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# Modelling the asymmetric relationship between energy and $CO_2$ emissions in the Visegrad group: empirical evidence from a panel NARDL approach

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## Abstract

The study aims to understand the impact of renewable energy consumption, non-renewable energy consumption, and economic growth on carbon dioxide ($CO_2$) emissions per capita (measured in metric tonnes) in the Visegrad countries between 1991 and 2021. Using a Nonlinear Autoregressive Distributed Lag (NARDL) model for panel data, the research captures both long-term dependencies and short-term dynamics. The results show that a reduction in $CO_2$ emissions yielded by a significant long-term decrease in non-renewable energy consumption is proportionally larger than the increase in the emissions caused by the growth in the consumption of such energy. What is more, GDP growth in the V4 countries increases $CO_2$ emissions, but GDP decline contributes significantly more to the reduction in emissions. In contrast, renewable energy consumption consistently reduces $CO_2$ emissions over the long term, with no significant asymmetry detected. In the short term, both economic growth and non-renewable energy consumption increase $CO_2$ emissions. The error correction factor suggests a rapid adjustment of $CO_2$ emissions towards a long-term equilibrium, with a decreasing trend over time. These results have some policy implications, i.e. they suggest that for the V4 countries, increasing investment in technologies and solutions that improve energy efficiency will be crucial for reducing non-renewable energy consumption and, consequently, $CO_2$ emissions, without negatively impacting economic growth. Additionally, stable and long-term promotion of renewable energy should be a policy priority in order to effectively contribute to emission reductions.

**Key words:** renewable energy, non-renewable energy, $CO_2$ emissions, growth, NARDL panel.

## 1. Introduction

Energy is a fundamental production factor in modern economies, without which no economic activity is possible (Stern 2019). The efficient use of energy resources is a key competitive advantage for individual economies, influencing their efficiency and

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cost intensity and therefore their economic development (Fanchi 2023). While energy is a key driver of economic growth, its production, particularly from conventional sources, has significant environmental implications (Ndoricimpa 2017). Since the Industrial Revolution, energy production, particularly from coal and oil, has contributed significantly to the emission of greenhouse gases, especially carbon dioxide ($CO_2$), which numerous studies have identified as a primary driver of global warming (Al-Ghussain 2019). The excessive release of greenhouse gases has resulted in a global temperature increase of 1.1°C, with further rises occurring at a rate of 0.2°C per decade (Pörtner et al. 2022).

The economic implications of climate change have become a key topic of discussion at the political and scientific levels. It is imperative that global economies pursue sustainable solutions in energy production and consumption (Czyżewski, Polcyn, and Brelik 2022). The need to improve environmental conditions and halt global warming has driven the global community to adopt regulations aimed at reducing the use of fossil fuels in energy production and thereby cutting $CO_2$ emissions. This effort began with the signing of the Kyoto Protocol in 1997, followed by the Paris Agreement in 2015 (Flanker 2016). Furthermore, in 2019, the European Union initiated the European Green Deal, which aims to halve $CO_2$ emissions by 2030 and achieve climate neutrality by 2050 (Samper, Schockling, and Islar 2021). The indicated actions have contributed to the green transformation, which can be defined as the integration of economic growth with environmental stewardship to ensure a high quality of life for current and future generations, while effectively and rationally utilizing available resources in line with civilizational progress (Cheba et al. 2022).

Achieving the stated goals while maintaining conditions for economic growth requires replacing non-renewable energy sources with renewable ones, which is part of the energy transformation process (Adedoyin et al. 2021). For countries with a significant reliance on fossil fuels in their energy mix, a transition to renewable energy sources will be particularly significant. The Visegrad Group is an example. It comprises the Czech Republic, Hungary, Poland and Slovakia. These countries have undergone substantial economic transformations, shifting to market economies while experiencing significant changes in their production structures and numerous economic shocks (Ambroziak et al. 2021). Despite experiencing substantial economic growth, these nations still rely significantly on fossil fuels, including coal, for energy production (Brodny and Tutak 2021). Consequently, the energy transformation process represents a significant challenge for these countries, given the substantial investments required to increase the share of renewable energy sources in their energy mix (Marzec and Zioło 2016). As highlighted by Bigos (2017), Poland and the Czech Republic are facing significant challenges in their energy sectors due to their substantial reliance on coal for electricity generation and heating. Slovakia faces greater challenges in adapting its industrial sector, while Hungary aims to achieve greater energy independence from fossil fuels, including variable gas, by 2030. However, the impact of potential energy transformation on economic growth and $CO_2$ emissions in these countries is still not fully understood, according to Suproń and Myszczyszyn (2023).

A growing body of research from a range of regions and countries indicates that renewable energy can play a role in reducing $CO_2$ emissions while supporting economic growth (Alper and Oguz 2016; Bhuiyan et al. 2022). However, the results are not always definitive. For example, Antonakakis et al. (2017) found that, in a sample of 106 countries, there is no definitive evidence that the use of renewable energy promotes growth more efficiently and sustainably for the environment. Many previous studies have concentrated on the linear relationships between energy, economic growth and environmental pollution (Mardani et al. 2019). However, Khan i Sun (2024) posits that assuming a linear relationship is a flawed approach that leads to oversimplified conclusions. This is because it assumes that variables change proportionally, which may not fully account for external shocks. It is important to note that many economic relationships based on data represent non-linear relationships, which reflect the nature of economic events (Chauvet and Jiang 2023).

Furthermore, research in environmental economics is increasingly emphasising the non-linearity of relationships between $CO_2$ emissions, energy production and economic factors (Iorember, Usman, and Jelilov 2019; Kirikkaleli, Abbasi, and Oyebanji 2023; Akadiri and Adebayo 2022). As Kouton (2019) notes, asymmetries emerge due to a range of economic and natural shocks, including technological changes, policy shifts, economic policies, and even natural disasters. Employing non-linear models facilitates a more comprehensive examination of time series, particularly during periods when such shocks have occurred.

Over the past 30 years, the Visegrad Group countries have faced a series of significant internal and external challenges. These include economic transformation, accession to the EU, the financial crisis, the Eurozone crisis and the impact of the global pandemic. As a result, economic data for these countries is characterized by a few structural breaks and non-linear stochastic processes. Additionally, some studies suggest that the relationships between $CO_2$ emissions and the economy and energy sector in these countries may exhibit non-linear U- or N-shaped patterns (Suproń 2024; Supron and Myszczyszyn 2023).

Considering the above rationale and the V4 countries' commitments to achieving climate neutrality, the aim of the study was to determine the short- and long-term impacts of renewable and non-renewable energy consumption, as well as economic growth, on $CO_2$ emissions in the V4 countries, incorporating non-linear effects. Based on the study objectives and existing literature, the following research hypotheses were formulated:

**Hypothesis H1:** There is a negative and asymmetric relationship between renewable energy consumption and $CO_2$ emissions in the Visegrad countries in the long term.

**Hypothesis H2:** There is a positive and asymmetric relationship between non-renewable energy consumption and $CO_2$ emissions in the Visegrad countries in the long term.

**Hypothesis H3:** Economic growth has a positive and asymmetric impact on $CO_2$ emissions in the Visegrad countries in the long term.

The choice of the research method was based on an analysis of the existing literature on the subject. Many studies analyzing the relationship between energy consumption, production, and $CO_2$ emissions use panel data, including econometric techniques such as linear VAR, ARDL, and the non-linear generalized method of moments (GMM) (Masron and Subramaniam 2018; Rasoulinezhad and Saboori 2018; Antonakakis, Chatziantoniou, and Filis 2017).

This study employs a modern estimation method based on the NARDL model, which differs from previous research in this field. The choice of this methodological approach is driven by the fact that traditional panel methods often encounter issues related to heteroskedasticity and cross-sectional dependence in time series data. These issues limit the applicability of traditional panel methods and necessitate compromises in the estimation process. The use of nonlinear methods addresses these methodological challenges and yields more accurate results. Additionally, NARDL allows for the modelling of long-term effects for both positive and negative deviations from equilibrium, as well as nonlinear short-term effects, which are often overlooked in traditional panel regression models (Shin, Yu, and Greenwood-Nimmo 2014; B. Li et al. 2023). Furthermore, these models are resilient to structural shifts in the data, a common challenge with economic indicators for Central and Eastern European countries, which have undergone substantial economic transformation and encountered numerous internal and external disruptions over the past three decades.

The novel aspects of this study can be summarized as follows. Firstly, this study employs a contemporary methodology based on the NARDL model, offering new insights that differ from those of earlier research. Secondly, the findings related to Central and Eastern European countries, particularly the Visegrad Group, have significant implications for countries that may undergo similar transformation processes in the future. Finally, to the best of our knowledge, no previous studies have used NARDL methodology to study the V4 group with relationships of energy, GDP and $CO_2$.

The remainder of this paper is structured as follows. Section 1 provides a review of the recent literature. Section 2 presents the methodology and the empirical model. Section 3 describes the data and the results of the empirical analysis. Section 4 provides a discussion to the results of the study. The final section provides a summary.

## 2. Literature review

There is a large body of theoretical and empirical research focusing on the relationship between energy consumption, economic growth, and $CO_2$, in both highly developed and developing economies (Bąk and Cheba 2023). The literature can be divided into three main streams of research: the first focuses on the causal relationship between energy consumption and $CO_2$, the second focuses on the relationship between production and air pollution. The third combines both, providing a unified framework for identifying the links between energy consumption, $CO_2$ emissions and economic growth (Antonakakis, Chatziantoniou, and Filis 2017).

Based on ample empirical evidence, existing aggregate reviews of the literature indicate the existence of unidirectional and bidirectional positive relationships between economic growth and $CO_2$, (Omri 2014; Ozturk 2010; Tugcu, Ozturk, and Aslan 2012). In contrast, some studies to date have not confirmed a significant interaction between economic growth and higher $CO_2$. However, it should be pointed out that individual studies differ both in the selection of countries, the study periods, the length of the time series and the methodology used (Haberl et al. 2020).

As previously mentioned, the second part of the research focused on the topics of energy consumption and production and the impact of the indicated variables on $CO_2$. Considering the previous research results in this area, most studies confirmed a positive unidirectional relationship between increased $CO_2$, and electricity production. (Aziz et al. 2022). Some authors have conducted more detailed analyses comparing the impact of renewable and non-renewable energy on economic growth. Based on the evidence, it has been indicated that renewable energy consumption promotes $CO_2$, but only after it has exceeded a certain share in the energy mix (Shahbaz & Sinha, 2019; Tiba & Omri, 2017). Thus, according to the existing scientific consensus, renewable energy appears to be an effective instrument for sustainable decarbonization (Bourcet 2020).

The rapid development of econometric methods has meant that previous studies have been conducted for both individual countries and groups of countries. The use of panel methods has contributed to the development of new results and conclusions from the estimation of broad data sets. A detailed characterization of recent studies using panel methods is presented in Table 1.

**Table 1:** A review of recent panel data studies and their results in the impact of economic growth and energy consumption on $CO_2$ emissions

| Source | Country (region) | Causality | Model | Period |
|---|---|---|---|---|
| Allard et al. (2018) | 74 countries | REW→ $CO_2$ (-) | PQARDL | 1994-2012 |
| Anwar et al. (2021) | ASEAN countries | REW→ $CO_2$ (-)<br>NREW→ $CO_2$ (+) | FMOLS / DOLS | 1980-2013 |
| Armeanu et al. (2017) | EU Countries | REW→ GDP (+) | PVAR | 2003-2014 |

**Table 1:** A review of recent panel data studies and their results in the impact of economic growth and energy consumption on $CO_2$ emissions (cont.)

| Source | Country (region) | Causality | Model | Period |
|---|---|---|---|---|
| Bekun et al. (2019) | EU countries | REW→ $CO_2$ (-)<br>NREW→ $CO_2$ (+) | ARDL-PMG | 1996-2014 |
| Ben Jebli et al. (2020) | 102 countries | REW→ $CO_2$ (-) | GMM | 1990-2015 |
| Bhattacharya et al. (2017) | 85 countries | NREW→ $CO_2$ (+)<br>REW→ $CO_2$ (-) | FMOLS | 1991-2012 |
| Busu & Nedelcu (2021) | EU countries | REW→ $CO_2$ (+) | OLS panel | 2000-2019 |
| Cai et al. (2018) | G7 countries | REW→ $CO_2$ (-) | ARDL-PMG | 1965-2015 |
| Charfeddine & Kahia (2019) | MENA countries | REW→ $CO_2$ (-) | PVAR | 1980-2015 |
| Chen et al. (2022) | 97 countries | REW→ $CO_2$ (-) | DPTRM | 1995-2015 |
| Cialani (2017) | 150 Countries | $CO_2$ ⇔ GDP | ECM panel | 1960-2008 |
| Gozgor et al. (2018) | OECD Countries | NREW→ GDP (+)<br>REW→ GDP (+) | ARDL | 1990 - 2013 |
| Inglesi-Lotz & Dogan (2018) | Africa countries | NREW→ $CO_2$ (+)<br>REW→ $CO_2$ (-) | DOLS | 1980-2011 |
| Ito (2017) | 42 developed countries | REW→ GDP (-) | OLS panel | 2002-2011 |
| Lazăr et al. (2019) | CEE Countries | GDP→ $CO_2$ (+) | FMOLS | 1996-2015 |
| Li et al. (2020) | Post-Communist Economies | GDP→ $CO_2$ (+) | OLS panel | 1996-2018 |
| Ma et al. (2021) | Germany and France | REW→ $CO_2$ (-)<br>NREW→ $CO_2$ (+) | FMOLS | 1995-2015 |
| Muço et al. (2021) | European transition economies | GDP→ $CO_2$ (+)<br>REW→ GDP (+) | PVAR | 1990-2018 |
| Ozcan and Ozturk (2019) | Emerging countries | REW ≠ GDP (+) | Causality panel | 1990-2016 |
| Pope et al. (2019) | EU Countries | REW→ GDP (+) | PVECM | 1990-2014 |
| Papież et al., (2019) | EU Countries | REW≠GDP<br>NREW ≠GDP | PVAR | 1995-2015 |
| Saqib et al. (2022) | GCC | NREW→ $CO_2$ (+) | OLS panel | 1993-2019 |
| Suproń (2024) | Visegrad countries | NREW → $CO_2$ (+)<br>GDP → $CO_2$ (+) | Asymmetric FGLS | 1991-2021 |
| Chen et al. (2022) | 24 countries | REW→ $CO_2$ (-)<br>NREW→ $CO_2$ (+) | ARDL-PMG | 1995-2014 |
| Zhang and Liu (2019) | NSEA-10 countries | REW→ $CO_2$ (-)<br>NREW→ $CO_2$ (-) | FMOLS | 1995-2014 |

*REW - use/consumption of renewable energy; NREW - use/consumption of non-renewable energy; $CO_2$ - carbon dioxide emissions; GDP - economic growth; (+) positive impact; (-) negative impact.*

*Source: author's study.*

As suggested by the summary presented in Table 1 on the impact of renewable and non-renewable energy consumption and economic growth on $CO_2$, some results show consensus, while others often generate contradictory conclusions. These discrepancies may be due to the different data used, different econometric methods and the quality of the time series, among other things (Antonakakis, Chatziantoniou, and Filis 2017; Stern and Common 2001; Yang and Zhao 2014).

Despite the wide range of research in this area, there still seems to be a research gap regarding the Visegrad countries. According to the literature analysis presented by Supruń & Myszczyszyn (2023) a panel study examining the relationship between energy consumption from different sources and economic growth on $CO_2$ emissions in the V4 countries has not yet been carried out.

Developments in econometrics, newer estimators and models make it possible to provide new evidence in many of the areas studied. An analysis of the existing literature indicates that the relationship between energy consumption and $CO_2$ emissions has not been extensively investigated using non-linear ARDL-PMG models. To date, this model has been used to establish relationships between $CO_2$, and labor force (Naseer et al. 2022) and foreign investment (Deng, Liu, and Sohail 2022) in the BRICS countries. There have also been studies using the NARDL panel model to analyze the asymmetric impact of education on $CO_2$ in MINT countries (Ahmed et al. 2022) and the ICT sector on environmental pollution in GCC countries (Saqib, Duran, and Hashmi 2022).

Although the impact of renewable and non-renewable energy and economic growth on $CO_2$ emissions has been extensively studied, significant research gaps remain, particularly regarding the use of non-linear methods for V4 economies. Non-linear analysis is crucial in this context, as it enables a more detailed examination of the relationship between changes in independent variables and $CO_2$ emissions (Ahmed et al. 2022). Despite this, the current literature does not confirm the existence of long-term asymmetric relationships between energy production from renewable and non-renewable sources, economic growth, and $CO_2$ emissions in the Visegrad countries.

## 3. Data and methodology

This study examined the relationship between renewable (REW) and non-renewable (NREW) electricity consumption and economic growth (GDP), as well as carbon dioxide ($CO_2$) emissions. The research was conducted for the V4 countries, with a time series covering the years from 1991 to 2021. Table 2 sets out the full characteristics of the time series studied. The study used a panel data set, with the variables transformed to the form of natural logarithms.

**Table 2:** Data, units and data sources

| Variable | Full name | Unit | Source |
|---|---|---|---|
| $CO_2$ | Carbon dioxide ($CO_2$) emissions per capita | Metric tonnes per capita | World Development Indicators (WDI) |
| GDP | GDP per capita | GDP per capita in constant 2015 US dollars | World Development Indicators (WDI) |
| REW | Electricity consumption from renewable sources | Tonnes of oil equivalent (per capita) | EEA / Eurostat |
| NREW | Electricity consumption from non-renewable sources | Tonnes of oil equivalent (per capita) | EEA / Eurostat |

*Source: World Bank Data and Eurostat Database*[2].

In this study, the NARDL methodology proposed by Shin et al. (2014) is employed to determine the relationship between $CO_2$ emissions, renewable energy consumption, non-renewable energy consumption, and economic growth. The NARDL-PMG model based on the ARDL-PMG model, which is applied to panel data, provides short- and long-term parameter estimation and support for integrated variables at both I(0) and I(1) levels (Pesaran, Shin, and Smith 2001). NARDL models are also effective for small samples and robust to structural breaks in the data. The NARDL approach is more flexible in relation to the dynamics of cointegration between variables. In addition, NARDL models allow the assessment of both long- and short-term effects of the independent variables on the dependent variable with consideration of asymmetric effects. Considering the purpose of the study and the literature, the basic specification of the model was defined as follows:

$$\Delta CO_{2_t} = f(GDP, REW, NREW) \tag{1}$$

To drop serial correlation and heteroskedasticity, the model was transformed to a log-linear form:

$$\Delta CO_{2_t} = \beta_0 + \beta_{1t} lnGDP_t + \beta_{2t} lnREW_t + \beta_{3t} lnNREW_t + \varepsilon_t \tag{2}$$

[2] WDI dataset: https://databank.worldbank.org/metadataglossary/world-development-indicators/series/EN.ATM.CO2E.PC, accessed on 31.05.2023; Eurostat dataset: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics, accessed on 31.05.2023.

The variables lnGDP and lnREW have been transformed into subtotals according to the assumptions of the NARDL model to highlight their asymmetric effects. This allows the study to consider both their positive and negative effects on $CO_2$ emissions. The subtotals of the variables studied are presented below in the form of equations (Shin, Yu, and Greenwood-Nimmo 2014):

$$\sum_{n=1}^{t} \Delta lnGDP_{it}^{-} = \sum_{n=1}^{t} \min(\Delta \ln GDP_{it}^{-}, 0) \cap \sum_{n=1}^{t} \Delta lnNREW_{it}^{-} = \sum_{n=1}^{t} \min(\Delta lnNREW_{it}^{-}, 0)$$

(3)

$$\sum_{n=1}^{t} \Delta lnGDP_{it}^{+} = \sum_{n=1}^{t} \max(\Delta \ln GDP_{it}^{+}, 0) \cap \sum_{n=1}^{t} \Delta lnNREW_{it}^{+} = \sum_{n=1}^{t} \max(\Delta \ln NREW_{it}^{+}, 0)$$

where $GDP^{+}$ and $NREW^{+}$ indicate positive changes in the series, $GDP^{-}$ and $NREW^{-}$ indicate negative changes in the series.

The full panel NARDL model including asymmetric effects and short- and long-term impacts is presented below:

$$\begin{aligned}\Delta \ln CO_{2,it} = \delta &+ \sum_{p=1}^{n1} \delta_{1p} \Delta \ln CO_{2,it-p} + \sum_{p=0}^{n2} \delta_{2p} \Delta lnGDP_{it-p}^{+} \\ &+ \sum_{p=0}^{n3} \delta_{3p} \Delta \ln GDP_{it-p}^{-} \sum_{p=0}^{n4} \delta_{4p} \Delta \ln NREW_{it-p}^{+} + \sum_{p=0}^{n5} \delta_{5p} \Delta lnNREW_{it-p}^{-} \\ &+ \sum_{p=0}^{n6} \delta_{6p} \Delta lnREW_{it-p} + \varphi_1 lnCO_{2,it-1} + \varphi_2 lnGDP_{it-1}^{+} + \varphi_3 lnGDP_{it-1}^{-} \\ &+ \varphi_4 lnNREW_{it-1}^{+} + \varphi_5 lnNREW_{it-1}^{-} + \varphi_6 lnREW_{it-1} + \varepsilon_t\end{aligned}$$

(4)

where i is the cross-sectional dimension, t is the time dimension, p is the corresponding order of delay, $\delta$ are the parameters of the short-term relation, and $\varphi$ the parameters of the long-term relationship.

The study used an estimation based on the Pooled Mean Group (PMG) estimator. The selection of the optimal number of delays in the model, on the other hand, was determined according to the Akaike Information Criterion (AIC). The PMG estimator provides greater reliability for cross-country data, as it takes into account regional specificities and allows for a better interpretation of the long-run equilibrium (Attiaoui and Boufateh 2019).

In addition, PMG allows for heterogeneity in short-run coefficients, while long-run coefficients can be identical and homogeneous for the entire panel area (Pesaran, Shin, and Smith 1999). Testing for asymmetry was carried out using the Wald test and the $x^2$

statistic (Andrews 1987; Shin, Yu, and Greenwood-Nimmo 2014). Because all variables tested are stationary at level I (1) and the cross-section of the panel tested was four objects, cointegration tests were applied Kao (1999). In order to strengthen the results obtained, causality was tested using the Dumitrescu-Hurlin panel pairwise procedure (Dumitrescu and Hurlin 2012).

## 4. Research results

### 4.1. Exploratory Data Analysis

Table 3 presents the fundamental descriptive statistics for the surveyed data for the years 1991 and 2021. The Visegrad Group countries (Czech Republic, Hungary, Poland, and Slovakia) experienced notable shifts in carbon dioxide ($CO_2$) emissions, per capita GDP, and energy consumption from renewable and non-renewable sources between 1991 and 2021. There was a notable decrease in $CO_2$ emissions per capita over the period in question. In 1991, the average $CO_2$ emissions were 9.36 metric tonnes per capita. By 2021, this figure decreased to 6.84 metric tonnes. The reduction in the standard deviation from 3.07 to 2.65 tonnes indicates a more uniform distribution of emissions across the region, likely reflecting improvements in environmental policies and industrial technologies. GDP per capita grew considerably. In 1991, the average GDP per capita was $7,284.27, rising to $17,286.35 by 2021. Despite this growth, the reduction in the standard deviation from $2,330.20 to $2,003.16 indicates a reduction in income inequality within the region, although significant disparities in living standards between countries persist.

There was an increase in the consumption of electricity from non-renewable sources, with the average rising from 0.36 to 0.47 tonnes of oil equivalent per capita. This was accompanied by a rise in the standard deviation, which increased from 0.11 to 0.16 tonnes. This indicates an increasing demand for energy and the potential for delays in the transition to renewable sources. In contrast, there was a notable increase in electricity consumption from renewable sources, with the average rising from 0.01 to 0.09 tonnes of oil equivalent per capita.

While the contribution of renewable energy to overall consumption remains relatively modest, the decline in the standard deviation from 0.01 to 0.02 tonnes suggests a more consistent uptake of renewable technologies across the countries. In conclusion, the period from 1991 to 2021 saw significant developments in the Visegrad Group countries, including reductions in $CO_2$ emissions and economic growth. The increased consumption of renewable energy reflects an ongoing energy transition, although challenges remain with rising energy use from non-renewable sources.

**Table 3:** Descriptive statistics

| Variable | 1991 | | | | 2021 | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | SD | Mean | Min | Max | SD |
| $CO_2$ | 9.36 | 6.47 | 13.65 | 3.07 | 6.84 | 4.25 | 9.87 | 2.65 |
| GDP | 7284.27 | 4743.75 | 10304.87 | 2330.20 | 17286.35 | 15485.47 | 19715.97 | 2003.16 |
| NREW | 0.36 | 0.25 | 0.51 | 0.11 | 0.47 | 0.32 | 0.68 | 0.16 |
| REW | 0.01 | 0.00 | 0.03 | 0.01 | 0.09 | 0.06 | 0.11 | 0.02 |

*Source: author's calculations.*

Figures 1–3 present main time series data for the V4 countries. The $CO_2$ emissions per capita have declined in all four countries since 1991 (Fig. 1), reflecting technological progress and reduced industrial intensity. The Czech Republic and Hungary showed steady decreases, with minor fluctuations. Poland and Slovakia also reduced emissions, despite periods of stagnation. Renewable energy consumption per capita increased in all countries (Fig. 2), most notably in Slovakia. Growth in the Czech Republic and Poland was moderate; Hungary accelerated after 2010. Non-renewable energy co-nsumption per capita remained relatively stable (Fig. 3), with slight increases in the Czech Republic and Poland, stagnation in Hungary, and fluctuations in Slovakia.

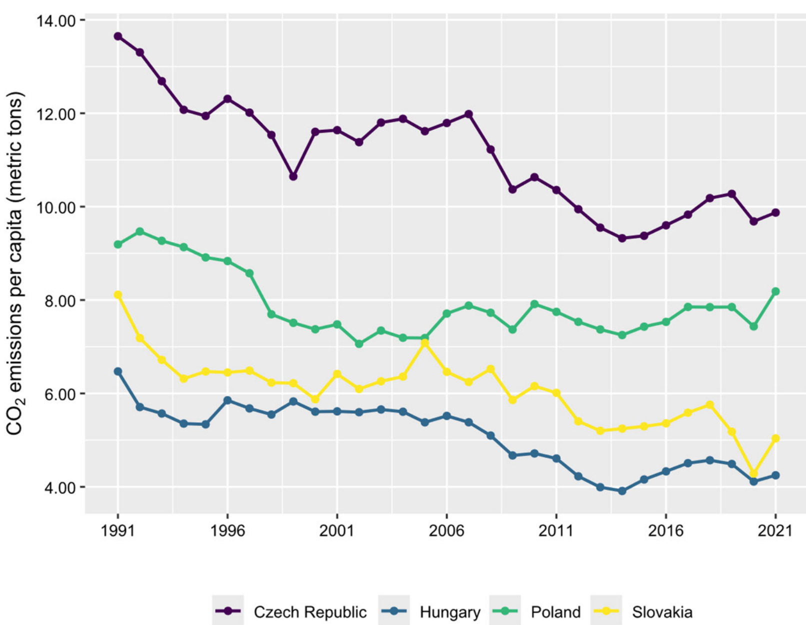


**Figure 1:** $CO_2$ emissions per capita in the study countries 1991–2021

*Source: WDI database.*

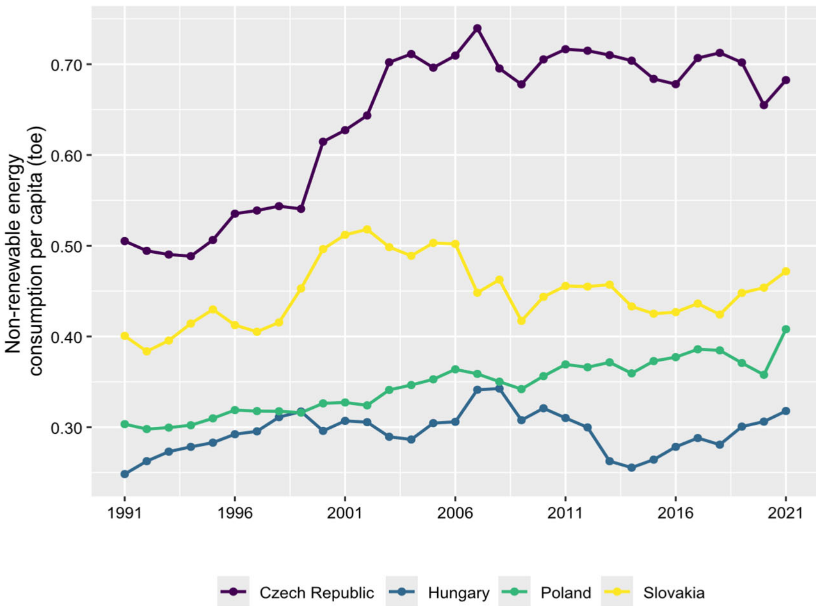


**Figure 2:** Electricity consumption from non-renewable sources in the study countries 1991–2021
*Source: EEA/Eurostat database.*

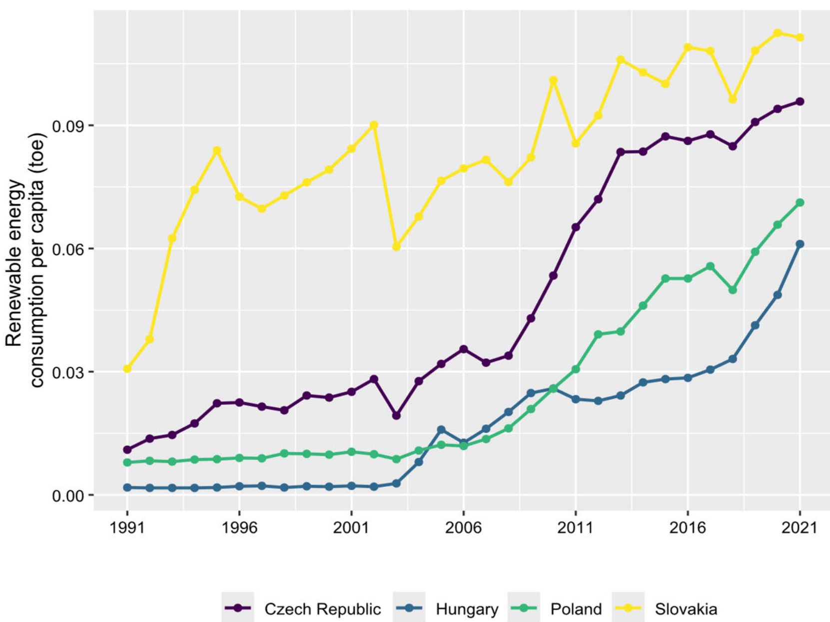


**Figure 3:** Electricity consumption from renewable sources in the study countries 1991–2021
*Source: EEA/Eurostat database.*

### 4.2. Model estimation result

The next step of the study was to conduct unit root tests. Three different types of tests were used for this purpose. The first was the unit root test of the second generation CIPS panel (Pesaran 2007) and the first generation test – Augmented Dickey–Fuller test (Dickey and Fuller 1979). The results of the tests are shown in Table 4. The tests performed indicate that all variables are stationary at the first difference, I (1). The results confirm that the tested variables meet the assumptions of the NARDL model.

**Table 2:** Panel data unit root tests

| Variable | I (0) Level | | I (1) First difference | |
|---|---|---|---|---|
| | CIPS | ADF | CIPS | ADF |
| $lnCO_2$ | -2.14 | -0.98 | -5.64* | - 7.24* |
| lnGDP | -1.54 | 0.75 | -3.61* | -5.85* |
| lnNREW | -2.08 | -0.26 | -4.95* | -6.68* |
| lnREW | -1.23 | 0.94 | -3.36* | -6.38* |

*The significance of the coefficients is indicated by an asterisk in the tables, where ***, **, * denotes 5%, 1%, and 0.1% significance level, respectively.*

*Source: author's calculations.*

Table 5 shows the results of the Wald test for the long-run coefficients and diagnostic tests. The results indicate that there is significant asymmetry in the long run for the GDP and NREW variables at the 10% significance level, while for the REW variable, the presence of statistically significant asymmetry could not be confirmed. Therefore, parameters for the REW variable were estimated using a linear method. The Kao cointegration tests (Kao 1999) for the panel data is also statistically significant at the 5% level. The result of the test performed confirms that there is a sustained strong relationship between the study variables in the long term.

**Table 5:** NARDL model asymmetry test results and diagnostics

| Variable | Statistics | Value | Probability |
|---|---|---|---|
| lnGDP | F | 4.594 | 0.034 |
| | $\chi 2$ | 4.595 | 0.032 |
| lnNREW | F | 2.833 | 0.095 |
| | $\chi 2$ | 2.834 | 0.092 |
| lnREW | F | 1.182 | 0.279 |
| | $\chi 2$ | 1.183 | 0.276 |
| Kao-cointegration test | t | -2.371 | 0.009 |
| Log likelihood | | | 257.1 |

*Source: author's calculations.*

The results of the estimation of the parameters of the long-run model are presented in Table 6. All the results obtained are statistically significant at the 10% significance level, allowing inference from the estimated model. The NARDL results indicate the existence of asymmetry in the long term regarding the impact of economic growth and energy production from non-renewable sources on $CO_2$ emissions in the studied countries. According to the obtained parameters, a 1% increase in non-renewable energy consumption leads to a 0.26% increase in $CO_2$ emissions, while a 1% decrease in consumption generates a 0.63% decrease in $CO_2$ emissions. In contrast, a 1% increase in GDP translates into a 0.21% increase in $CO_2$ emissions, while a 1% decrease in GDP results in a 1.02% decrease in $CO_2$ emissions. The results also show that the increase in energy consumption from renewable sources in the long term does not show significant asymmetry. Its increase by 1% is associated with a decrease in $CO_2$ emissions of 0.05%.

**Table 6:** NARDL long-run results

| Variable | Coefficient | Standard error | t-statistics | Probability |
|---|---|---|---|---|
| lnREW | -0.045 | 0.016 | -2.831 | 0.005 |
| $\varphi^+$ lnNREW | 0.269 | 0.158 | 1.700 | 0.092 |
| $\varphi^-$ lnNREW | 0.637 | 0.098 | 6.496 | 0.000 |
| $\varphi^+$ lnGDP | 0.208 | 0.062 | 3.340 | 0.001 |
| $\varphi^-$ lnGDP | 1.022 | 0.339 | 3.014 | 0.003 |
| Const. | 1.442 | 0.098 | 14.588 | 0.000 |

*Source: author's calculations.*

Table 7 shows the results of the estimation of the short-term model. The results confirm the impact of economic growth and energy consumption from non-renewable sources on $CO_2$. However, no statistically significant short-term correlations between renewable energy consumption were confirmed. As a result of the model estimation, an error correction factor (ECT T-1) of -0.61 was also estimated. The negative and statistically significant correction factor is in line with the convergence requirements and further confirms the existence of long-term cointegration. In interpreting the ECT coefficientt-1, it is important to point out the relatively rapid adjustment of $CO_2$, to long-run equilibrium (within about 1.5 years) in the face of shocks, and the general downward trend in the long run in the countries studied.

**Table 7:** NARDL short-run results

| Variable | Coefficient | Standard error | t-statistics | Probability |
|---|---|---|---|---|
| ECTt-1 | -0.614 | 0.312 | -1.970 | 0.032 |
| $\Delta lnCO_2$ t-1 | 0.168 | 0.186 | 0.905 | 0.368 |
| $\Delta lnCO_2$ t-2 | -0.063 | 0.137 | -0.459 | 0.647 |
| $\Delta lnCO_2$ t-3 | -0.118 | 0.226 | -0.521 | 0.604 |
| ΔlnREW | -0.029 | 0.041 | -0.700 | 0.486 |
| ΔlnREW t-1 | -0.038 | 0.026 | -1.421 | 0.159 |
| ΔlnREW t-2 | 0.012 | 0.038 | 0.304 | 0.762 |
| ΔlnREW t-3 | -0.003 | 0.036 | -0.080 | 0.936 |
| ΔlnNREW | 0.355 | 0.190 | 1.868 | 0.065 |
| ΔlnGDP | 0.512 | 0.258 | 1.985 | 0.050 |
| ΔlnGDP t-1 | 0.083 | 0.195 | 0.428 | 0.670 |
| ΔlnGDP t-2 | 0.205 | 0.049 | 4.138 | 0.000 |
| ΔlnGDP t-3 | 0.236 | 0.342 | 0.691 | 0.491 |

*Source: author's calculations.*

In the final stage of the study, a causality test was conducted based on the Dumitrescu & Hurlin panel data test (2012). The test results indicate the existence of unidirectional causality from lnGDP to $lnCO_2$, from lnNREW to $lnCO_2$, from lnREW to $lnCO_2$, and from lnGDP to lnREW. Additionally, causality is observed from lnGDP to lnNREW, at the 10% significance level. Thus, according to the results of the causality test, all the variables tested have an impact on $CO_2$, which aligns with the model estimation results obtained. Furthermore, the causality test indicates that economic growth in the V4 countries induces energy consumption from both renewable and non-renewable sources.

**Table 8:** Results of Pairwise Dumitrescu-Hurlin panel causality tests

| Cause → Effect | W-Stat. | Zbar-Stat. | Prob. |
|---|---|---|---|
| lnGDP → $lnCO_2$ | 4.211 | 1.698 | 0.090 |
| $lnCO_2$ → lnGDP | 1.286 | -0.750 | 0.453 |
| lnNREW → $lnCO_2$ | 2.514 | 1.851 | 0.081 |
| $lnCO_2$ → lnNREW | 2.475 | 0.245 | 0.806 |
| lnREW → $lnCO_2$ | 4.244 | 1.726 | 0.084 |
| $lnCO_2$ → lnREW | 2.571 | 0.326 | 0.745 |
| lnNREW → lnGDP | 3.499 | 1.102 | 0.270 |
| lnGDP → lnNREW | 5.531 | 2.802 | 0.005 |
| lnREW → lnGDP | 1.521 | -0.553 | 0.580 |
| lnGDP → lnREW | 12.200 | 8.224 | 0.000 |
| lnREW → lnNREW | 1.297 | -0.741 | 0.459 |
| lnNREW → lnREW | 2.836 | 0.547 | 0.584 |

*Source: author's calculations.*

## 5. Discussion

In summary, the results of the study provide significant insights into the relationships between economic growth, renewable and non-renewable energy consumption, and $CO_2$ emissions in the V4 countries. The study indicates that there are both symmetric and asymmetric relationships between $CO_2$ emissions, renewable energy consumption, and economic growth. Notably, the impact of asymmetry on $CO_2$ emissions was confirmed only for the long term, while in the short term, all relationships were symmetric. These results demonstrate that asymmetric relationships between $CO_2$ emissions, energy consumption, and economic growth become more apparent over longer periods, reflecting long-term structural processes within the economy. In the short term, responses are often quicker and more uniform, leading to symmetric relationships.

However, over a longer time horizon, factors such as technology adaptation, changes in energy policies, and shifts in economic structure can result in more complex, asymmetric interactions. Additionally, the analysis of short-term asymmetric relationships would require higher frequency data (quarterly or monthly) for all variables studied, which are currently unavailable. In such cases, it would be possible to account for potential discrete non-linear dependencies.

The study indicates that the long-term asymmetric impact on $CO_2$ emissions is primarily driven by non-renewable energy consumption and economic growth. Specifically, a GDP decrease leads to a significantly larger reduction in emissions than a GDP increase causes a rise. Similarly, a decrease in non-renewable energy consumption results in a much greater drop in $CO_2$ emissions than an increase causes a rise.

Combining these findings, it can be noted that further economic development in the V4 countries may not have such a negative impact on the environment. This is associated with shifting growth towards more efficient energy use, developing less emissions-intensive economic sectors, and adopting ecological energy sources. According to the results, a fundamental issue for the V4 countries is their heavy reliance on non-renewable sources compared to renewable sources. The asymmetric relationship suggests that a significant reduction in emissions could be achieved either by curbing economic activity or by decreasing non-renewable energy consumption. Since causality tests indicate that economic growth in the V4 countries is driven by increased energy consumption, ensuring sustainable economic development can only be achieved by replacing non-renewable sources with renewable ones. The study indicates that only in the long term does an increase in renewable energy usage have a negative and symmetric effect on $CO_2$ emissions.

These observations align with findings by Papież et al. (2019), who noted that the positive economic aspects associated with renewable energy consumption become apparent only when the share of renewable energy in the energy mix is significantly increased. Similarly, Ben Jebli et al. (2020) found that renewable energy positively impacts economic growth and reduces $CO_2$ emissions in higher-income countries. Therefore, it appears crucial in this context that efforts to reduce $CO_2$ emissions in the V4 countries may follow only two pathways: first, by merely reducing non-renewable energy consumption, which could result in decreased economic activity, or second, by increasing the use of renewable energy, thereby ensuring sustainable economic development. The significance of renewable energy consumption's impact only in the long term suggests that the energy transformation process requires a substantial period to achieve its goals. In summary, the results obtained confirm hypotheses H2 and H3 and partially verify hypothesis H1 concerning the effect of renewable energy on $CO_2$ reduction, but only in a linear manner.

It is not straightforward to compare these results with those presented in earlier studies for three reasons. Firstly, to date, no study using the NARDL-PMG method has fully addressed the variables examined in this study. Secondly, the group of countries analyzed here does not overlap with those in previous studies. The V4 countries have mostly been included in broader sets of countries studied (e.g. all EU countries). Thirdly, this study employed the widest possible time range for the time series analyzed, which allowed for more precise results compared to previous research. Nevertheless, when limiting the comparison to studies that have investigated linear and non-linear relationships between energy consumption, economic growth, and $CO_2$ emissions, the results obtained are somewhat like those of previous studies.

In reference to studies specifically concerning the V4 group, the results obtained in this research align with those of Supron and Myszczyszyn (2023), which indicate a negative impact of non-renewable energy on environmental pollution and a positive effect of renewable energy. Similarly, the study by Litavcová and Chovancová (2021), which did not cover all V4 countries, also partially confirms these findings, particularly in the context of $CO_2$ emissions. This suggests that higher energy consumption leads to increased emissions but is necessary to sustain economic growth.

However, with some caution when considering studies using non-linear methods, including NARDL, that involve different countries, there are notable similarities. Kirikkaleli et al. (2023) and Akadiri & Adebayo (2022) confirm an asymmetric relationship between economic growth and $CO_2$ emissions in India, where a decrease in GDP results in a greater reduction in emissions than an increase in GDP leads to an increase in emissions. In contrast, the results of this study differ from those obtained for GCC countries by Islam & Rahaman (2023), who, using the NARDL-PMG model, did not confirm a non-linear but only a linear relationship between economic growth and $CO_2$ emissions in the long term. Additionally, studies using linear panel models by Li et al.

(2014), Lazăr et al. (2019) and Muço et al. (2021) confirmed a positive linear relationship between economic growth and $CO_2$ emissions.

Bekun et al. (2019), using the ARDL-PMG model, confirmed that an increase in renewable energy consumption contributes to a decrease in $CO_2$ emissions, while non-renewable energy consumption results in an increase in $CO_2$ emissions in the long term within EU countries, consistent with the results of this study. Furthermore, Chen et al. (2022), who studied a larger number of countries using non-linear methods (GMM), obtained similar results for developed countries, finding that a 1% increase in consumption from renewable sources results in a 0.04% decrease in $CO_2$ emissions, while a 1% increase from non-renewable sources results in a 0.6% increase. These findings are comparable to those obtained in this study.

## 6. Conclusions

The results provide robust evidence of a persistent and long-term relationship between renewable and non-renewable energy consumption, economic growth and $CO_2$ emissions in the V4 countries. The estimated model indicates that changes in these variables have a lasting impact on $CO_2$ emissions in this region. The study also confirmed that there is a significant asymmetry in the long-term relationship between non-renewable energy consumption and $CO_2$ emissions. This suggests that efforts to reduce non-renewable energy consumption may have a more significant impact on emission reductions. Also, economic growth shows an asymmetric impact on $CO_2$ emissions in the V4 countries, where a decrease in economic growth has a greater impact on $CO_2$ reduction than its increase. In view of this, energy efficiency improvements will be necessary to reduce $CO_2$ emissions without negative effects on economic growth. Investment in technologies and solutions for more efficient energy use should therefore be a priority in the V4 countries. Unlike non-renewable energy, renewable energy consumption does not show a significant asymmetry in the long-term relationship with $CO_2$. This suggests that policies promoting the use of renewable energy sources can contribute to reducing $CO_2$ emissions in the long term. At the same time, increasing the use of renewable energy should occur in a stable and long-term manner.

This study, like any empirical work, has certain limitations that could guide future research. First, environmental pollution is represented by $CO_2$ emissions. Future research could expand the analysis of the impact of energy consumption on the environment by including other greenhouse gases resulting from human economic activities (such as sulfur hexafluoride, carbon monoxide, and nitrous oxide). This would allow for more precise information and enable a comparative analysis of the effects of different types of gases. Second, this study considers economic activity as the total output expressed through GDP. To increase accuracy, future studies could focus on examining the asymmetric impact of individual economic sectors on environmental pollution. Finally, the study focuses on a narrow geographical area, encompassing the V4 countries. In future research, to draw broader conclusions, the presented model could be applied to a larger number of countries, covering the entire EU. This could also involve using classification methods and analyzing countries in groups based on characteristics such as the level of economic development and renewable energy usage.

Moreover, the NARDL model itself has certain limitations due to the way data is estimated. The model yields the best results when using relatively long time series with high frequency. As environmental and energy data for many countries have only been collected since the mid-1990s, trade-offs between measurement accuracy and the number of variables and lags are necessary. In addition, many important indicators have an even shorter measurement history. As the number of data periods increases, future studies could introduce additional variables into the model, such as innovation, research and development and social factors. This would increase the breadth and depth of knowledge, making it more detailed and accurate.

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