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Assessing the long-term asymmetric relationship between energy consumption and CO\textsubscript{2} emissions: Evidence from the Visegrad Group countries

Błażej Suproń\textsuperscript{1}

Abstract

This study investigates the impact of renewable (REW) and non-renewable (NREW) energy usage, along with economic growth (GDP), on carbon dioxide (CO\textsubscript{2}) emissions in the Visegrad countries, which rely heavily on traditional energy sources. Using data from 1991 to 2021, the analysis employs a panel asymmetric regression with Driscoll-Kraay and FGLS standard errors. The latent cointegration test reveals long-term relationships with asymmetry among the variables. Real GDP fluctuations exhibit a negative impact on CO\textsubscript{2} emissions for both positive and negative shocks. A reduction in conventional energy source consumption leads to a greater CO\textsubscript{2} emission reduction, confirming asymmetry. Conversely, an increase in consumption positively impacts CO\textsubscript{2} reduction. However, non-conventional energy sources show no asymmetries. The OLS-based model proposed by Driscoll-Kraay showed reduced standard errors, but lower significance in the estimated parameters compared to the FGLS model. The findings recommend a sustainable energy transition for Visegrad countries by eliminating traditional sources and promoting renewable resources.

Keywords

• CO\textsubscript{2} emissions
• renewable energy
• asymmetric causality
• energy transition
• Visegrad Group
• asymmetric panel data

JEL codes: C32, C33, Q40, Q43

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Introduction

At the 2015 Paris Conference, where climate change and global warming were discussed, the international community adopted the goal of concerted action to reduce greenhouse gases, including carbon dioxide. The main task emerging from the conference, as well as from subsequent events to lower global temperatures, was the need for an energy transition to low- and zero-emission sources (Flanker, 2016). Consequently, the energy transition has become a major challenge for both developed and developing countries in recent years (Pastukhova & Westphal, 2020). Meeting climate targets requires a change in the structure of energy production through significant financial investments. At the same time, this should be integrated into the pursuit of sustainable development, which will ensure existing or better economic living standards (Coy et al., 2021).

Many studies point to excessive CO$_2$ emissions from the burning of fossil fuels as a direct cause of global warming (Zoundi, 2017). Due to their large coal and lignite resources, a significant proportion of economies obtain their energy mainly from the combustion of these raw materials, thus contributing to environmental pollution (Antonakakis et al., 2017). Abandoning fossil fuels through the energy transition will therefore have a direct impact on economic development and pose a significant challenge for countries whose economies rely on cheap energy from coal combustion (Inglesi-Lotz & Dogan, 2018).

The ‘Fit For 55’ package adopted by the European Union in 2021, through which Europe aims to achieve climate neutrality by 2050, represents a further step in the fight against global warming. At the same time, this comprehensive package of reforms will have different social and economic impacts in different member states. The effects of Fit for 55 will differ from country to country, due to differences in energy mix and natural resources (LaBelle et al., 2022). Central European countries such as the Czech Republic, Hungary, Poland and Slovakia, which make up the Visegrad Group (V4) could experience very severe economic impacts of achieving climate neutrality due to their production structure and fossil fuel-based energy sector (Ambroziak et al., 2021).

This study aims to explore the relationship between renewable and non-renewable energy consumption, economic growth and CO$_2$ emissions in the
Visegrad countries using asymmetric panel econometric models. It also aims to determine whether there are any asymmetric effects of energy consumption and economic growth on CO\(_2\) emissions. Additionally, the study investigates the impact of long-run shocks on CO\(_2\) emissions in economies undergoing an energy transition. The text examines whether decreasing non-renewable energy usage and increasing renewable energy usage can lower CO\(_2\) emissions while sustaining economic growth. It analyses the effects of positive and negative long-term economic shocks on CO\(_2\) emissions in the countries under study.

The results can guide the harmonisation of climate and economic policies. The use of novel research methods can produce more accurate evidence. The study synthesises the methodology used in previous research on asymmetric relationships in environmental economics. Econometric techniques, including cointegration analysis for asymmetrical time series and data, modelling using the panel FGLS method, and testing for asymmetrical causality were employed.

Given these considerations, this study aims to fill the gap in the practical application of asymmetric panel econometric models by explaining how renewable and non-renewable energy consumption and economic growth affect CO\(_2\) emissions in the Visegrad countries. In addition, the study synthesises the methodology used in previous research on asymmetric relationships in environmental economics. The research applied econometric techniques, including cointegration analysis for asymmetrical time series and data, modelling using the panel FGLS method, and testing for asymmetrical causality.

While there is extensive literature on the relationship between energy consumption, economic growth and CO\(_2\) emissions, there is still a lack of research focusing specifically on the Visegrad countries, especially using asymmetric econometric models. The V4 countries are a particular example of a successful transition from centrally planned to market economies. They are also a model example of the economic success of European integration.

These countries are also playing an increasingly important economic role in Europe, becoming the site of many global economic investments (Brodny & Tutak, 2021). The issue of ensuring climate-neutral energy security is of great importance, especially in the “New” EU countries, where the energy transition began later than in the rest of the countries (the so-called Old EU. The Visegrad countries provide insights into the complex dynamics of energy transition. The example of the Visegrad countries can be used to draw conclusions about other countries that will one day embark on the path of economic integration, such as Ukraine and the Balkan countries, as well as countries pursuing a sustainable energy transition (Dzikuć et al., 2021).

The article is organised as follows: Section 1 reviews the recent empirical literature; Section 2 presents the range of data used and the methodology; Section 3 contains the results of the empirical analysis. The final part summarises the results of the study.
1. Literature review

The general basis for all considerations of the systematic and asymmetric determinants of CO$_2$ is the research on the Environmental Kuznets curve (EKC), which assumed a relationship between CO$_2$, energy production and economic growth (Apergis & Ozturk, 2015). In subsequent stages, other variables were added to the original model, such as renewable and non-renewable energy consumption (Adedoyin et al., 2021), urbanisation (Ahmad et al., 2021), industry (Rahman & Kashem, 2017), taxation and innovation (Sadiq et al., 2023), and the technical armament of labour (Alvarado et al., 2021). However, the vast majority of ECC-related studies in the European Union and other regions cite energy consumption as the main cause of environmental pollution (Al-mulali et al., 2014; Litavcová & Chovancová, 2021; Muço et al., 2021). The studies indicate that an increase in coal, electricity and oil usage leads to higher carbon dioxide emissions, while a reduction in coal, electricity, gas and oil usage results in lower carbon dioxide emissions in the long run (Abbasi et al., 2021; Adedoyin et al., 2021; Ito, 2017) among others. It is therefore essential to identify such factors that may play a constructive role in economic growth. In doing so, this study investigates the determinants of economic growth in Pakistan from 1972 to 2018. The dynamic autoregressive distributed lag (ARDL).

Additionally, the use of renewable energy has been found to reduce CO$_2$ emissions in the European Union region both in the short and long run (Azam et al., 2021; Deka et al., 2023; Grodzicki & Jankiewicz, 2022) panel unit root tests, panel heterogeneous co-integration method, panel Fully Modified Ordinary Least Square and the Granger causality method are employed. The primary outcomes of this study are as follows: (1. It is also observed that an increase in the share of renewable energy use leads to fewer CO$_2$ emissions (Rasheed et al., 2022). Most research indicated a negative, mostly U-shaped relationship between renewable energy consumption and CO$_2$ reduction, whether for Asian countries (Muhammad & Khan, 2019) energy use, CO$_2$ emissions and capital role in the economic growth. This study applies generalized method of moments (GMM, African (Inglesi-Lotz & Dogan, 2018), OECD (Bilgili et al., 2016), the European Union (Muço et al., 2021), United States (Ali et al., 2020), 150 countries of the world (Cialani, 2017), or all economies (Dissanayake et al., 2023).

The subject matter and scope of research conducted to date is so extensive that it has been the subject of numerous, comprehensive literature reviews (Haberl et al., 2020; Mardani et al., 2019). In the case of the Visegrad countries, which are the subject of this study, an overview of recent research and methods in the area of the EKC curve has so far been provided by Suproń and Myszczyszyn (2023) and Leitão et al. (2023). The symmetrical relationship be-
between CO₂ emissions and energy consumption in the Visegrad countries was also analysed by Myszczyszyn and Suproń (2021). Previous studies of the relationship between CO₂ emissions and economic factors have used constantly improving methods, estimating symmetric single series models and panel data such as VECM, VAR, ARDL, NARDL, FMOLS, DOLS (Debone et al., 2021).

Recently, there have been a growing number of studies on the role of asymmetric effects of different factors on CO₂ emissions. Givens et al. (2019) analysed the theory of unequal ecological exchange. Recent advancements in econometric models and quantitative methods have sparked a surge of research into the asymmetric effects of various determinants on CO₂ emissions; Ullah et al. (2020) examined the asymmetric effect of deindustrialisation on pollution in Pakistan; Naseer et al. (2022) conducted a study of the asymmetric effect of education on CO₂ emissions in BRICS countries; Akram et al. (2020) using the asymmetric ARDL model, established the non-linear impact of energy efficiency and renewable energy on economic growth in the BRICS countries.

Mawejje (2023) also confirmed the asymmetric relationship between economic growth, CO₂ emissions and energy consumption in 19 Eastern and Southern African countries. Using an asymmetric model, Razaq et al. (2023) provided new evidence that the development of international tourism drives economic growth and increases carbon emissions asymmetrically at different levels of economic growth and carbon emissions. McGee and York (2018), on the other hand, conducted a study of the asymmetric relationship between urbanisation and CO₂ emissions in less developed countries.

In conclusion, despite numerous studies on the subject, there is still a scarcity of research concerning the relationship between energy consumption, economic growth, and CO₂ emissions when using an asymmetric approach over a prolonged period. This is particularly the case for European countries, including the Visegrad countries. The literature review highlights a significant research gap in this field, particularly concerning the use of Feasible Generalized Least Squares (FGLS) models. So far, only sporadic research has been undertaken in this domain (Naqvi et al., 2022). Considering the foregoing, and given the current state of research, our study bridges the methodological gap.

2 Methodology and data

2.1. Methodology and econometric framework

Research on asymmetric time series estimation methods was initiated by Granger and Yoon (2002), who were the first to formulate the assumption of latent cointegration and to present a formula for partial cumulative sums for
positive and negative components. Subsequently, the concept of asymmetric causality and cointegration tests was further developed by Hatemi-J (2012). Moreover, Shin et al. (2014), following on from earlier work, proposed the NARDL model to test both long- and short-run asymmetric relationships between variables. York and Light (2017) presented a method for estimating asymmetric models for panel data based on the Ordinary least squares (OLS) method with fixed effect. In contrast, Allison (2019), referring to previous studies, pointed out in his paper that standard fixed effects regression methods assume that the effects of variables are symmetric. At the same time, he stated that a GLS model is optimal. Furthermore, the concept of methods for modelling and testing asymmetric relationships for time series was developed by Hatemi-J (2022) and Hatemi-J and El-Khatib (2016).

In the methodological area, this study draws on the work of Granger and Yoon (2002), Hatemi-J (2012), Shin et al. (2014), York and Light (2017), Alison (Allison, 2019) in examining asymmetric relationships in time series and panel data. A basic model form was adopted to demonstrate asymmetric relationships between CO₂ emissions and economic growth, renewable and non-renewable energy consumption:

\[
CO_2_t = \beta_0 + \beta_{1t} GDP_t + \beta_{2t} REW_t + \beta_{3t} NREW_t + \epsilon_t
\]  

The above equation (1) is a long-run model and allows estimation of the model parameters for the long run. In order to capture asymmetric effects, all variables were transformed based on the method developed by Granger and Yoon (2002) and developed by Hatemi-J (2012):

\[
\sum_{n=1}^t \Delta x^-_n = \sum_{n=1}^t \min(\Delta x^-_n, 0) \\
\sum_{n=1}^t \Delta x^+_n = \sum_{n=1}^t \max(\Delta x^+_n, 0)
\]

The variables under consideration were transformed into a natural logarithm form and were assigned symbols: lnREW for renewable energy consumption, lnNREW for non-renewable energy consumption, lnGDP for gross domestic product and lnCO₂ for carbon dioxide emissions. After transformation of the data to partial cumulative sums for positive and negative components and logarithmic transformation, the analytical form of the model under study was determined as follows:

\[
\ln CO_2_t = \beta_0 + \beta_{1t} \ln GDP_t^+ + \beta_{2t} \ln GDP_t^- + \beta_{3t} \ln REW_t^+ + \beta_{4t} \ln REW_t^- + \beta_{5t} \ln NREW_t^+ + \beta_{6t} \ln NREW_t^- + \epsilon_t
\]
Due to the fact that the study used panel data for 4 countries, the first step was to test for the presence of cross-sectional dependence (CSD) based on the Breusch-Pagan LM method (Baltagi et al., 2012). This method is applicable to panel data with a small number of cross-sectional units. In addition, multicollinearity tests were carried out (Daoud, 2017), along with serial correlation (Wooldridge, 2010) and heteroskedasticity (White, 1980), in order to determine the optimal estimation method. In the next step, the stationarity of the variables was tested at the level and for the first difference using the panel unit root test, second generation CIPS (Pesaran, 2007). To establish the asymmetric impact of energy consumption and economic growth, cointegration was examined using the Kao test (Hatemi-J, 2020; Kao, 1999).

In the present study, two models were estimated in line with previous research to compare their results. The Driscoll-Kraay model (Driscoll & Kraay, 1998), which is a modification of ordinary least squares (OLS) regression that is robust in terms of cross-sectional dependence and heteroskedasticity, and the FGLS model (Baum, 2001), which follows on from the findings presented by Allison (2019). The FGLS model itself is a regression model, appropriate for small panels with many observations over time \((T > N)\), which is robust with regard to cross-sectional dependence and heteroskedasticity. The general form of the FGLS model is shown below:

\[
\hat{\beta}_{FGLS} = (X' \hat{\Omega}^{-1} X)^{-1} X' \hat{\Omega}^{-1} y
\]

In addition to model estimation, the study also conducted an asymmetric causality test to detect causal relationships between variables based on the Dumitrescu-Hurlin method (2012). This test considers the heterogeneity of the panel data, resulting in resilient outcomes. The null hypothesis posits that there is no causal relationship between the variables, whilst the alternative hypothesis proposes the existence of such a relationship.

### 2.2. Data and preliminary analysis

The proposed methodology was used to analyse the asymmetric, long-term relationship between renewable, non-renewable energy consumption (in tonnes of oil equivalent per capita) and economic growth (in constant 2015 USD per capita), and CO\textsubscript{2} emissions (in metric tonnes per capita) using the example of the Visegrad countries. All variables were extracted from the World Bank database and applied in a panel format. The data used in the study had an annual frequency and covered the period from 1991 to 2021 \((t = 31)\). Table 1 presents the descriptive statistics for the variables CO2, GDP, NREW, and REW.
All four variables exhibit significant variability and deviations from normality. Skewness values indicate right-skewed distributions, while kurtosis values of 2 indicate moderate-to-strong leptokurtosis. The results of the Jarque-Bera test were significant for all four variables, further confirming that the data did not conform to a normal distribution. The variables under consideration are therefore asymmetric.

The correlation matrix is presented in Table 2, while Table 3 shows the results of the multicollinearity test for the time series studied. No multicollinearity problem was found for the variables tested, and the mean index for the Variance Inflation Factor (VIF) test was 1.68. Based on the descriptive statistics and preliminary analyses, non-parametric or robust econometric methods are necessary to achieve the research objectives.

Table 1. Descriptive statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>CO₂</th>
<th>GDP</th>
<th>NREW</th>
<th>REW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>125.24</td>
<td>11870.73</td>
<td>0.44</td>
<td>4.34</td>
</tr>
<tr>
<td>Median</td>
<td>82.57</td>
<td>11596.03</td>
<td>0.32</td>
<td>3.91</td>
</tr>
<tr>
<td>Maximum</td>
<td>362.71</td>
<td>20248.30</td>
<td>1.13</td>
<td>7.40</td>
</tr>
<tr>
<td>Minimum</td>
<td>23.38</td>
<td>4743.75</td>
<td>0.02</td>
<td>2.56</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>107.97</td>
<td>3842.17</td>
<td>13.79</td>
<td>240.80</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.94</td>
<td>0.20</td>
<td>0.71</td>
<td>2.23</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>2.30</td>
<td>2.15</td>
<td>1.93</td>
<td>8.06</td>
</tr>
<tr>
<td>Jarque-Bera</td>
<td>20.92</td>
<td>4.54</td>
<td>16.26</td>
<td>234.77</td>
</tr>
<tr>
<td>Probability</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Observations</td>
<td>124</td>
<td>124</td>
<td>124</td>
<td>124</td>
</tr>
</tbody>
</table>

Source: own calculations.

Table 2. Correlation matrix

<table>
<thead>
<tr>
<th>Variables</th>
<th>lnCO₂</th>
<th>lnGDP⁺</th>
<th>lnGDP⁻</th>
<th>lnNREW⁺</th>
<th>lnNREW⁻</th>
<th>lnNREW⁺</th>
<th>lnNREW⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnCO₂</td>
<td>1.000</td>
<td>−0.261</td>
<td>0.535</td>
<td>−0.369</td>
<td>0.543</td>
<td>−0.370</td>
<td>0.429</td>
</tr>
<tr>
<td>lnGDP⁺</td>
<td>−0.261</td>
<td>1.000</td>
<td>−0.418</td>
<td>0.730</td>
<td>−0.690</td>
<td>0.657</td>
<td>−0.681</td>
</tr>
<tr>
<td>lnGDP⁻</td>
<td>0.535</td>
<td>−0.418</td>
<td>1.000</td>
<td>−0.781</td>
<td>0.852</td>
<td>−0.702</td>
<td>0.793</td>
</tr>
<tr>
<td>lnNREW⁺</td>
<td>−0.369</td>
<td>0.730</td>
<td>−0.781</td>
<td>1.000</td>
<td>−0.836</td>
<td>0.893</td>
<td>−0.948</td>
</tr>
<tr>
<td>lnNREW⁻</td>
<td>0.543</td>
<td>−0.690</td>
<td>0.852</td>
<td>−0.836</td>
<td>1.000</td>
<td>−0.794</td>
<td>0.842</td>
</tr>
<tr>
<td>lnREW⁺</td>
<td>−0.370</td>
<td>0.657</td>
<td>−0.702</td>
<td>0.893</td>
<td>−0.794</td>
<td>1.000</td>
<td>−0.843</td>
</tr>
<tr>
<td>lnREW⁻</td>
<td>0.429</td>
<td>−0.681</td>
<td>0.793</td>
<td>−0.948</td>
<td>0.842</td>
<td>−0.843</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Source: own calculations.
3. Research results

Table 4 shows the results of the initial diagnostics for the asymmetric panel data. These results indicate that there is a problem with autocorrelation, heteroskedasticity and cross-sectional dependence in the series under investigation. The results are in line with expectations presented for asymmetric data by Allison (Allison, 2019). In view of the above, standard OLS models cannot be used in the estimation process.

<table>
<thead>
<tr>
<th>Test</th>
<th>Statistic</th>
<th>Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooldridge test for autocorrelation</td>
<td>F</td>
<td>30.364</td>
<td>0.012</td>
</tr>
<tr>
<td>Heteroskedasticity White Test</td>
<td>$\chi^2$</td>
<td>33.560</td>
<td>0.001</td>
</tr>
<tr>
<td>Breusch-Pagan LM Residual Cross-Section Dependence Test</td>
<td>$\chi^2$</td>
<td>15.447</td>
<td>0.017</td>
</tr>
</tbody>
</table>

In the initial stage of this study, the unit root tests were conducted using the second-generation CIPS test, which considers the issue of cross-sectional dependence and is known for its high statistical power. The results of the test are shown in Table 5. The test performed confirms that all variables are stationary at first difference I (1).

Building on previous work by Hatemi-J, a cointegration test procedure for asymmetric series was carried out in the next step by applying tests to Kao panel data. Cointegration analysis was applied in pairs and jointly. All tests confirmed the presence of cointegration in the asymmetric series, but not in the symmetrical pairs test. This indicates the presence of latent cointegration. The results of the cointegration tests are shown in Table 6.

Based on the obtained preliminary results, an OLS model with fixed effect and robust standard errors was estimated based on the Driscoll-Kraay method for panel data with heteroskedasticity and autocorrelation problems. The
Table 5. Panel data CIPS unit root tests

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level</th>
<th>First difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnCO₂</td>
<td>–2.294*</td>
<td>–5.210***</td>
</tr>
<tr>
<td>lnCO₂⁺</td>
<td>2.042</td>
<td>–5.291***</td>
</tr>
<tr>
<td>lnCO₂⁻</td>
<td>–2.025</td>
<td>–4.628***</td>
</tr>
<tr>
<td>lnGDP</td>
<td>–1.457</td>
<td>–3.490***</td>
</tr>
<tr>
<td>lnGDP⁺</td>
<td>–1.316</td>
<td>–3.325***</td>
</tr>
<tr>
<td>lnGDP⁻</td>
<td>–0.924</td>
<td>–4.902***</td>
</tr>
<tr>
<td>lnNREW</td>
<td>–2.060</td>
<td>–4.760***</td>
</tr>
<tr>
<td>lnNREW⁺</td>
<td>–1.213</td>
<td>–4.178***</td>
</tr>
<tr>
<td>lnNREW⁻</td>
<td>1.186</td>
<td>–4.204***</td>
</tr>
<tr>
<td>lnREW</td>
<td>–2.930***</td>
<td></td>
</tr>
<tr>
<td>lnREW⁺</td>
<td>–3.354***</td>
<td></td>
</tr>
<tr>
<td>lnREW⁻</td>
<td>–2.685***</td>
<td>–5.717***</td>
</tr>
</tbody>
</table>

Note: The significance of the coefficients is indicated by an asterisk in the tables, where *, **, *** denotes 10%, 5%, and 1% significance level, respectively.

Source: own calculations.

Table 6. The results of panel hidden cointegration tests

<table>
<thead>
<tr>
<th>Variables</th>
<th>ADF</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnCO₂, lnREW</td>
<td>–0.026</td>
<td>0.490</td>
</tr>
<tr>
<td>lnCO₂, lnNREW</td>
<td>0.728</td>
<td>0.233</td>
</tr>
<tr>
<td>lnCO₂, lnGDP</td>
<td>–0.013</td>
<td>0.495</td>
</tr>
<tr>
<td>lnCO₂⁺, lnGDP⁺, lnREW⁺, lnNREW⁺</td>
<td>–1.761</td>
<td>0.039</td>
</tr>
<tr>
<td>lnCO₂⁻, lnGDP⁻, lnREW⁻, lnNREW⁻</td>
<td>–2.146</td>
<td>0.016</td>
</tr>
<tr>
<td>lnCO₂⁺, lnGDP⁺, lnREW⁺, lnNREW⁺</td>
<td>–1.284</td>
<td>0.009</td>
</tr>
<tr>
<td>lnCO₂⁻, lnGDP⁻, lnREW⁻, lnNREW⁻</td>
<td>–2.041</td>
<td>0.021</td>
</tr>
<tr>
<td>lnCO₂⁺, lnREW⁺, lnREW⁺, lnNREW⁺, lnGDP⁺, lnGDP⁻</td>
<td>–2.761</td>
<td>0.003</td>
</tr>
<tr>
<td>lnCO₂⁻, lnREW⁻, lnREW⁻, lnNREW⁻, lnGDP⁺, lnGDP⁻</td>
<td>–2.556</td>
<td>0.005</td>
</tr>
<tr>
<td>lnCO₂⁺, lnREW⁺, lnREW⁺, lnNREW⁺, lnGDP⁺, lnGDP⁻</td>
<td>–3.023</td>
<td>0.001</td>
</tr>
<tr>
<td>lnCO₂⁻, lnCO⁻, lnREW, lnREW⁺, lnNREW⁺, lnREW⁻, lnGDP⁺, lnGDP⁻</td>
<td>–3.245</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Source: calculations.

Estimation results are presented in Table 7. The lnREW variable and lnGDP had a statistically significant effect on the dependent variable. The model coefficients reveal that a 1% increase in renewable energy consumption causes
a 0.02% drop in CO$_2$ emissions in the countries under study. Conversely, if there is a negative change in lnGDP by 1%, CO$_2$ emissions decrease by 2.39%.

### Table 7. Asymmetric Model Estimated with fixed effect (robust)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>t-statistics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnREW$^+$</td>
<td>$-0.024$</td>
<td>$0.003$</td>
<td>$-7.570$</td>
<td>$0.005$</td>
</tr>
<tr>
<td>lnREW$^-$</td>
<td>$-0.159$</td>
<td>$0.147$</td>
<td>$-1.080$</td>
<td>$0.359$</td>
</tr>
<tr>
<td>lnNREW$^+$</td>
<td>$0.272$</td>
<td>$0.313$</td>
<td>$0.870$</td>
<td>$0.448$</td>
</tr>
<tr>
<td>lnNREW$^-$</td>
<td>$0.109$</td>
<td>$0.063$</td>
<td>$1.740$</td>
<td>$0.181$</td>
</tr>
<tr>
<td>lnGDP$^+$</td>
<td>$0.057$</td>
<td>$0.146$</td>
<td>$0.390$</td>
<td>$0.721$</td>
</tr>
<tr>
<td>lnGDP$^-$</td>
<td>$2.390$</td>
<td>$0.866$</td>
<td>$2.760$</td>
<td>$0.070$</td>
</tr>
<tr>
<td>Const.</td>
<td>$2.173$</td>
<td>$0.033$</td>
<td>$65.090$</td>
<td>$0.000$</td>
</tr>
</tbody>
</table>

Note: F-statistics of the model is 26.681 with p-value 0.000, R$^2$ of 0.723.

Source: own calculations.

In the next stage of the study, a long-term asymmetric model was estimated using the FGLS method. The estimation results are presented in Table 8. Based on the results obtained, it can be concluded that the GLS model showed a larger number of statistically significant variables and a different value of the estimated parameters. In contrast, the model estimated by the Driscoll-Kraay method has about ¼ smaller standard errors compared to the GLS model. At the same time, the standard errors of the GLS model are similar in their magnitude to those obtained by Şanlı et al. (2023) population density and sources of energy supply is critical in assessing environmental quality. Recent empirical studies paid limited attention to the role of renewable (RE for the NARDL model.

According to the results obtained for the FGLS model, an increase in renewable energy consumption in the countries studied contributes to a decrease in CO$_2$ of 0.23%. At the same time, the results of the Wald test for the joint significance of the coefficients did not confirm a significant asymmetry for renewable energy consumption. In the case of non-renewable energy consumption, the model tested indicates that a 1% increase in non-renewable energy consumption leads to a 0.34% increase in CO$_2$, while a decrease leads to a 0.71% reduction in CO$_2$. Wald tests simultaneously confirmed for these two variables a significant asymmetry at a significance level of 10%.

The final variable studied was GDP. The results showed statistically significant coefficients for both positive and negative changes. It should be noted that in the countries investigated, a 1% increase in GDP results in a 1.19% decline in CO$_2$ emissions, while a decrease leads to a long-term reduction of
5.66% in CO₂ emissions. The asymmetry observed in this variable is also statistically significant.

To confirm whether changes in the structure of energy production can have a significant impact on CO₂ reduction, as well as to establish their asymmetric impact, a causality test was conducted in the final stage of the study. For this purpose, a paired test based on the Dumitrescu & Hurlin panel data test was applied (2012) in conjunction with the method discussed by Hatemi-J (2012). The results indicate that there is bidirectional causality between lnCO₂ ↔ lnREW, lnREW⁻ ↔ lnCO₂⁻, lnREW⁺ ↔ lnCO₂⁺, lnNREW⁻ ↔ lnCO₂⁻. Unidirectional causality, on the other hand, has been demonstrated for the variables: lnCO₂⁻ → lnREW⁻, lnNREW⁻ → lnCO₂⁻, lnGDP → lnCO₂⁺ → lnGDP⁺, lnCO₂⁻ → lnGDP⁻ (Table 9).

The findings suggest a feedback loop between positive and negative interactions of CO₂ and renewable energy consumption. Causality tests establish that a reduction in non-renewable energy leads to a decrease in CO₂ emissions. However, results imply that economic growth has a non-linear impact on CO₂ emissions in the countries studied. Emissions initially increase, but then decline after a certain point.

The presence of multiple bidirectional and unidirectional asymmetric causality suggests that the relationships between variables are intricate and necessitate a comprehensive approach. In determining energy production strat-
egies, a range of factors should be considered, including the energy source type, economic growth, and greenhouse gas emissions. Transforming the energy mix has the potential to affect CO\textsubscript{2} emissions, but it requires a balanced approach that considers various factors to tackle climate change effectively.

The results obtained for the asymmetric effect of economic growth on CO\textsubscript{2} emissions in the long term are consistent with those presented by Toumi & Toumi (2019). The results for GDP are at the same time different from those obtained by Iqbal et al. (2022), who showed no significant asymmetry in the long term. Both studies in question simultaneously confirm the long-term asymmetry for the relationship between renewable energy and CO\textsubscript{2} emissions, which could not be confirmed for the V4 countries. In contrast, the result obtained is consistent with the study by Şanlı et al. (2023), who only confirmed the positive impact of renewable energy on the decrease in CO\textsubscript{2} emissions, while indicating the presence of a statistically significant asymmetry in the relationship between non-renewable energy and CO\textsubscript{2} emissions.

Table 9. Results of pairwise Dumitrescu-Hurlin panel causality tests

<table>
<thead>
<tr>
<th>Causality</th>
<th>Z-bar statistics</th>
<th>p-value</th>
<th>Causality</th>
<th>Z-bar statistics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnCO\textsubscript{2} → lnREW</td>
<td>1.936</td>
<td>0.053</td>
<td>lnCO\textsubscript{2} → lnNREW\textsuperscript{–}</td>
<td>–0.420</td>
<td>0.674</td>
</tr>
<tr>
<td>lnREW → lnCO\textsubscript{2}</td>
<td>2.870</td>
<td>0.004</td>
<td>lnNREW\textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>4.489</td>
<td>0.000</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>1.082</td>
<td>0.279</td>
<td>lnCO\textsubscript{2} → lnNREW\textsuperscript{–}</td>
<td>23.575</td>
<td>0.000</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnREW\textsuperscript{–}</td>
<td>16.156</td>
<td>0.000</td>
<td>lnNREW → lnCO\textsubscript{2}</td>
<td>2.137</td>
<td>0.033</td>
</tr>
<tr>
<td>lnREW → lnCO\textsubscript{2}</td>
<td>2.325</td>
<td>0.020</td>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnNREW\textsuperscript{–}</td>
<td>0.908</td>
<td>0.364</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnREW\textsuperscript{–}</td>
<td>12.417</td>
<td>0.000</td>
<td>lnGDP → lnCO\textsubscript{2}</td>
<td>2.111</td>
<td>0.035</td>
</tr>
<tr>
<td>lnREW → lnCO\textsubscript{2} \textsuperscript{–}</td>
<td>–0.071</td>
<td>0.943</td>
<td>lnCO\textsubscript{2} → lnGDP</td>
<td>–0.789</td>
<td>0.430</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnREW\textsuperscript{–}</td>
<td>1.368</td>
<td>0.171</td>
<td>lnGDP\textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>0.571</td>
<td>0.568</td>
</tr>
<tr>
<td>lnREW → lnCO\textsubscript{2} \textsuperscript{–}</td>
<td>2.567</td>
<td>0.010</td>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnGDP\textsuperscript{–}</td>
<td>1.720</td>
<td>0.086</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnREW\textsuperscript{–}</td>
<td>2.137</td>
<td>0.033</td>
<td>lnGDP\textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>–0.937</td>
<td>0.349</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} → lnNREW</td>
<td>0.785</td>
<td>0.433</td>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnGDP\textsuperscript{–}</td>
<td>3.303</td>
<td>0.001</td>
</tr>
<tr>
<td>lnNREW → lnCO\textsubscript{2}</td>
<td>0.816</td>
<td>0.414</td>
<td>lnGDP\textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>3.912</td>
<td>0.000</td>
</tr>
<tr>
<td>lnNREW \textsuperscript{+} → lnCO\textsubscript{2} \textsuperscript{–}</td>
<td>1.333</td>
<td>0.183</td>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnGDP\textsuperscript{–}</td>
<td>4.432</td>
<td>0.000</td>
</tr>
<tr>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnNREW\textsuperscript{+}</td>
<td>–0.482</td>
<td>0.630</td>
<td>lnGDP\textsuperscript{–} → lnCO\textsubscript{2}</td>
<td>4.755</td>
<td>0.000</td>
</tr>
<tr>
<td>lnNREW \textsuperscript{–} → lnCO\textsubscript{2} \textsuperscript{–}</td>
<td>8.843</td>
<td>0.000</td>
<td>lnCO\textsubscript{2} \textsuperscript{–} → lnGDP\textsuperscript{–}</td>
<td>–0.063</td>
<td>0.950</td>
</tr>
</tbody>
</table>

Source: own calculations.
Conclusions

The objective of this paper was to examine the enduring and uneven influence of renewable and non-renewable energy consumption, as well as economic growth, on CO$_2$ emissions, with a case study focusing on the Visegrad countries from 1991 to 2021. The study used the Driscoll-Kraay and FGLS models to address challenges arising from serial correlation, panel group heteroskedasticity, cross-sectional dependence, and the heterogeneity of asymmetrically modified data. The findings indicate the presence of cointegration for all variables, encompassing various combinations, in the asymmetrically transformed series. The OLS-based model proposed by Driscoll-Kraay showed reduced standard errors, but lower significance in the estimated parameters compared to the FGLS model.

These differences are due to different estimation rules, in particular the distribution of model residuals and the accuracy of these methods. However, the results tend to converge to some extent in terms of the strength and direction of the effects. It is important to emphasise the need for further research in this area, particularly on panels with more observations per unit of time, to develop optimal estimation techniques for an asymmetric effect.

Research also indicates that a rise in renewable energy consumption has a direct and proportional negative impact on CO$_2$ levels, thereby contributing to the mitigation of greenhouse gases. In contrast, a decrease in non-renewable energy consumption brings about a significant decrease in CO$_2$ emissions in the long term. Moreover, GDP was found to have an asymmetric effect on CO$_2$, where a decrease in GDP induces a greater decrease in GHG emissions than an increase in GDP. Thus, the research confirms that economic development, combined with increasing the share of renewable energy, is a source of stable and sustainable socio-economic development, while also being environmentally friendly. Furthermore, the application of asymmetric Dumitrescu-Hurlin causality tests confirms the existence of bidirectional causality between an increase in renewable energy consumption and a reduction in CO$_2$, a decrease in GDP and a decrease in CO$_2$, and a unidirectional relationship between a decrease in non-renewable energy consumption and a decrease in CO$_2$.

The study’s findings may inform energy policy decisions. The estimation results obtained suggest that economic growth can be sustained during an energy transition. To achieve this, it is essential to develop renewable energy sources in a sustainable and well-considered manner. This goal can be achieved both through the involvement of domestic resources and foreign funds, including European funds and loans from institutions such as the World Bank.

The policy implications of the research suggest that the Visegrad governments should implement robust incentive programmes and subsidies to encourage investment in renewable energy projects. To fully realize the potential
of renewable energy, a two-pronged approach is essential: providing financial incentives to encourage its adoption, and modernizing the energy infrastructure to ensure efficient integration of different energy sources. To accelerate the transition to clean energy, policymakers should focus on two key areas: Firstly, investing in smart grid technologies to improve the flexibility and reliability of existing infrastructure, enabling efficient integration of renewable energy sources. Secondly, increasing government support for renewable energy research and development (R&D) to unlock the full potential of these technologies and pave the way for a sustainable energy future. Collaboration between academia, industry and research institutions can lead to breakthroughs that make renewable energy more accessible and cost-effective.

In line with the latest initiatives from the European Union aimed at reducing CO$_2$ emissions, it is essential to enhance human capital. Therefore, implementing training schemes and educational programmes is necessary to develop a skilled workforce capable of effectively managing, sustaining, and innovating within the renewable energy sector. Incorporating vocational training, academic programmes, and collaborations with industries can ensure a smooth transition in the labour market.

The Visegrad countries should actively participate in global collaboration, recognizing the interdependence of environmental concerns. Accelerating the transition and effectively tackling worldwide climate challenges can be achieved by exchanging best practices, technological advancements, and policy insights with other nations. It would be beneficial for the group to establish a collective fund and attract investors through a public-private partnership.

The study has some limitations that could be addressed in future research. For instance, the sample size is relatively small, with only four participants from Central and Eastern Europe (CEE), which may limit the generalizability of the findings to other regions. While economic growth and energy use are often seen as the primary drivers of CO$_2$ emissions, a singular focus on these factors overlooks potentially influential contributors such as green taxes, innovative climate solutions, population trends, and urban planning. To equip policymakers with deeper insights into effective plans for curbing CO$_2$ emissions and fostering sustainable economic growth in CEE economies, future research should expand its reach to encompass a broader range of countries and delve deeper into the influence of additional factors, along with examining potential interactions between them. Moreover, conducting research utilizing innovative estimation methods like Fourier ARDL or ARDL CS could yield compelling insights.
References


Azam, A., Rafiq, M., Shafique, M., Zhang, H., Ateeq, M., & Yuan, J. (2021). Analyzing the relationship between economic growth and electricity consumption from re-


Aims and Scope

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