ASSESSMENT OF THE RELATIONSHIP BETWEEN ECONOMIC GROWTH, ENERGY CONSUMPTION, CARBON EMISSIONS AND RENEWABLE ENERGY SOURCES IN THE V4 COUNTRIES

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ABSTRACT. The aim of this paper is to assess the long-term and short-term relationships between economic growth, energy consumption, CO_2 emissions and the share of energy produced from renewable energy sources in the V4 countries in the period 1992-2019. The autoregressive distributed lag (ARDL) bounds testing methodology was applied for each of the examined variables as a dependent variable. The ARDL bounds reliably confirmed long-run cointegration between carbon emissions, energy consumption, economic growth, and renewables in Czechia, Slovakia, and Poland. Economic growth has a significant impact on carbon emissions in the long run in all of these three countries. Energy consumption has a significant impact on carbon emissions in the long-run in Poland; however, renewables significantly impact carbon emissions in Czechia and Slovakia. Understanding the interrelationships between the variables examined is essential for making informed and responsible decisions on climate and energy policies, strategies and actions in individual countries.

Introduction

Energy has been inextricably linked to human development since its beginning. It fueled and accelerated the industrial revolution more than two hundred years ago, and up to this day, it supports a highly complex interplay of human needs, desires, activities, and technologies. Although energy is fundamental for economic growth, its production and consumption are responsible for a number of negative environmental impacts. One of the most challenging global issues is anthropogenic greenhouse gas emissions, coming mainly from fossil fuel combustion for energy production. Rising concentrations of greenhouse gas emissions (especially CO_2) in the atmosphere are causing air temperature increases, resulting in climate change. According to the IPCC report, human-induced global warming reached approximately 1°C above pre-industrial levels and in the absence of efficient mitigation policies aimed at a sharp decline in greenhouse gas emission, global warming is likely to surpass 1,5°C sometime between 2030 and 2045 (IPCC, 2021). These unprecedented changes pose a threat to humanity and ecosystems in the form of various natural disasters, rapid weather changes, health problems, threats to biodiversity, etc.

Although EU greenhouse gas emissions are gradually being reduced, the energy sector is still the largest producer of these emissions. Until 2009, the second-largest share of greenhouse gas (GHG) emissions was accounted for by the industrial sector, whose emissions fell after that year and were replaced by those of the transport sector. As CO_2 accounts for up to 80% of total greenhouse gas emissions, it is considered the primary driver of climate change (EEA, 2021; Tiseo, 2021). An overview of GHG emissions by sector, accounting for the largest share of EU GHG emissions, is shown in Figure 1.
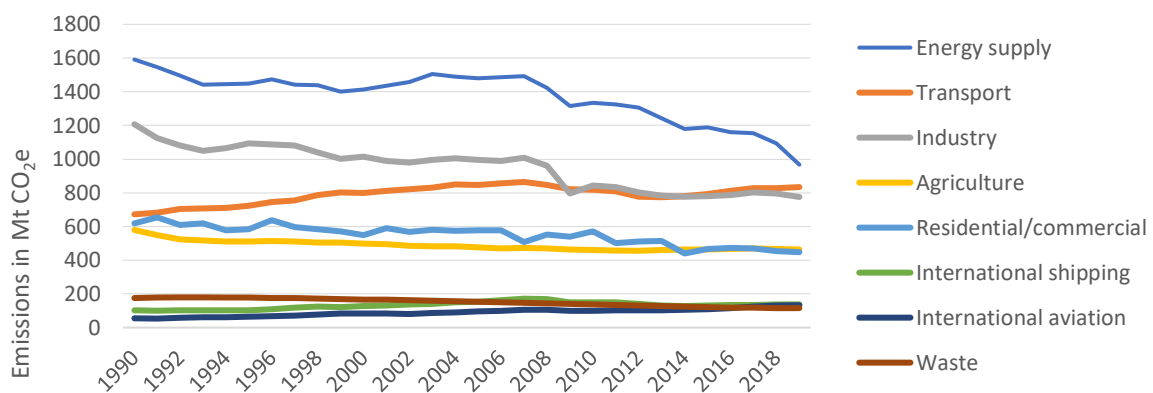

Figure 1. Annual greenhouse gas emissions in the European Union from 1990 to 2019, by sector (in million metric tons of CO_2-equivalent)
Source: *own processing, based on Eurostat*

The adverse effects of rising carbon dioxide levels in the atmosphere have become a central topic in global discussion on transition to a carbon-neutral, green economy (EC, 2020; OECD, 2014; United Nations, 2015). The importance of these issues is also reflected in the European Union's political and strategic decisions. In December 2019, the EU introduced an ambitious proposal to make the bloc climate-neutral by 2050 (EC, 2019). This objective is at the heart of the European Green Deal and is in line with the EU's commitment to global climate action under the Paris Agreement. However, not all countries are proponents of green growth visions. Especially in V4 countries, Poland and the Czech Republic are reluctant to reduce greenhouse gases at the expense of economic development. The aim of the paper is to discuss the link between economic growth, energy consumption, CO_2 emissions and the share of renewable energy sources in energy production in the V4 countries. Assessing the relationship between the four variables will shed light on the driving forces of CO_2 emission production and the potential mitigation effect of renewables.

The paper is structured as follows. First, the theoretical background and overview of the previous empirical research carried out in this area are presented. Section 2 outlines the research methodology and data used. In the third section, the results of analysis are presented, followed by the fourth section discussing the results and limitations of the research. The last section concludes the paper.

Theoretical background

Numerous studies focus on investigating the relationship between economic growth, energy use and GHG emissions, testing the validity of the Environmental Kuznets Curve (EKC) hypothesis that postulates an inverted U-shaped relationship between environmental degradation and per capita income in different countries/regions.

The use of EKC can be observed on two levels: theoretical and empirical. Theoretical studies devoted to the EKC can be traced to the early 1990s. One of the seminal works in this field was a study on measures to improve air quality (Grossman & Krueger, 1991). Other theoretical works from this period include (Panayotou, 1994) and (Shafik, 1994), in which the authors provide the earliest and most detailed explanation of the possible relationship between the degree of environmental degradation and the level of economic development expressed by the EKC (Yandle et al., 2004).

The empirical research on EKC focused mainly on two areas. The first group consists of studies examining the validity of the EKC for various indicators of environmental pollution (e.g., Diao et al., 2009; Hilton & Levinson, 1998; Kaika & Zervas, 2013; Sapkota & Bastola, 2017; Sarkodie, 2018; Selden & Song, 1994). These studies confirm the EKC's hypothesis that although economic growth leads to an increase in emissions at the beginning of economic development, over time these emissions may decrease due to various technological and structural changes in the economy. The second group of studies focuses on turning points for specific pollutants and countries (e.g. Apergis & Ozturk (2015); Gawande et al. (2000); Özokcu & Özdemir (2017); Park & Lee (2011); Patel et al. (1995); Zaim & Taskin (2000). Numerous studies on extensive material empirically demonstrate the validity of the EKC for various pollutants and processes in the environmental sphere (air, water, deforestation), as well as for economic sectors and countries. The validity of the EKC hypothesis, confirmed by many empirical studies, has led to its application in complex international research (e.g. Bölük & Mert (2014); Chovancová & Vavrek (2019); Cole et al. (1997); Miglietta et al. (2017); Sarkodie & Strezov (2018); Shafiei & Salim (2014); Waqih et al. (2019)).

However, the relationship between economic growth and environmental impacts is not straightforward, and other variables enter into this relationship. The United Nations report (UN, 2021), which assesses the achievement of sustainable development goals, emphasizes that energy consumption is responsible for 60% of total global greenhouse gas emissions. In light of this, the interaction between environmental degradation, energy consumption, and economic growth has been a frequently discussed issue in the energy economics literature in the last few decades. Ang (2007) first examined the dynamic relationship between pollutant emissions, energy consumption and economic development in France between 1960 and 2000. Ang points out that if these three variables are intensely interconnected, omitting one of them can cause serious problems in empirical analysis. Tiba & Omri (2017) conducted a comprehensive literature review on the relationship between energy, the environment, and economic growth at the level of individual countries and regions. After Ang, different authors explore the interrelationships of the three variables for different countries: e.g. Soytas et al. (2007) focused on the USA, Zhang & Cheng (2009) analyzed the situation in China, Halicioglu (2009) in Turkey, Acaravci & Ozturk (2010) analyzed nineteen EU Member States, Vavrek & Chovancová (2020) examined energy performance of EU28, Baloch et al. (2019) performed the analysis of BRICS countries, Ozcan & Tzeremes (2020) surveyed 27 OECD countries and Litavcová & Chovancová (2021) performed the analysis of Danube region countries.

Researchers and practitioners point to renewable energy sources as a possible avenue for rebalancing economic growth, and environmental quality. Hence, the development of renewable energy has attracted the attention of many countries, including the EU member states. Therefore, this study examines the interrelationship between economic growth, energy consumption, greenhouse gas emissions, and the share of energy from renewable sources as a possible tool for mitigating negative environmental impacts.

Data and methodology

Data

The paper examines the relationship between economic growth (GDP per capita), energy consumption per capita, CO_2 emissions per capita, and the share of renewable energy sources in the Visegrad Group (V4) countries (Czech Republic, Hungary, Poland, and Slovakia) in the period 1992-2019. The data were retrieved from the World Bank's databases (GDP per capita in constant 2010 US $)

and Eurostat (energy consumption per capita in kWh, CO_2 per capita in tons, renewable energy sources in % of gross final energy consumption).

The descriptive statistics are presented in Table 1, where the mean, minimum and maximum values, and standard deviation are calculated for each of the V4 countries. Stata 15.1 was used as the software tool for data processing and statistical analysis.

Table 1. Descriptive Statistics, n=28

| | | Czechia | Slovakia | Hungary | Poland |
		CZ	SK	HU	PL
GDP per capita	Mean	29978,67	21194,98	20461,56	22901,04
	Min	20760,05	11690,94	10714,66	15854,16
	Max	40696,31	31871,33	33120,52	32553,52
	Std.Dev.	6156,32	6523,68	6604,11	4807,33
Per capita CO2 emissions	Mean	11,590	7,508	8,639	5,428
	Min	9,430	6,020	7,090	4,350
	Max	13,969	9,040	9,940	6,143
	Std.Dev.	1,292	0,897	0,602	0,521
Energy consumption per capita	Mean	46878,68	37557,10	29018,28	27758,85
	Min	43317,38	32904,99	25954,79	24560,78
	Max	51297,28	41549,63	32106,32	30463,14
	Std.Dev.	2284,56	2684,21	1582,11	1373,81
Renewables (% sub energy)	Mean	2,569	6,515	2,342	1,593
	Min	0,808	2,529	0,380	0,198
	Max	5,183	9,700	6,182	4,017
	Std.Dev.	1,645	1,583	2,133	1,360

Source: *own processing, based on Eurostat and World Bank*

The Czech Republic leads the table in GDP per capita, per capita CO_2 emissions, and energy consumption per capita. The share of renewables in this country is the second-lowest, with a maximum of 5,183%.

Energy consumption per capita reaches the highest number in Slovakia, but renewables are also in the highest place among the surveyed countries. However, all of these countries lag far behind the EU average of 19.7% in 2019 in renewable energy production.

Significant heterogeneity of individual variables can be observed in some countries, which is reflected in the high value of standard deviation. Hungary and Slovakia are examples of countries where the signifficant growth of GDP can be observed. However, despite significant GDP growth, except for the Czech Republic, all countries in the survey group are below the EU average GDP per capita, which was 35,070.328 USD in December 2019.

Methodology

The theoretical and empirical literature indicates that economic growth, CO_2 emissions, and energy consumption are bound together, as well as that employing renewable energy sources has a mitigating effect on the production of greenhouse gas emissions. We work with such data from four countries, collectively known as the Visegrad Group. All variables related to economic growth, energy consumption, CO_2 emissions, and renewables are utilized in natural logarithmic form. We use the abbreviations logGDPt, logCO2t, logECt, and logRESt to denote their values at time t.

This research utilizes the unit root test of Dickey & Fuller (Dickey & Fuller, 1979), and bound test for cointegration of Pesaran et al. (Pesaran et al., 2001) which is extended by critical values and approximate p-values of Kripfganz and Schneider (Kripfganz & Schneider, 2020).

Some time series are bound together due to equilibrium forces even though the individual time series might move considerably. We focus on four of such series, logGDPt, logCO2t, logECt, and logRESt. The methodology to determine this long-term impact and significance of considered variables uses an

autoregressive distributed lag (ARDL) modelling approach, widely developed by Pesaran and Shin (Pesaran & Shin, 1999) and Pesaran, Shin and Smith (Pesaran et al., 2001), which allows establishing whether there is cointegration between the variables, even if they are of a different order. For the purpose of efficient estimation of the model coefficients, an optimal lag order is obtained with model selection criteria such as the Akaike or Schwarz information criterion. However, for testing purposes, it is of primary concern that the error term is free of serial correlation. Once a conclusion from the test is drawn, a more parsimonious model can be estimated (Kripfganz & Schneider, 2020).

An additional advantage of its estimation is that it allows obtaining unbiased and efficient parameters when the presence of endogeneity and serial correlation problems is suspected. In addition, it is more appropriate for estimating short and long term on small samples, which is also our case.

For the first, the stationarity test was done using the Augmented Dickey–Fuller (ADF) test to ensure that none of the series employed in this study is I(2) (Litavcová & Chovancová, 2021).

To find a cointegration relationship between economic growth, CO_2 emissions, energy consumption, and renewables employed ARDL(p,q_1,q_2,q_3) model can be expressed as follows:

$$y_t = c_0 + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=0}^{q_1} \beta_{1,i} x_{1,t-i} + \sum_{i=0}^{q_2} \beta_{2,i} x_{2,t-i} + \sum_{i=0}^{q_3} \beta_{3,i} x_{3,t-i} + u_t \tag{1}$$

where $p \geq 1, q_1 \geq 0, q_2 \geq 0, q_3 \geq 0$ are optimal lag orders for dependent variable y and three independent variables x_1, x_2 and x_3; φ-s and β-s are coefficients; c_0 is a constant; u_t is the error term. Independent variables allowed to be I(0) or I(1) or cointegrated. For each of the considered countries, we estimate four ARDL models, for each of the four variables logGDPt, logCO2t, logECt, and logRESt in the position of the explained variable.

The existence of a long-run cointegrating relationship can be tested based on the error correction representation. A bounds testing procedure allows to find out this relationship regardless the variables are integrated of order zero or one, I(0) or I(1), respectively. In this way, if the value calculated for the F-statistic is above the critical value of the upper limit, the null hypothesis of no cointegration is rejected and the existence of a long-term relationship is concluded. On the contrary, if the F-statistic is below the critical value of the lower limit, it implies the absence of cointegration (Pesaran et al., 2001).

However, where there is cointegration according to Pesaran et al. (2001), the model can be represented by an error correction form. The error-correction form of the ARDL model separates the adjustment coefficient to deviations from long-run equilibrium, long-run coefficients, and short-run coefficients. The model can be written as follows:

$$\Delta y_t = c_0 - \alpha\big(y_{t-1} - \theta_1 x_{1,t} - \theta_2 x_{2,t} - \theta_3 x_{3,t}\big) +$$
$$+ \sum_{i=1}^{p-1} \psi_i \Delta y_{t-i} + \sum_{i=0}^{q_1-1} \gamma_{1,i} \Delta x_{1,t-i} + \sum_{i=0}^{q_2-1} \gamma_{2,i} \Delta x_{2,t-i} + \sum_{i=0}^{q_3-1} \gamma_{3,i} \Delta x_{3,t-i} + u_t \tag{2}$$

where α is the speed adjustment coefficient; θ-s are long-run, ψ-s and γ-s are short-run coefficients. To confirm the long-term relationship, the coefficient α is expected to be negative and statistically significant. Likewise, to ensure the validity of the results of the cointegration test, the tests of heteroscedasticity, autocorrelation and normality of the residuals are applied. In line with Odugbesan and Rjoub (Odugbesan & Rjoub, 2020), we also employed Breusch–Godfrey Serial Correlation LM (Lagrange multiplier) test to investigate a serial correlation in each equation, and Breusch–Pagan–Godfrey heteroskedasticity test was also used to determine that the model is free from the heteroskedasticity problem. To test the normality of residuals, the SW test was used. Finally, as (Pesaran et al., 2001) recommend, the cumulative sum of recursive residuals (CUSUM) should be applied in determining the stability of the ARDL model.

Results

Unit Root Test

The unit root test was applied to determine the stationarity of our data set. This is necessary to avoid an unpredictable outcome in our time series analysis (Odugbesan & Rjoub, 2020). There exist several tests of stationarity. In this analysis, one of them, particularly the augmented Dickey-Fuller unit-root test (ADF) on the level and on the first difference was employed. The three-time series are stationary already at level, i.e. logRES in Slovakia, and logCO2 in Poland and in Hungary. In the case of logGDP and logEC, the time series of all countries have unit root at a level and are stationary after the first differences. Also variables logCO2 and logRES meet the requirements for further analysis because they

are stationary at the first difference. None of the variables employed in the analysis is integrated at I(2) so as not to violate the assumptions of ARDL (Pesaran et al., 2001).

Table 2 Augmented Dickey-Fuller unit-root test

	logGDP		logCO2		logEC		logRES	
Country	Level	First difference	Level	First difference	Level	First difference	Level	First difference
Czechia	-0.567	-3.449**	-1.541	-7.003***	-1.465	-4.689***	-0.784	-5.978***
Slovakia	-1.216	-3.919**	-1.679	-8.092***	-1.091	-7.407***	-4.175***	-6.119***
Poland	-1.517	-3.154*	-3.238*	-9.731***	-1.230	-4.408***	-0.050	-4.421***
Hungary	0.121	-3.374*	-3.119*	-8.756***	-1.710	-4.441***	-0.505	-3.447**

Note: *The significance of the ADF test is indicated by an asterisks in the table where "*", "**", "***" denotes 5%, 1%, and 0.1% significance level.*

ARDL bound testing for cointegration

The results of the bound test show F-values and the lower and upper critical F-values of Kripfganz & Schneider (Kripfganz & Schneider, 2020) at 5% are captured in table 3.

Table 3. The ARDL Bound Testing for cointegration with Kripfganz and Schneider (Kripfganz & Schneider, 2020) critical values and approximate p-values

Country	Variable	F-statistic	I(0) bound (5%)	I(1) bound (5%)	Co-integration	Decision
CZ	logCO2	12.355	3.979	5.729	Yes	error correction model
	logLEC	4.953	3.967	5.660	Yes	error correction model (in 10% cv)
	logGDP	1.744	3.929	5.454	No	short-run model
	logRES	5.718	3.992	5.798	Yes	error correction model
SK	logCO2	crashed			Yes	error correction model
	logLEC	2.652	3.941	5.523	No	short-run model
	logGDP	crashed			Yes	error correction model
	logRES	5.737	3.916	5.385	Yes	error correction model
PL	logCO2	21.169	3.904	5.317	Yes	error correction model
	logLEC	11.189	3.979	5.729	Yes	error correction model
	logGDP	4.830	3.904	5.317	No	short-run model
	logRES	3.350	3.941	5.523	No	short-run model
HU	logCO2	crashed			No	short-run model
	logLEC	crashed			No	short-run model
	logGDP	5.630	3.916	5.385	No	short-run model (due t test)
	logRES	6.121	3.954	5.591	Yes	error correction model

In the case of Czechia, if CO_2 is the dependent variable, then the cointegration among CO_2, GDP, energy consumption and renewables was detected. This indicates that there are possibilities of a long-run relationship among the variables. So there will be necessary to estimate the error correction model to determine the speed of adjustment in case there is a shock. The same applies for the energy consumption and renewables as dependent variables. Based on the result of the ARDL bounds test for cointegration, for GDP as a dependent variable, it is necessary to apply only the ARDL short-run model. Here, the cointegration was not confirmed.

In the case of Poland, when CO_2 and energy consumption are considered ependent variables, the cointegration with the other three variables was revealed and the error correction model was performed to determine the significance of the long-run relationship and the speed of adjustment. For GDP and renewables in the position of dependent variable, there is no cointegration, i.e. only a short-run model was applied.

As for Slovakia, the result from the bounds test shows a cointegration when renewables is the dependent variable, while in the case of $logCO_2$ and logGDP bound test failed due to the small number of data. When examining both models, i.e. long-run and short-run, based on the results we decided for the error correction model.

Considering Hungary, the same situation occurred. Similarly, as in Slovakia, we decided for the ARDL (short-run) models for variables CO_2 and energy consumption because the time series were too short. In this country, the selection of the error correction model was verified by a bound test only for renewables as the dependent variable. The bound test showed the suitability of the short-run model for variable logGDP.

Estimates for causal relationship

For Czechia, Slovakia and Poland, the error correction model was estimated to determine the long-run relationship and the speed of adjustment due to the long-run relationship among CO_2 emissions, economic growth, energy consumption, and renewables. As can be seen in Table 4, the economic growth and CO_2 emissions have a stable long-run causal relationship in all of these three countries. The Error Correction Term (ECT) coefficients for these countries are −2.41, −1.04, and −1.47; all of them are negative and statistically significant. The first of them is too low - this implies that it will take a long period for the system to adjust back to equilibrium in the presence of shock and equilibrium will be adjusted in a dampening manner (Odugbesan & Rjoub, 2020). Diagnostic tests reveal that models for Czechia and Slovakia have a serious problem with serial correlation and the model for Poland has a problem with the normality of residuals. As the time series were too short, a better model could not be found. If there is no validity problem, the result implies that in the presence of shock, it will take a long time to return back to equilibrium as a result of the high speed of adjustment in these countries (Odugbesan & Rjoub, 2020).

The results in Table 5 reveal statistically significant short-run causality running from economic growth to CO_2 emissions in Slovakia and Hungary. The short-run causality running from energy consumption to CO_2 emissions has been demonstrated in the same countries, i.e. Slovakia and Hungary, and the short-run causality running from renewables to CO_2 emissions has been demonstrated in Czechia, Slovakia and Hungary. The results for Hungary are the product of a valid short-run model.

The variables that contribute to the economic growth in the V4 countries are depicted in Table 4. The results reveal that only in one country, i.e. Slovakia, the CO_2 emissions, and renewables have a long-run relationship with economic growth. But, as diagnostic tests reveal, there is a problem with serial correlation in this model.

The results shown in Table 5 indicate that there is a short-run causality running from CO_2 emissions to economic growth in three countries: Czechia, Slovakia and Poland, whereas the other two variables, energy consumption and renewables, have short-run causality to economic growth in Slovakia, Poland and Hungary.

The existence of cointegration, i.e. long-run relationship among energy consumption, economic growth, CO_2 emissions and renewables was present in Czechia and Poland, as it follows from Table 4. The ECT coefficient for Czechia is −0.47 and the long-run relationship is stable and valid. This implies that the energy consumption converges to the long-run equilibrium by 47% in one period with the speed adjustment via the channel of economic growth, CO_2 emissions, and renewables (Türsoy, 2017). As in the model for Poland, random errors are not normally distributed; the model is not valid. However, a better model could not be found. Statistically significant short-run causality running from economic growth to energy consumption was present only in Czechia, as it follows from Table 5. The short-run causality running from CO_2 emissions to energy consumption has been proved in Poland and Hungary, and the short-run causality running from renewables to energy consumption has been demonstrated in Slovakia, Poland, and Hungary.

On the variables that contribute to the increase of renewables use for energy production in the V4 countries, the results depicted in Table 4 reveal that in Czechia, Slovakia, and Hungary economic growth, CO_2 emissions, and energy consumption a long-run relationship with renewables is present, with good validity of all three long-run models. Table 4 shows that economic growth and CO_2 emissions have a stable long-run causal relationship with renewables in Czechia and Hungary. However, energy consumption has a stable long-run causal relationship with renewables only in Slovakia. The ECT coefficient of a stable long-run relationship for Slovakia is −0.84. Therefore, this implies that the renewables converge to the long-run equilibrium by 84% in one period with the speed adjustment via the channel of economic growth, CO_2 emissions, and energy consumption (Hobijn et al., 1998).

Moreover, the results shown in Table 5 reveal that there is also a short-run causality running from economic growth to renewables in Hungary, running from CO_2 emissions to renewables in Czechia and Hungary. The significant short-run relationship running from energy consumption to renewables has not been demonstrated in any of the V4 countries. This implies that energy consumption in the V4 countries does not cause renewable energy consumption.

The diagnostic tests mentioned in the previous chapter was used for verification of the validity of each model. It was found that 9 of all 16 models are valid and relevant and can support responsible

and evidence-based decisions and policy making. Also, the testing of the stability of the models revealed that they all fall within the 5% significance level boundary.

Table 4 Long-run statistic and Diagnostic test

Part A: Long run statistics

	Dependent variable	logGDPt	logCO2t	logLECt	logLRESt	ECT
CZ	ΔlogCO2t	0.14*		-0.15	-0.22***	-2.41***
	ΔlogLECt	0.56**	0.37		-0.16*	-0.47**
	ΔlogGDPt					
	ΔlogRESt	0.74**	-4.36***	-0.71		-1.99**
SK	ΔlogCO2t	-0.51***		0.04	0.33*	-1.04***
	ΔlogLECt					
	ΔlogGDPt		-1.90***	0.11	0.69**	0.32**
	ΔlogRESt	-0.01	-0.50	-1.98**		-0.84***
PL	ΔlogCO2t	-0.16*		0.78***	0.02	-1.47***
	ΔlogLECt	0.15**	0.89***		-0.001	-1.61***
	ΔlogGDPt					
	ΔlogRESt					
HU	ΔlogCO2t					
	ΔlogLECt					
	ΔlogGDPt					
	ΔlogRESt	4.68***	-5.44**	3.64		-0.67***

Part B: Diagnostic tests

	Dependent variable	Normality Shapiro Wilk p-value	Ser. Corr bgodfrey p-value	Homoskedasticity imtest white p-value	Stability
CZ	**ΔlogCO2t**	0.20	0.01**	0.40	stable
	ΔlogLECt	0.81	0.14	0.40	stable
	ΔlogGDPt	0.31	0.68	0.76	stable
	ΔlogRESt	0.29	0.09	0.40	stable
SK	**ΔlogCO2t**	0.72	0.02*	0.40	stable
	ΔlogLECt	0.96	0.93	0.40	stable
	ΔlogGDPt	0.34	0.02*	0.40	stable
	ΔlogRESt	0.07	0.32	0.26	stable
PL	**ΔlogCO2t**	0.02*	0.34	0.52	stable
	ΔlogLECt	0.01*	0.58	0.40	stable
	ΔlogGDPt	0.85	0.04*	0.40	stable
	ΔlogRESt	0.04*	0.58	0.40	stable
HU	**ΔlogCO2t**	0.98	0.47	0.40	stable
	ΔlogLECt	0.86	0.20	0.40	stable
	ΔlogGDPt	0.13	0.01*	0.40	stable
	ΔlogRESt	0.15	0.64	0.40	stable

Note: The significance of the coefficients is indicated by an asterisks in the tables where "*", "**", "***" denotes 5%, 1%, and 0.1% significance level.

Table 5. Short-run statistic

Part A	ΔlogGDP					ΔlogCO2				
Dependent variable	t	t-1	t-2	t-3	t-4	t	t-1	t-2	t-3	t-4
CZ ΔlogCO2t							0.89**	0.58**		
ΔlogLECt	0.25	-0.79**	0.12	-0.53*						
ΔlogGDPt		0.39*				0.21*				
ΔlogRESt						6.03**	3.25*	2.12*		
SK ΔlogCO2t	2.08***	1.86**					-0.72***	-0.66***	-0.38***	
ΔlogLECt	-0.17					0.18				
ΔlogGDPt		-1.09**				0.01	0.46***	0.41***	0.23**	
ΔlogRESt										
PL ΔlogCO2t										
ΔlogLECt						-1.07***	-0.57**	-0.18		
ΔlogGDPt		0.76**	-0.49*	-0.19		-0.14*	-0.02	-0.17	-0.20*	-0.20**
ΔlogRESt	-16.1	13.3	-6.39	-5.83		-2.01	0.84	-1.63	-3.09	-3.46
HU ΔlogCO2t	1.89	-2.28*	2.77**	-1.25*	-1.56*		-0.53*			
ΔlogLECt	0.46					0.26**	0.29**	0.41***	0.19**	
ΔlogGDPt		0.62*	-0.64*	0.52*		0.07	-0.04	-0.18		
ΔlogRESt	-9.21**	-3.41				1.49*				

Part B	ΔlogEC					ΔlogRES				
Dependent variable	t	t-1	t-2	t-3	t-4	t	t-1	t-2	t-3	t-4
CZ ΔlogCO2t						0.36**	0.34***	0.29**	0.12*	
ΔlogLECt		0.38*								
ΔlogGDPt	0.29					0.01				
ΔlogRESt	-1.93						1.18**	1.09**	0.45	
SK ΔlogCO2t	-0.02	-0.29	-0.69**	-0.57**		-0,33**	-0,34***	-0.23**	-0.13***	
ΔlogLECt		-0.26				-0.06	0.04	-0.14*		
ΔlogGDPt	0.03	0.18	0.45**	0.34**		0.21**	0.22***	0.14***	0.08**	
ΔlogRESt	1.26									
PL ΔlogCO2t										
ΔlogLECt		0.62**	0.42*			-0.08*				
ΔlogGDPt	0.05	0.20*	0.38**	-0.05	0.26	-0.03	0.04	0.07	-0.06*	-0.05*
ΔlogRESt	-1.43	2.17	6.30	-1.60	3.23		0.86	1.52*	-0.85	-1.07
HU ΔlogCO2t	1.85**	1.55**	-0.11	-0.65	1.87**	0.05	-0.23**	0.34**	-0.33**	0.42**
ΔlogLECt		-0.28	-0.49**	-0.34	-0.22*	0.03*	0.03*	-0.01	0.04*	-0.04
ΔlogGDPt	0.15	-0.26	0.35	0.22	-0.24*	-0.02	0.06*	-0.09**	0.07*	-0.10**
ΔlogRESt							0.48*			

Note: *The significance of the coefficients is indicated by an asterisks in the tables where "*", "**", "***" denotes 5%, 1%, and 0.1% significance level.*

Discussion

As shown in Tables 4 and 5, the analysis of the long-run and short-run relationships among four variables economic growth, energy consumption, carbon emissions, and renewables in the V4 countries reveals contrasting findings. To better understand these complex relationships, we have captured them graphically in table 6.

From the long-run perspective, the results for Czechia show the existence of a bi-directional relationship between renewables and carbon emissions, indicating that these two variables are jointly determined and affect each other, which supports the feedback hypothesis (Aydin, 2019). Economic growth has a positive effect on energy consumption, CO₂ and renewables. This implies that conservation policies aimed at energy efficiency and promoting the use of renewable energy sources do not influence economic growth (Menegaki & Tugcu, 2016). A bi-directional relationship between renewables and carbon emissions is also present in the short run.

Bi-directional long-run causality between economic growth and carbon emissions was found only in the case of Slovakia. This relationship was also confirmed in the study by Al-Mulali & Che Sab (2018) for South Korea. Renewables have a positive effect on GDP and CO₂, where uni-directional long-run causality can be observed. However, energy consumption negatively affects the share of renewable energy. Similarly, a bi-directional relationship between economic growth and carbon emissions is present in terms of a short-run relationship. In the short run, the negative effect of energy consumption

on the production of CO_2 emissions is also evident. Renewables contribute to a decline in CO_2 emissions and have a positive effect on the economic growth of the country in the short-term perspective. The wider adoption of renewable energy sources in this case brings multiple benefits – it improves the quality of the environment and public health and supports economic development. In a broader perspective, it presents a possible path for the V4 countries in meeting the climate neutrality targets set at the EU level (Hafner & Raimondi, 2020).

Table 6 Relationship between variables

Country	Long-run relationship	Short-run relationship
Czechia		
Slovakia		
Poland		
Hungary		

Note 1: ◄──────── *Uni-directional long-run relationship*
◄──────► *Bi-directional long-run relationship*
Note 2: *GDP – gross domestic product, CO₂ – carbon dioxide, EC – energy consumption, RES – renewable energy sources.*

Results for Poland show a positive uni-directional relationship between GDP and energy consumption, suggesting that an increase in GDP causes an increase in energy consumption in the long run. Similar results were achieved by Ozturk et al. (2010) in their study, where this relationship applied to low-income countries. The introduction of decarbonisation and energy efficiency measures will play an important role in this country. The negative uni-directional relationship between economic growth and CO_2 emissions implies that with a growing economy, CO_2 emissions decrease. This may be due to technological advancement and/or structural changes in the economy. This fact supports the EKC hypothesis, suggesting that at a certain level of economic development countries invest more in environmental measures, which is reflected in improving the quality of the environment. A feedback effect is evident between energy consumption and carbon emissions. The neutrality hypothesis applies to renewables, where there is no relationship between other variables in the long run, which complies with the findings of Menegaki (2011) for EU 27 countries. In the short run, CO_2 emissions affect negatively the economic growth of the country.

From a long-term perspective, we can observe only two uni-directional relations in the case of Hungary: the positive effect of economic growth on renewable energy sources and the negative effect of CO_2 on renewables. However, short-run relations are more complex. Feedback effects can be observed between renewables and CO_2 emissions, economic growth and renewables, as well as CO_2 emissions and energy consumption, implying that these variables affect each other. In the short term, unidirectional relationships can be observed running from GDP to CO_2 emissions, from energy consumption to GDP, and from renewables to energy consumption.

Conclusions

In the context of escalating global environmental pressures, it has become increasingly clear that Europe's prevailing model of economic development — based on steadily growing resource use and harmful emissions — cannot be sustained in the long term. Therefore, one of the priorities of the European Union and the V4 countries that are the subject of our research is the transition to a resource-efficient and a low-carbon society.

This study examines the long- and short-run relationships and causality between economic growth, energy consumption, and carbon emissions in V4 countries, including renewable energy, in a multivariate framework.

The ARDL bounds reliably confirm long-run cointegration between CO_2 emissions, energy consumption, economic growth, and renewables in Czechia, Slovakia, and Poland. Economic growth impacts significantly the levels of CO_2 emissions in the long run in all of these three countries. Also, energy consumption is a strong driver for carbon emissions in the long-run in Poland. However, renewables significantly impact carbon emissions in Czechia and Slovakia. In the short run, the impact of economic growth and energy consumption is significant in Slovakia and Hungary. The impact of renewables in Czechia, Slovakia and Hungary is also significant. Likewise, when examining cointegration between carbon emissions, energy consumption, economic growth, and renewables in the short run, a significant contribution of CO_2 emissions to energy consumption in Poland and Hungary was detected as a result of four models.

The analysis confirmed the existence of heterogeneous relationships between the examined variables in the individual V4 countries. Revealing the interrelationships between these variables represents an important knowledge base for decision-makers and other stakeholders responsible for the formulation of new and revision of existing climate and energy policies.

Acknowledgements

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