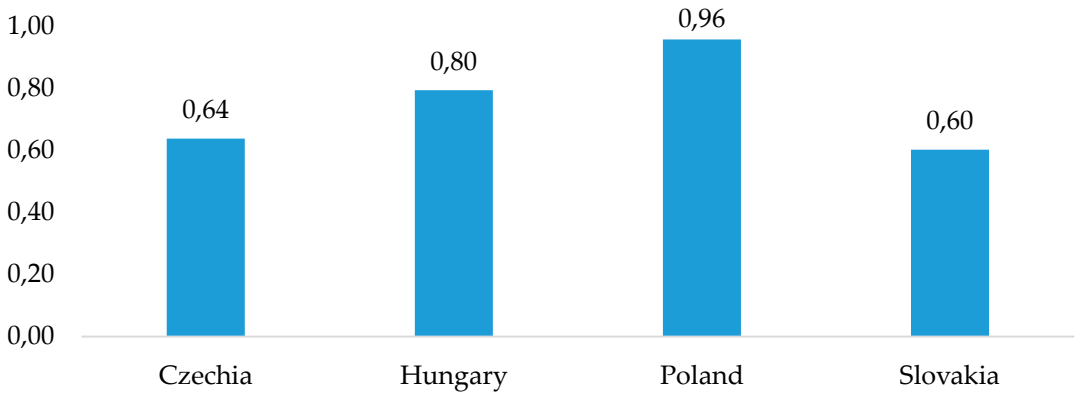



Figure 1. Pearson's correlation coefficients between sustainable development indicators and energy companies' economic security in the Visegrad Group, 2008 to 2020, $p$ <0.05 ($n$ = 13)
Source: own study based on Eurostat n.d.

Table 2 shows the results of OLS regressions that analyze the relationship between SD and ES in the Visegrad Group from 2008 to 2020. The OLS estimations confirmed the absence of collinearity, autocorrelation, heteroskedasticity, and deviations from the normal distribution of variables. They also indicated that ES had a significant impact on SD ($p < 0.05$). The relationship between the variables was positive in all countries but varied in strength. The strongest positive correlation was observed in Poland (0.5091), while the weakest was recorded in Hungary

(0.1302). The coefficient determination ranged from 0.3638 in Slovakia (indicating an unsatisfactory model fit) to 0.9185 in Poland (a very good fit to the model data).

Table 2. The results of the OLS regressions in the Visegrad Group, 2008 to 2020 ($p < 0.05$): $SD = \alpha_0 + \alpha_1 \cdot ES + \varepsilon_i$

| Country | Independent variable | Coefficient | Std. error | *p*-value | R2 |
|---|---|---|---|---|---|
| Czechia | const | 0.3582 | 0.0365 | < 0.0001 | 0.4086 |
| | ES | 0.1829 | 0.0663 | 0.0187 | |
| Hungary | const | 0.4336 | 0.0156 | < 0.0001 | 0.6320 |
| | ES | 0.1302 | 0.0299 | 0.0012 | |
| Poland | const | 0.2180 | 0.0240 | < 0.0001 | 0.9185 |
| | ES | 0.5091 | 0.0457 | < 0.0001 | |
| Slovakia | const | 0.3898 | 0.0529 | < 0.0001 | 0.3638 |
| | ES | 0.2418 | 0.0964 | 0.0291 | |

Source: own study based on Eurostat (n.d.).

Table 3 presents the results of the SUR estimation, which examines the relationships between E, S, Env and ES, E, S, Env (depending on the model specification) in the Visegrad Group from 2008 to 2020. The impact of the examined factors on E, S, and Env varied across countries. In Poland and Slovakia, ES affected all three dimensions. In Czechia, it mainly affected Env, while in Hungary influenced S and Env.

The relationships between the variables were both positive and negative, with varying degrees of strength. The strongest positive relationship was recorded in Slovakia (2.7053, between E and S), while the weakest positive association was observed in Poland (0.1535, between S and ES). Conversely, the most pronounced negative relationship was found in Czechia (2.9984, between Env and S), while the weakest negative relationship was observed in Slovakia (0.1607, between S and ES).

Table 3. Results of the SUR regressions in the Visegrad Group, 2008 to 2020 ($p$ < 0.05):

$$\begin{cases} E = \propto_0 + \propto_1 \cdot ES_i + \propto_2 \cdot S + \propto_3 \cdot Env + \varepsilon_i \\ S = \propto_0 + \propto_1 \cdot ES_i + \propto_2 \cdot E + \propto_3 \cdot Env + \varepsilon_i \\ Env = \propto_0 + \propto_1 \cdot ES_i + \propto_2 \cdot E + \propto_3 \cdot S + \varepsilon_i \end{cases}$$

| Country | Dependent variable | Independent variable | Coefficient | Std. error | *p*-value | R2 |
|---|---|---|---|---|---|---|
| Czechia | E | const | −0.7816 | 0.0957 | 9.82E-06 | 0.8708 |
| | | S | 2.3324 | 0.1688 | 7.70E-08 | |
| | | Env | 0.5082 | 0.0900 | 0.0002 | |
| | S | const | 0.3365 | 0.0229 | 4.23E-08 | 0.8981 |
| | | E | 0.4269 | 0.0309 | 7.70E-08 | |
| | | Env | −0.2190 | 0.0360 | 0.0001 | |
| | Env | const | 1.1296 | 0.1155 | 4.31E-06 | 0.8678 |
| | | ES | 0.2222 | 0.0572 | 0.0037 | |
| | | E | 1.1513 | 0.1987 | 0.0003 | |
| | | S | −2.9984 | 0.4079 | 4.32E-05 | |
| Hungary | E | const | 1.4678 | 0.1479 | 1.70E-06 | 0.7944 |
| | | S | −1.5137 | 0.3073 | 0.0006 | |
| | | Env | −0.6212 | 0.0728 | 6.66E-06 | |
| | S | const | 0.6301 | 0.0380 | 1.32E-08 | 0.5886 |
| | | ES | −0.1905 | 0.0357 | 0.0003 | |
| | | E | −0.2631 | 0.0606 | 0.0015 | |
| | Env | const | 0.7761 | 0.0873 | 4.63E-06 | 0.9099 |
| | | ES | 0.5013 | 0.0827 | 0.0001 | |
| | | E | −0.8883 | 0.1396 | 8.21E-05 | |
| Poland | E | const | 0.1262 | 0.0514 | 0.0319 | 0.777 |
| | | ES | 0.6596 | 0.0980 | 3.24E-05 | |
| | S | const | 0.3906 | 0.0137 | 1.17E-11 | 0.7265 |
| | | ES | 0.1535 | 0.0261 | 0.0001 | |
| | Env | const | 0.1371 | 0.0487 | 0.0167 | 0.8203 |
| | | ES | 0.7142 | 0.0987 | 9.32E-06 | |

| Country | Dependent variable | Independent variable | Coefficient | Std. error | *p*-value | R2 |
|---|---|---|---|---|---|---|
| Slovakia | E | const | –1.0550 | 0.1787 | 0.0002 | 0.6983 |
| | | ES | 0.4080 | 0.0962 | 0.0017 | |
| | | S | 2.7053 | 0.3064 | 4.91E-06 | |
| | S | const | 0.4050 | 0.0245 | 1.37E-08 | 0.8035 |
| | | ES | –0.1607 | 0.0908 | 0.0006 | |
| | | E | 0.3376 | 0.0379 | 4.53E-06 | |
| | Env | const | 0.1376 | 0.0607 | 0.0448 | 0.8270 |
| | | ES | 0.8737 | 0.1108 | 7.51E-06 | |

Source: own study based on Eurostat (n.d.).

The coefficient of determination ranged from 0.5886 (in Hungary for S, signifying a weak fit to the model data) to 0.9099 (also in Hungary, but for Env; a very good fit).

## Discussion

The development of the sustainable energy sector is a key issue for the Visegrad Group countries, as it is strongly related to national security and constitutes the basis for sustainable socioeconomic development (Silvestre and Ţîrcă 2019; Wang, Chen, and Li 2022; Zhou et al. 2022).

We recorded a positive increase in the Sustainable Development Index and ES in the four countries, which is consistent with Siksnelyte et al. (2018), Kochanek (2021), Misztal, Kowalska, and Fajczak-Kowalska (2022), and Uğurlu (2022). However, this development was marked by slight fluctuations, which can be attributed to negative developments stemming from the financial crisis and the situation in the energy raw material market.

We confirmed the main research hypothesis, as ES demonstrated a statistically significant positive impact on SD in all four countries, although the strength of this influence varied. This variation may have resulted from different policies implemented by the countries, different approaches to environmental protection and renewable energy sources, and the structure and susceptibility to external conditions of each economy (Heffron et al. 2021).

In response to the first research question, the dynamics of the Sustainable Development Index showed a positive trend in all countries. The highest growth was observed in Poland, while the lowest was recorded in Hungary. The SD of the energy sector is particularly crucial for the Polish economy, as the adoption of innovative technologies will help the country achieve ambitious goals and challenges in this area (Cable 1995; Kochanek 2021). Hungary, on the other hand, remains highly dependent on energy imports from Russia, necessitating a comprehensive system of reforms to improve energy security and sustainability.

ES indicators are growing much faster than those for SD. The highest dynamics level was recorded in Czechia and Poland, while the lowest was in Slovakia. It is notable how these countries gradually emerged from the financial crisis through macroeconomic, fiscal, and monetary

policies. The impact of ES on the three pillars of sustainability varied. In Czechia, ES only affected Env. In Hungary, it affected S and Env, while in Poland and Slovakia, it affected E, S, and Env. The results of the SUR estimation indicate that ES is extremely important for SD in Poland and Slovakia, which may suggest that the sector is highly dependent on macroeconomic policy. On the other hand, in Czechia, ES affected only environmental aspects, and there was a large interdependence between the pillars of SD. This may mean that the internal situation in the sector is of vital importance for its SD.

The theoretical implications of this analysis include the development of an original conceptual framework that links ES with sustainable energy development. It contributes to the broader economic and sustainability literature by highlighting the role of macroeconomic stability in fostering green transitions. The findings support existing theories of economic resilience and SD while providing new insights into the specific dynamics within the Visegrad Group countries.

From an empirical perspective, this study comprehensively assesses the interplay between ES and SD, using robust econometric techniques, such as OLS and SUR models. The results validate the importance of macroeconomic indicators in shaping sustainability outcomes, reinforcing the need for data-driven policymaking. Furthermore, empirical evidence can be a reference point for future studies that explore similar relationships in other regions.

These findings have significant practical implications for policymakers, business leaders, and stakeholders in the energy sector. Governments can employ them to design policies that balance ES and environmental goals. Businesses operating in the energy sector can use the results to align their investment strategies with national and regional sustainability priorities. Future research should focus on expanding the scope to include additional economic and social dimensions and offer a more holistic understanding of the sustainability – economic security nexus.

In our research, we used a deliberately selected custom set of indicators for analysis, which may limit the inference process involving the existing interdependencies.

From a theoretical perspective, the study introduces original definitions of SD in the energy sector and ES. Furthermore, it presents a novel approach to the indicator-based assessment of these phenomena and develops impact models that illustrate the relationship between ES and SD. These contributions expand the existing body of knowledge and provide a foundation for further research in this field.

Practical implications may provide support in decision-making in energy sector companies.

## Conclusions

The analysis of the Visegrad Group countries confirms that the sustainable development of the energy sector and economic security are closely linked and show positive growth trends. The results indicate that ES has a significant impact on the sustainability of the energy sector, although the strength and direction of this impact vary from country to country. This

differentiation comes from varied national energy policies, the level of investment in renewable energy sources, and macroeconomic conditions.

Poland recorded the highest increase in sustainability indicators, which points to the effectiveness of their economic policies and investments in green energy. Hungary, on the other hand, showed the lowest growth dynamics, which underlines the need for further reforms and diversification of energy sources. Czechia and Slovakia exhibited moderate but stable growth in both SD and ES.

From a macroeconomic perspective, ES factors such as GDP growth, foreign trade balances, and wage levels contribute positively to SD, while higher unemployment rates and inflation exert a negative influence. The SUR estimation results suggest that ES affects all three SD pillars in Poland and Slovakia. In Czechia, it mainly affects ecological aspects, while in Hungary, it impacts social and environmental issues.

The results underscore the importance of coordinated macroeconomic policies to ensure the long-term sustainability of the energy sector. Reinforcing financial stability, supporting investments in renewables, and implementing policies that increase resilience in the labor market are key steps toward energy security and sustainability.

In conclusion, the energy sector in the Visegrad Group countries is undergoing a positive transformation towards sustainable development. However, to reduce existing disparities and accelerate the transition towards a greener and safer energy future, targeted policies, strategic investments, and innovation-based reforms are needed.

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## Bezpieczeństwo energetyczne i zrównoważony rozwój sektora energetycznego – analiza na przykładzie krajów Grupy Wyszehradzkiej

Zrównoważony rozwój sektora energetycznego ma kluczowe znaczenie dla stabilnego i zrównoważonego rozwoju społeczno-ekonomicznego kraju, w harmonii z ochroną środowiska naturalnego. Jednym z czynników wpływających na jego poziom jest bezpieczeństwo ekonomiczne, które jest podstawą funkcjonowania państwa. Głównym celem artykułu jest ocena wpływu bezpieczeństwa ekonomicznego na zrównoważony rozwój sektora energetycznego w krajach Grupy Wyszehradzkiej, czyli w Czechach, na Węgrzech, w Polsce i na Słowacji, w latach 2008–2020. Aby ocenić statystycznie istotną zależność między wskaźnikami ($p < 0,05$), wykorzystano współczynniki korelacji, metodę najmniejszych kwadratów oraz model SUR. Wyniki badań wskazują, że bezpieczeństwo ekonomiczne ma wpływ na zrównoważony rozwój sektora energetycznego. Zaleca się koordynację polityki makroekonomicznej w celu osiągnięcia pozytywnych rezultatów w sektorze energetycznym. Energia odnawialna i zielone źródła energii mogą odegrać tutaj kluczową rolę.

Słowa kluczowe: sektor energetyczny, zrównoważony rozwój, bezpieczeństwo ekonomiczne