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# Heterogeneous Relationships Between $CO_2$ Emissions and Renewable Energy in Agriculture in the Visegrad Group Countries

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**Abstract**

This manuscript analyzes the relationship between carbon dioxide emissions and selected factors for the agricultural sector in the Visegrad Group (V4) countries. The aim of the study was to identify and assess short-term relationships and directions of causality between carbon dioxide emissions, renewable energy consumption, economic openness, labor productivity, and income levels in the agricultural sector of the V4 countries. Short-term ARDL modeling was used for each V4 country, along with Granger causality. The analyses offer a broad perspective on how agricultural practices shape greenhouse gas emissions and provide information to mitigate their environmental impact. Heterogeneous interactions between the studied factors and specific causal relationships were identified in each country. Only in Hungary and Slovakia was a unidirectional causality observed, namely $CO_2 \rightarrow$ renewable energy (RE) sources, while in Poland and the Czech Republic, no direct causal relationship with emissions was observed. However, these relationships were indirect through income and economic openness. Strong drivers include, in particular, labor productivity, the share of renewable energy, and economic openness. Based on the analyses, decision-makers are recommended to create incentives, including economic ones, to increase the share of renewable energy in agricultural production. This improves economic and environmental outcomes, both locally and nationally.

**Keywords:** agriculture; environmental economics; $CO_2$ emission; Granger causality; agriculture income; economic openness

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## 1. Introduction

Technological changes and ongoing progress, increasing the use of robots and leading to the substitution of human labor with objectified labor in agricultural production, are forcing a constant increase in energy demand. The intensive use of fossil fuel energy to sustain agricultural production growth increasingly faces both environmental and social barriers. In recent years, agri-food production has accounted for approximately one-third of total anthropogenic greenhouse gas emissions [1,2]. This is due to the increasing intensity of agricultural production, the development of high-energy agricultural production systems, and the use of additional chemical and organic inputs [3]. In the case of agricultural production, it is both a greenhouse gas emitter and a system that suffers the negative effects of this process. This necessitates a gradual transition from the exclusive use of fossil fuels towards renewable energy sources [4]. The issue is therefore important from

the point of view of energy security, but also controversial due to the development of technologies promoting the production of renewable energy. It often fails to deliver the expected environmental benefits due to political and economic mismatches [5]. Because most renewable energy sources are not yet economically viable, many countries offer numerous incentives, such as subsidies and tax breaks, to increase the share of renewable energy in the total energy mix [6]. This requires ongoing research and monitoring of the effects of adopted national policies. Therefore, initiatives are being undertaken internationally, supported by international agreements such as the Paris Protocol, aimed at limiting the anthropological impact on climate change, reducing the use of conventional energy sources, and promoting zero emissions [7]. This issue encompasses not only environmental issues but also highlights the relationship between environmental degradation and economic growth [8]. It also requires taking into account the issue of globalization, especially in terms of promoting a sustainable global emission pattern, and emphasizes the importance of convergence processes of macroeconomic policies for green growth [9]. This is supported by technological innovations in the field of energy, which ensure the acceleration of the energy transformation process [10]. Developing energy strategies and promoting the implementation of energy efficiency frameworks is recommended for the use of clean energy [11]. This makes it possible to control $CO_2$ emissions even in the case of continuous GDP growth, provided that the use of renewable energy is increased, the sectoral structure of production is improved, and the efficiency of fossil fuel technologies increases [12]. This issue is important due to the ongoing efforts to support energy transformation, but also due to the apparent interdependencies between economic growth and environmental degradation [13,14] and attempts to determine the relationship between $CO_2$ emissions and production [15], taking into account the sustainable development paradigm [16]. In light of previous research, it can be indicated that it is particularly important to understand how variables such as renewable energy consumption, labor productivity, economic openness, and income levels affect $CO_2$ emissions in the agricultural sector, as well as whether there are causal relationships between these variables. In the spatial context, in this case, the V4 countries, which are characterized by diverse agricultural and energy potential and different energy transition trajectories, this analysis takes on particular significance. Therefore, empirically examining the relationships and directions of causality between greenhouse gas emissions and selected economic and technical variables in the agricultural sector is particularly important. This approach allows for a better understanding of the mechanisms by which energy and economic policies impact agricultural production and the environment in which it occurs, as well as identifying potential actions to support emission reduction at a national level. This fills a research gap with a new number of countries and also highlights differences in the causal factors of agricultural structures. The aim of the study was to identify and assess short-term relationships and directions of causality between carbon dioxide emissions, renewable energy consumption, economic openness, labor productivity, and income levels in the agricultural sector of the V4 countries. The analysis takes into account the specific characteristics of each V4 country, enabling the identification of heterogeneous relationships and structural differences influencing the energy transition process in agriculture.

This study utilized short-term ARDL (Autoregressive Distributed Lag) modeling for selected factors influencing $CO_2$ emissions in agriculture in the V4 countries, supported by Granger causality analysis. The aim of the study was to determine the strength and direction of the impact of economic variables on greenhouse gas emissions in the agricultural sector and to identify the directions of causality. The research question was as follows: Is there homogeneity in the causal relationships between carbon dioxide emissions and factors such as renewable energy consumption, openness of the economy, factor income, and labor

productivity in the V4 countries? Furthermore, are there any short-term Granger causality relationships between the analyzed variables, indicating dynamic feedback over time? The main hypothesis was established as follows: there is a lack of homogeneity in the causal relationships between the analyzed variables in the V4 countries. This study fills a research gap in the agricultural sector in the V4 group and expands the scope of existing knowledge by identifying the directions of causality in agriculture.

## 2. The Relationships Between $CO_2$ Emissions and Economic, Social, and Technological Factors—Literature Review

### *2.1. Relationships Between $CO_2$ Emissions and Groups of Factors*

The relationships between $CO_2$ and economic, social, and energy factors are currently being widely studied in many countries, including European Union countries [17] and broad groups of countries using panel methods [18–21]. This assessment utilizes a wide range of econometric methods and variables, proposing specific policy implications [22]. Several important directions and observations can be identified that determine the need for further research. For the Chinese economy, $CO_2$ emissions were examined in relation to renewable energy, fossil fuels, urbanization, and economic growth. The results confirmed a positive impact of conventional energy on $CO_2$ emissions and a negative relationship between renewable energy and $CO_2$ [23]. However, research conducted by [24] in Pakistan demonstrated a negative relationship between renewable energy consumption and $CO_2$ emissions. Econometric models indicated that introducing renewable energy sources into the energy mix can reduce $CO_2$ emissions. In the case of agricultural production, positive and significant associations with emission levels were revealed.

Using the environmental Kuznets curve method for the EU [25] demonstrated a negative impact of renewable energy on carbon dioxide emissions, while non-renewable energy had a positive impact on $CO_2$ emissions. Directions of causality between variables were also indicated, including the existence of bidirectional causality between renewable energy and carbon dioxide emissions. Unidirectional causality was observed for the relationship between real income and carbon dioxide emissions, $CO_2$ emissions and non-renewable energy, and trade openness and $CO_2$ emissions. The results obtained using the same method showed a negative impact of renewable energy on $CO_2$ emissions and were also confirmed for the group of 17 OECD countries [26]. The negative impact of renewable energy on $CO_2$ emissions was confirmed for the G-20 group of countries, with a simultaneous positive impact of GDP and financial flows, and economic openness was insignificant [27]. In the case of the USA, the results of ARDL modeling indicate a mitigating impact of renewable energy consumption on environmental degradation processes, while a positive relationship between non-renewable energy consumption and $CO_2$ emissions was indicated [28]. Similar conclusions were drawn for India [29]. However, such causality analysis results are not universal. A study conducted on a group of nine developed countries [30] found no causal relationships between renewable energy and $CO_2$ emissions, although they were evident in other groups of variables, such as between renewable energy and GDP, bidirectional causality between labor and capital and between $CO_2$ emissions and capital, and a unidirectional causal relationship between GDP and $CO_2$ emissions, which was also reflected in many studies on the environmental Kuznets curve. Short-term causality studies for China revealed a bidirectional relationship between foreign trade, $CO_2$ emissions, and the share of non-renewable energy to renewable energy [31]. For Turkey, changes in GDP and non-renewable energy consumption were found to be correlated with increases in $CO_2$ emissions, while expenditures on healthcare and renewable energy sources were found to be correlated with reductions in $CO_2$ emissions in the long run. In the short run, GDP and renewable energy were found to be positively correlated with $CO_2$ emissions.

The causality test also showed a unidirectional causality between all variables and $CO_2$ [32]. For Thailand, unidirectional causality was found in the relationship between non-renewable energy and $CO_2$ emissions [33]. Subsequent studies also demonstrated a negative impact on emissions in the short term [34]. Using wave coherence analysis (WTC) for the Swedish economy, a negative correlation was found between $CO_2$ emissions and energy efficiency measures, ranging from short to long periods. Both the urbanization rate variable and the share of renewable energy had negative relationships with $CO_2$ emissions [35]. The research results consistently demonstrate a research trend concluding that increasing renewable energy consumption leads to a decrease in carbon dioxide emissions.

### 2.2. Research Methods Used

In light of the reviewed literature, it can be concluded that researchers represented two approaches in their analyses: those using econometric techniques examining the real impact of a specific group of factors on $CO_2$ reduction (e.g., ARDL, DOLS, FMOLS, or GMM models). This group also includes researchers examining social factors and cultural values that may influence emission levels [36]. The second group focused on cause-and-effect relationships, examining the directions of influence of specific variables and presenting evidence that increasing $CO_2$ emissions leads to an increase in RE consumption, but not always the other way around. This indicates that some countries may be increasing RE use in response to ongoing environmental degradation [37]. An additional trend can be identified, which currently presents extensive scientific achievements, derived from the environmental Kuznets curve (EKC) theory, indicating changes in the negative impact of economic growth on environmental degradation after reaching a certain growth level (turning point) [38]. Referring to the locational diversity of research, we can point to premises resulting from assessments of the European market. Europe has experienced numerous transformations in agricultural product markets, such as the development of sales channels for fresh fruit and vegetables; the liberalization of the European market; and changes in the production structure, technologies used, and the system of financial support for agriculture. However, this has resulted in an increase in energy demand for the entire agricultural sector [39], and consequently, an increase in greenhouse gas emissions. This is a consequence of the use of fossil fuel-based fertilizers, agricultural machinery, and biomass combustion in agricultural production [40]. This issue is important for decision-makers, as agricultural activity should meet food security goals and ensure beneficial impacts not only on the environment but also on social and economic issues [41]. Research also points to the growing importance of ecological innovations in agriculture and their impact on the sustainable development of the entire economy, combining economic benefits with environmental protection [42]. Unfortunately, these solutions often encounter barriers in the form of high initial costs compared to current technologies [43]. One option for supporting the environment is to examine the links between the transition to renewable energy sources in agriculture and $CO_2$ emissions. As studies indicate, the results are not clear and sometimes even contradictory (Appendix A). Research on the European market indicates several significant, but also specific, distinguishing features. In Western European countries with advanced agriculture, the potential for $CO_2$ emission reduction is relatively high due to high so-called "shadow prices" of $CO_2$ emissions, which, despite the use of various institutional solutions, are not fully internalized [41]. Furthermore, studies conducted using DEA and IDA (Index Decomposition Analysis) methods indicate that the main factor leading to a decrease in emissions is the reduction in the energy intensity of agricultural production [44,45]. Agricultural practices and institutional factors forcing changes to these practices are also important factors [46]. It is also worth referring to forecasts formulated in this area. Carozzi et al.'s [47] studies, using scenario methods, indicate that $CO_2$ emissions

will increase due to rising temperatures in the future, and their increase may exceed the capacity of ecosystems to absorb $CO_2$. Here, too, the spatial asymmetry of transformations is visible, which makes their reduction through implemented policies difficult. Changes on one side (e.g., increased production) have a stronger impact than reduced production, which makes emission-reduction policies more difficult if they are based solely on production constraints [48]. This consequence is particularly important. Numerous studies on agriculture demonstrate a lack of consistency in the relationship between renewable energy and $CO_2$ (Appendix A). The presented results indicate that the statistically significant RE variable for Slovakia caused an increase in $CO_2$ emissions. This is consistent with the results obtained by [49,50], although [51,52] indicate the opposite conclusions. Additionally, the income factor operated differently in different V4 economies depending on the order of the lag. This seems to confirm the presence of different economies on growth paths and whether or not they reached a turning point according to the environmental Kuznets curve. Intensifying trade in agriculture may force the use of conventional fuels on a larger scale, which also leads to a short-term increase in $CO_2$ emissions. Globalization processes [50,53], which are a consequence of trade liberalization, may act in a similar way. Agricultural productivity in the Czech Republic had a negative impact on emissions. This indicates better utilization of the labor factor, achieving the same or greater agricultural product with lower inputs. This result is also confirmed by studies [54]. If productivity growth goes hand in hand with the implementation of new technologies, it will result in reduced energy consumption. Therefore, the authors of [10] rightly note the need for technological innovations in the energy sector, which may also affect the agricultural sector. Causal relationships varied in each economy, demonstrating the heterogeneity of the agrarian structure and the relationships between variables. Such cases have been reflected in many studies (Appendix A).

### *2.3. Indication of Research Directions and Research Gaps*

The literature reviewed reveals several significant research gaps. Based on the literature review, it can be concluded that general or global studies on the relationship between energy consumption and $CO_2$ emissions predominate, but few studies focus on the agricultural sector, which has its own specific energy and emission characteristics. There is a lack of comprehensive research on the directions and strength of the causal relationships between $CO_2$ emissions and economic and technological factors in the agricultural sector of the Visegrad Group countries. Most studies assume a uniform structure of production and energy policy, ignoring the fact that, in reality, countries differ. Hence, there is no explanation of how the energy transformation taking place in the V4 countries affects the efficiency and competitiveness of agriculture, or whether this process can support emission reduction without limiting the growth of agricultural production, especially given the growing importance of food security. Consequently, the conducted research will allow us to determine which factors determine emissions in agricultural production to the greatest extent, determine the directions of interactions between variables, identify structural differences between the V4 countries, and, in terms of recommendations, indicate the directions of energy and agricultural policies that will support emission reduction while maintaining productivity growth.

## 3. Materials and Methods

This study utilized short-term ARDL (Autoregressive Distributed Lag) modeling for selected factors influencing $CO_2$ emissions in agriculture in the V4 countries, supported by Granger causality analysis. The aim of the study was to determine the strength and direction of the impact of economic variables on greenhouse gas emissions in the agricultural sector

and to identify the directions of causality. The research question was as follows: Is there homogeneity in the causal relationships between carbon dioxide emissions and factors such as renewable energy consumption, openness of the economy, factor income, and labor productivity in the V4 countries? Furthermore, are there any short-term Granger causality relationships between the analyzed variables, indicating dynamic feedback over time? The main hypothesis was established as follows: there is a lack of homogeneity in the causal relationships between the analyzed variables in the V4 countries. This study fills a research gap in the agricultural sector in the V4 group and expands the scope of existing knowledge by identifying the directions of causality in agriculture.

The study used statistical data for the years 2004–2023, concerning $CO_2$ emissions from agriculture, renewable energy consumption in agriculture, economic openness measured by the Grubel–Lloyd index, and farmers' income. The data were sourced from Eurostat databases. A full description of the variables is presented in Table 1. This study utilized short-term ARDL modeling for $CO_2$ emissions from agriculture and its relationships with farmers' income, agricultural labor productivity, economic openness, and renewable energy consumption for the V4 Group. It is worth noting that, due to the analysis of the full population of observations, *p*-values were treated as auxiliary measures of the strength and stability of the relationships. The modeling was supplemented by the identification of causal relationships using Granger causality. Taking action to reduce greenhouse gas emissions in agricultural production addresses at least three key challenges: reduction. The following hypotheses were adopted in this study:

**H1.** *In the Visegrad Group countries, there are short-term causal relationships between $CO_2$ emissions and renewable energy consumption.*

**H2.** *There is heterogeneity in the causal relationships between the analyzed variables across the Visegrad countries.*

**H3.** *Economic openness, labor productivity, and income influence the level of $CO_2$ emissions in the agricultural sector of the Visegrad countries in the short term.*

**Table 1.** Selection and description of variables.

| Variable | Variable Name | Description | Unit | Source |
|---|---|---|---|---|
| $CO_2$ emission | $CO_2$ emission | Greenhouse gas emissions by agriculture. | Thousand tonnes | Eurostat |
| RE | Renewable energy | Renewable energy consumption by agriculture | Thousand tonnes of oil equivalent | Eurostat |
| OP | Openness | Openness of the economy measured by the Grubel–Lloyd index. | million of ECU/EURO | Eurostat |
| FI | Factor income (Chain-linked volumes (2015)) | Measures the remuneration of all factors of production regardless of whether they are owned or borrowed/rented and represents all the value generated by a unit engaged in an agricultural production activity. | million euro | Eurostat |
| LP | Labor productivity | Labor productivity in agriculture calculated as the value added in agriculture to labor force in agriculture | million euro/Total labor force | Eurostat |

Source: own study.

ARDL (Autoregressive Distributed Lag) models were used to analyze the relationships between variables. Additionally, all variables were logarithmically transformed, allowing the results to be interpreted as percentage changes in the dependent variable per 1% change in the independent variables. ARDL models offer several advantages in time series analysis. They can be used regardless of whether the underlying variables are I(0), I(1), or a combination of both. Second, ARDL tests capture the data generation process by including the appropriate number of lags within the general and specific modeling framework. Furthermore, short-term adjustments can be integrated into long-term equilibrium in ARDL by deriving an error correction mechanism (ECM) using a simple linear transformation, without relying on long-term information. Furthermore, the ARDL approach outperforms the Johansen and Juselius approach in small samples [55]. The number of lags in the models was determined based on the Akaike criterion. The general form of the model is as follows:

$$\begin{aligned} &\boldsymbol{lnCO_2} = \boldsymbol{\alpha}_0 + \sum_{i=1}^{p} \boldsymbol{\beta}_1 \boldsymbol{lnCO_{2t-i}} + \\ &\sum_{i=0}^{q} \boldsymbol{\beta}_2 \boldsymbol{lnRE_{t-i}} + \sum_{i=0}^{q} \boldsymbol{\beta}_3 \boldsymbol{lnFI_{t-i}} + \sum_{i=0}^{q} \boldsymbol{\beta}_4 \boldsymbol{lnOP_{t-i}} + \sum_{i=0}^{q} \boldsymbol{\beta}_5 \boldsymbol{lnLP_{t-i}} + \boldsymbol{e_t}, \end{aligned} \quad (1)$$

where

$i$—lag index (from 0 to $q$ or from 1 to $p$);
$p$—number of lags of the endogenous variable;
$q$—number of lags of the explanatory variables;
$e_t$—random component.

Cointegration, heteroscedasticity, and autocorrelation tests were conducted to verify the model. The analysis was supplemented by identifying causal relationships using Granger causality. These methods are widely used in agricultural research and have been applied in numerous studies [56].

## 4. Results and Discussion

Time series data typically contain unit roots, which must be identified before proceeding with econometric modeling. Various unit root tests are used to detect these problems and eliminate undesirable results. Following the procedure for testing stationarity in time series modeling [57] and the presence of unit roots, the unit roots ADF test was performed (Table 2).

**Table 2.** ADF tests for I(0) and first differences.

| Country | Variable | I(0) | | I Diff. | |
|---|---|---|---|---|---|
| | | T-Stat | *p*-Value | T-Stat | *p*-Value |
| Poland | $CO_2$ | −3.386 | 0.0114 | - | - |
| Poland | FI | −1.811 | 0.3748 | −6.372 | 0.0000 |
| Poland | OP | −0.898 | 0.7888 | −3.948 | 0.0017 |
| Poland | RE | −2.868 | 0.0492 | - | - |
| Poland | LP | −0.529 | 0.8863 | −5.222 | 0.0000 |
| Czechia | $CO_2$ | −1.88 | −0.3415 | −3.89 | 0.0021 |
| Czechia | FI | −1.893 | 0.3352 | −3.879 | 0.0022 |
| Czechia | OP | −2.211 | 0.2024 | −5.765 | 0.0000 |
| Czechia | RE | −1.035 | 0.7401 | −3.194 | 0.0203 |
| Czechia | LP | −1.424 | 0.5708 | −4.338 | 0.004 |
| Hungary | $CO_2$ | −1.153 | 0.6934 | −3.653 | 0.0048 |
| Hungary | FI | −1.861 | 0.3504 | −5.570 | 0.0000 |
| Hungary | OP | −1.367 | 0.5981 | −4.541 | 0.0002 |
| Hungary | RE | −0.981 | 0.7600 | −6.021 | 0.0000 |
| Hungary | LP | −0.783 | 0.8241 | −5.687 | 0.0000 |
| Slovakia | $CO_2$ | −1.152 | 0.6940 | −4.607 | 0.0001 |
| Slovakia | FI | −1.966 | 0.3015 | −4.958 | 0.0000 |
| Slovakia | OP | −2.042 | 0.2684 | −3.415 | 0.0104 |
| Slovakia | RE | −1.600 | 0.4835 | −4.154 | 0.0008 |
| Slovakia | LP | −1.454 | 0.5561 | −5.252 | 0.0000 |

Source: Own calculations based on Stata17.

The vast majority of variables were found to be stationary in first differences. Only in the case of Poland, the $CO_2$ and RE variables were found to be stationary in levels and did not require further differentiation. This arrangement of variables justifies the choice of the ARDL model, due to the combination of I(0) and I(1). It becomes necessary to determine the choice of lags for the variables in the model. For this purpose, the Akaike information criterion was used. The final results are presented in Tables 3–6.

**Table 3.** ARDL for Poland.

| Variable | Coefficient | Std. Err. | t | $p > \|t\|$ | | |
|---|---|---|---|---|---|---|
| $CO_2$ emission | | | | | F(5, 13) | 2.06 |
| L1 | −0.0592416 | 0.2836246 | −0.21 | 0.838 | Prob > F | 0.1369 |
| FI | −0.7536137 | 0.3738006 | −2.02 | 0.065 * | R-sq | 0.4416 |
| OP | −0.7589263 | 0.7323196 | −1.04 | 0.319 | Adj R-sq | 0.2269 |
| RE | 0.4835829 | 0.2994055 | 1.62 | 0.130 | | |
| LP | 0.303178 | 0.2141912 | 1.42 | 0.180 | | |
| const | 10.84934 | 4.437334 | 2.45 | 0.029 ** | | |

*—statistical significance at the 10% level, **—statistical significance at the 5% level. Source: Own calculations based on Stata17.

**Table 4.** ARDL for Czechia.

| Variable | Coefficient | Std. Err. | t | $p > \|t\|$ | | |
|---|---|---|---|---|---|---|
| $CO_2$ emission | | | | | F(7, 11) | 8.59 |
| L1 | 0.2079111 | 0.2286387 | 0.91 | 0.383 | Prob > F | 0.0010 |
| FI | 0.4733999 | 0.4987974 | 0.95 | 0.363 | R-sq | 0.8453 |
| L1 | 2.024484 | 0.7066955 | 2.86 | 0.015 ** | Adj R-sq | 0.7469 |
| OP | 1.519463 | 1.444356 | 1.05 | 0.315 | | |
| RE | −0.136458 | 0.092139 | −1.48 | 0.167 | | |
| LP | 0.3411636 | 0.3637617 | 0.94 | 0.368 | | |
| L1 | −1.123848 | 0.3803664 | −2.95 | 0.013 ** | | |
| const | −11.39983 | 4.471094 | −2.55 | 0.027 ** | | |

**—statistical significance at the 5% level. Source: Own calculations based on Stata17.

**Table 5.** ARDL for Hungary.

| Variable | Coefficient | Std. Err. | t | $p > \|t\|$ | | |
|---|---|---|---|---|---|---|
| $CO_2$ emission | | | | | F(6, 12) | 10.53 |
| L1 | 0.7882761 | 0.2802783 | 2.81 | 0.016 ** | Prob > F | 0.0003 |
| FI | 0.1597288 | 0.4759663 | 0.34 | 0.743 | R-sq | 0.8404 |
| OP | −1.59434 | 1.452889 | −1.10 | 0.294 | Adj R-sq | 0.7606 |
| RE | 0.0614932 | 0.2450448 | 0.25 | 0.806 | | |
| L1 | 0.3599044 | 0.2353443 | 1.53 | 0.152 | | |
| LP | −0.3522758 | 0.3595091 | −0.98 | 0.346 | | |
| const | −1.336955 | 2.924411 | −0.46 | 0.656 | | |

**—statistical significance at the 5% level. Source: Own calculations based on Stata17.

**Table 6.** ARDL for Slovakia.

| Variable | Coefficient | Std. Err. | t | $p > \|t\|$ | | |
|---|---|---|---|---|---|---|
| $CO_2$ emission | | | | | F(6, 12) | 17.68 |
| L1 | 0.4638607 | 0.1941306 | 2.39 | 0.034 ** | Prob > F | 0.0000 |
| FI | −0.350018 | 0.474688 | −0.74 | 0.475 | R-sq | 0.8984 |
| OP | −1.473752 | 0.9784794 | −1.51 | 0.158 | Adj R-sq | 0.8476 |
| L1 | 1.77198 | 0.936989 | 1.89 | 0.083 * | | |
| RE | 0.135299 | 0.0712454 | 1.90 | 0.082 * | | |
| LP | 0.2500207 | 0.1950518 | 1.28 | 0.224 | | |
| const | 3.613934 | 2.877902 | 1.26 | 0.233 | | |

*—statistical significance at the 10% level, **—statistical significance at the 5% level. Source: Own calculations based on Stata17.

In the case of Poland, the income variable proved particularly significant. Each 1% increase in income resulted in a 0.75% short-term decrease in $CO_2$ emissions. This may be related to the substitution of non-renewable energy with renewable energy, which initially requires higher financial outlays. In the long term, a shift in the structure of energy consumption in agriculture is possible, driven by the use of renewable energy sources. Paradoxically, a higher share of renewable energy sources may be associated with higher energy consumption, which should be interpreted as economies of scale. Compared to other countries, there is a clear lack of inertia, and the observed changes are more the result of current factors than established trends. This suggests a lower stability of these relationships over time. In this case, the model's ability to explain the changes is also relatively low, in contrast to other countries. In the case of the Czech Republic, the income variable, lagged by one period, had a positive effect on emissions. Each 1% increase in income resulted in a 2% increase in emissions. This phenomenon is commonly observed in studies on the environmental Kuznets curve [58], which demonstrate that agricultural production initially developed alongside a simultaneous increase in greenhouse gas emissions, only to return to a sustainable development path after reaching a turning point. In the Czech Republic, every 1% increase in agricultural labor efficiency in the preceding period resulted in a 1.12% decrease in emissions. Higher labor efficiency leads to better resource utilization and favors reducing practices that increase $CO_2$ emissions in agriculture. The impact of labor productivity over time is multidirectional. It is positive in the current period, but with a smaller impact, and negative with a time lag, but with a much stronger impact. Therefore, an increase in labor productivity only in subsequent periods allows for changes in the ratio of production factors and a reduction in greenhouse gas emissions. In this case, both income and labor productivity from the previous period have a significant impact on emissions. It should therefore be recognized that the effects of ongoing structural changes in agriculture manifest themselves with a time lag. In the case of Hungary, only the $CO_2$ emissions variable from the previous period proved particularly significant, having a positive impact on the current emission value. The same pattern was observed in Slovakia. In this case, every 1% increase in the "openness" variable from the previous period resulted in a 1.77% increase in emissions, and every 1% increase in renewable energy consumption increased emissions by 0.13%. Despite the widely known economic benefits associated with the intensification of trade, in the case of agriculture, situations may arise where the share of products requiring higher energy intensity increases, and the opening of the economy itself then increases the scale of production, which also requires greater inputs of production factors. Moreover, investments in renewable energy often achieve results after a certain period, as confirmed by the positive impact of renewable energy from the current period on emissions. In the case of Slovakia, $CO_2$ emissions are influenced by inertia, lagged income effects, and, less typically, by the positive impact of renewable

energy. This latter factor requires a closer look at the efficiency of the technologies used in renewable energy sources. Cointegration, heteroscedasticity, and autocorrelation tests were used to verify the modeling accuracy (Tables 7–9). It should also be noted that in the Czech Republic, Slovakia, and Hungary, greenhouse gas emissions are partially self-reinforcing, and an increase in renewable energy and income can—paradoxically—lead to an increase in emissions, among other things, due to the effect of increased production scale. Therefore, structural transformations improving the competitiveness of the agricultural sector in these countries are also becoming an emission-generating process. In the case of the V4 countries, factor inertia is significant. Agriculture in Poland is characterized by a certain difference. Here, the current effect of income growth is very unfavorable. This is important because in Poland, this increase was relatively high.

**Table 7.** Pesaran, Shin, and Smith bounds test.

| Countries | | 5% | | *p*-Value | | |
|---|---|---|---|---|---|---|
| | **F and t Stat** | **I(0)** | **I(1)** | **I(0)** | **I(1)** | **Decision** |
| Poland | F = 3.724<br>t = −3.735 | 3.878<br>−3.013 | 5.515<br>−4220 | 0.057<br>0.014 | 0.160<br>0.096 | no rejection |
| Czechia | F = 3.935<br>t = −3.464 | 3.973<br>−3.002 | 5.753<br>−4.233 | 0.051<br>0.024 | 0.147<br>0.131 | no rejection |
| Hungary | F = 1.770<br>t = −0.755 | 3.926<br>−3.008 | 5.634<br>−4.226 | 0.321<br>0.719 | 0.592<br>0.898 | no rejection |
| Slovakia | F = 1.684<br>t = −2.762 | 3.926<br>−3.008 | 5.63<br>−4.23 | 0.374<br>0.075 | 0.623<br>0.289 | no rejection |

Source: Own calculations based on Stata17.

When the cointegration test was applied, the test statistic was not confirmed to exist within the range that could confirm the presence of cointegration. The non-stationary I(1) variables confirmed in the study do not exhibit a stable, long-term equilibrium relationship, which prevented their examination in the long-term relationship. Additionally, the Breuch–Pagan/Cook–Weisberg test for heteroskedasticity (Table 8) and the Breuch–Godfrey LM test for autocorrelation (Table 9) were conducted.

**Table 8.** Breuch–Pagan/Cook–Weisberg test for heteroskedasticity.

| | **Poland** | **Czechia** | **Hungary** | **Slovakia** |
|---|---|---|---|---|
| chi2(1) | 2.75 | 2.69 | 2.93 | 2.34 |
| Prob > chi2 | 0.0972 | 0.0853 | 0.0871 | 0.126 |

Source: own calculations based on Stata17.

**Table 9.** Breusch–Godfrey LM test for autocorrelation.

| | **Lags (p)** | **chi2** | **df** | **Prob > chi2** |
|---|---|---|---|---|
| Poland | 1 | 3.701 | 1 | 0.0544 |
| Czechia | 1 | 0.006 | 1 | 0.9407 |
| Hungary | 1 | 0.056 | 1 | 0.8124 |
| Slovakia | 1 | 0.037 | 1 | 0.8474 |

Source: own calculations based on Stata17.

All analyzed cases were homoscedastic, and no autocorrelation was detected. To illustrate the direction of the relationship between variables, the next procedure employed a short-run Granger causality test based on the created VAR (vector autoregression) model. This complements the analysis because it was impossible to test the VECM (vector error

correction) model in the absence of cointegration and to examine long-run relationships. The test results are presented in Table 10 and Figure 1 (bold font indicates statistical significance of the result).

**Table 10.** Granger causality test.

| | | Poland | | Czechia | | Hungary | | Slovakia | |
|---|---|---|---|---|---|---|---|---|---|
| **Equation** | **Excluded** | **chi2** | **Prob > chi2** | **chi2** | **Prob > chi2** | **chi2** | **Prob > chi2** | **chi2** | **Prob > chi2** |
| $CO_2$ | FI | 0.29361 | 0.588 | 1.9679 | 0.161 | 3.3057 | **0.069** | 0.56398 | 0.754 |
| $CO_2$ | OP | 0.00258 | 0.957 | 0.30537 | 0.581 | 0.06335 | 0.801 | 8.5558 | **0.014** |
| $CO_2$ | RE | 1.5111 | 0.219 | 0.64539 | 0.422 | 2.3343 | 0.127 | 1.6582 | 0.436 |
| $CO_2$ | LP | 0.88208 | 0.348 | 1.2101 | 0.271 | 1.4722 | 0.225 | 0.34663 | 0.841 |
| FI | $CO_2$ | 0.08542 | 0.770 | 0.00768 | 0.930 | 9.2871 | **0.002** | 2.1979 | 0.333 |
| FI | OP | 2.1989 | 0.138 | 1.9041 | 0.168 | 0.01523 | 0.902 | 8.9585 | **0.011** |
| FI | RE | 4.3382 | **0.037** | 2.198 | 0.138 | 2.6939 | 0.101 | 12.907 | **0.002** |
| FI | LP | 0.0033 | 0.954 | 0.95598 | 0.328 | 5.1268 | **0.024** | 3.5982 | 0.165 |
| OP | $CO_2$ | 0.08415 | 0.772 | 0.63273 | 0.426 | 0.3645 | 0.546 | 1.9312 | 0.381 |
| OP | FI | 6.9885 | **0.008** | 0.59913 | 0.439 | 1.5158 | 0.218 | 35.625 | **0.000** |
| OP | RE | 1.4443 | 0.229 | 0.46038 | 0.497 | 0.03921 | 0.843 | 0.37878 | 0.827 |
| OP | LP | 4.868 | **0.027** | 3.0376 | **0.081** | 1.611 | 0.204 | 27.059 | **0.00** |
| RE | $CO_2$ | 0.90226 | 0.342 | 0.03534 | 0.851 | 3.2466 | **0.072** | 20.154 | **0.000** |
| RE | FI | 4.6731 | **0.031** | 0.1805 | 0.671 | 3.9963 | **0.046** | 32.383 | **0.000** |
| RE | OP | 5.5449 | **0.019** | 0.00079 | 0.978 | 2.4275 | 0.119 | 33.989 | **0.000** |
| RE | LP | 0.35184 | 0.553 | 4.0058 | **0.045** | 4.2334 | **0.04** | 12.807 | **0.002** |
| LP | $CO_2$ | 0.13828 | 0.71 | 0.01375 | 0.907 | 8.8174 | **0.003** | 10.686 | **0.005** |
| LP | FI | 1.1459 | 0.284 | 0.79588 | 0.372 | 0.23854 | 0.625 | 7.4369 | **0.024** |
| LP | OP | 4.6612 | **0.031** | 0.41112 | 0.521 | 1.5591 | 0.212 | 9.0444 | **0.011** |
| LP | RE | 0.18632 | 0.666 | 3.0966 | **0.078** | 1.9687 | 0.161 | 12.791 | **0.002** |

Source: own calculations based on Stata17.

The results of the Granger test confirm that the causal relationships between $CO_2$ emissions and economic and energy factors vary depending on the country. The causal relationships in the Visegrad Group countries differ significantly in terms of the scale and direction of the relationship. In Poland, the most active causal factor was labor efficiency in agriculture. Income contributed to both the openness of the economy and renewable energy. Interestingly, changes (or rather, increases) in the share of renewable energy precede changes in income. Therefore, investments in renewable energy sources influence the profitability of agricultural production. This is a crucial finding for the further promotion and development of renewable energy. Improved productivity also supports the openness of the economy, and thus agricultural production in the context of foreign exchange (a similar situation occurs in the Czech Republic). However, no relationships were observed between $CO_2$ and RE, and no causal relationships were found between $CO_2$ and the other variables. The same was true for the Czech Republic, where a reciprocal causality was observed between economic openness and labor productivity. Furthermore, economic openness causally influenced the economic environment. The interplay between the economic environment and the state of the art indicates the ongoing technological transformation and the economic path of agricultural production development in this country. Causal relationships with $CO_2$ were observed in Hungary and Slovakia. In Hungary, bilateral causality between $CO_2$ and income was observed, while unilateral causality between $CO_2$ and RE and labor productivity was observed. Furthermore, the increased openness of the economy and agricultural markets contributed to the growth of farm income and the share of renewable energy. For the remaining variables, except for emissions, bilateral causal relationships were observed. In this case, it is worth noting the impact of RE on both income and productivity. This situation indicates strong coupling

between the energy transition and the structure of the agricultural sector. Therefore, these transformations are strongly interconnected. Unilateral causal relationships for emission levels in Slovakia are associated with RE variables and labor productivity. In Slovakia, the relationships between the analyzed variables are the most extensive and identifiable. This applies to the relationships between RE, LP, OP, and $CO_2$. This indicates that energy policy has both direct and indirect impacts on greenhouse gas emissions and the economic performance of the agricultural sector. A special role is played by labor productivity (especially in Hungary and Slovakia); renewable energy, which can both support and worsen environmental effects; and the openness of the economy, which has both a direct impact (e.g., in Slovakia) and indirectly (e.g., through income in Poland).

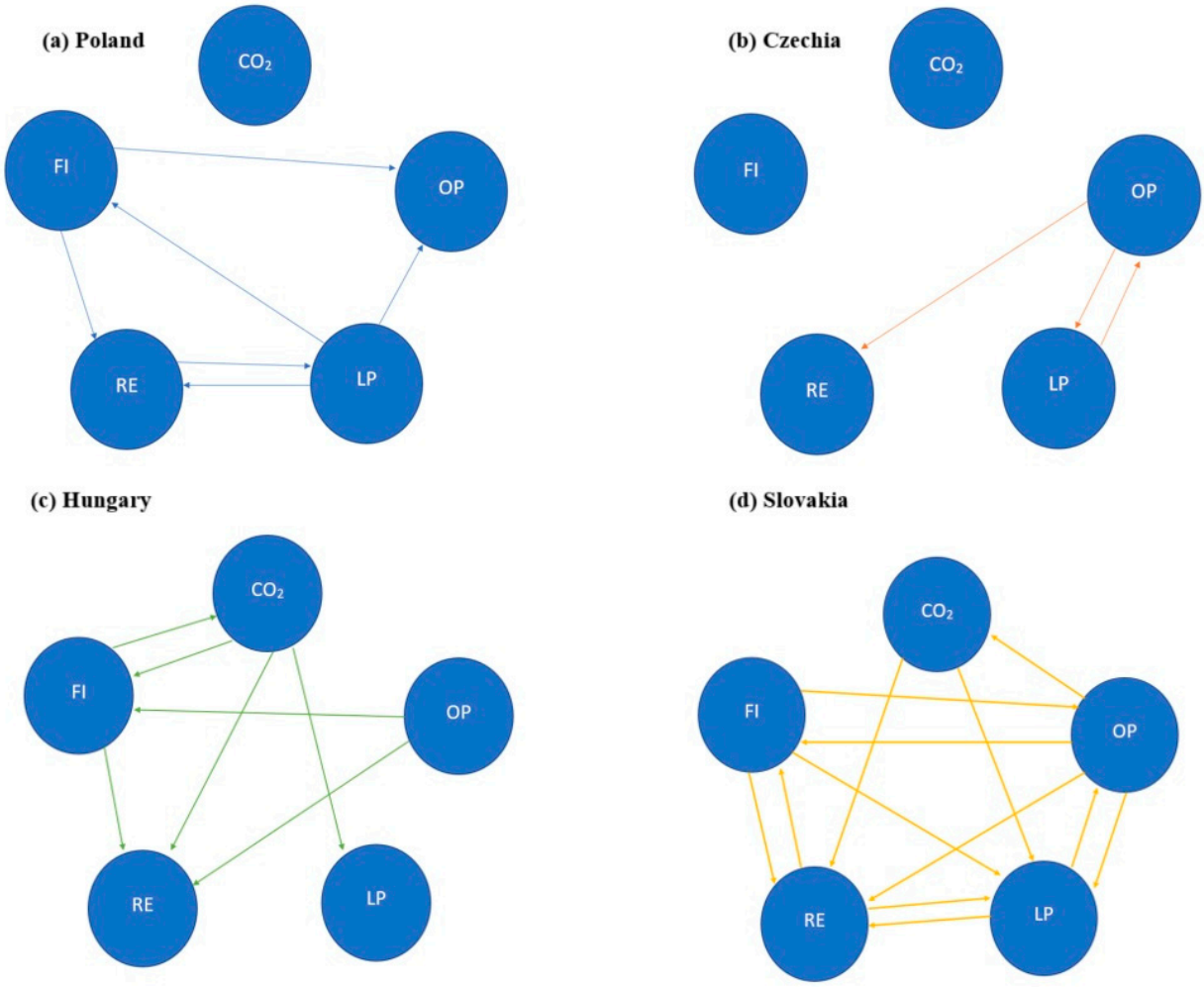


**Figure 1.** Directions of Granger causality. Source: prepared based on research results.

## 5. Conclusions and Recommendations

The causality analysis confirmed the existence of causal relationships between $CO_2$ emissions and the economic, market, and technological factors considered. However, these relationships are heterogeneous and vary across countries. Strong drivers include labor productivity (especially in Hungary and Slovakia), the share of renewable energy, and economic openness (especially directly in Slovakia and indirectly in Poland). This confirms the first research hypothesis (H1) in the short term. This differentiation was also confirmed, positively verifying the second hypothesis (H2), as was the third hypothesis.

Promoting income growth in the agricultural sector can contribute to emission reductions—for example, by supporting technology, farm modernization, and efficient

resource use. The effectiveness of these actions depends not only on the technologies used but also on the structure of production and trade. In this situation, better coordination of agricultural and climate policies is necessary. Energy transition must be viewed not as a technical problem (energy transformation), but as a systemic one. It is essential to ensure the interplay of technological change, transformations in systems, and production structures. The analysis shows that in some countries, greater economic openness (measured by the share of trade in GDP) was associated with higher emissions, which may be the result of export specialization in more energy-intensive production types. In such cases, technological investments alone (e.g., in renewable energy sources or energy efficiency) may not be sufficient if the production model and export structure remain carbon-intensive. The high inertia of $CO_2$ emissions, particularly pronounced in some countries (Hungary, Slovakia), necessitates the implementation of long-term reforms that extend beyond individual programming periods. This inertia effect means that current $CO_2$ emissions in the agricultural sector are strongly dependent on emissions from previous periods. In countries with relatively high emissions, including the V4, this poses a significant barrier. In Hungary and Slovakia, in particular, significant inertia of the $CO_2$ variable was observed, indicating the structured and stable nature of emission sources. This stems from established technologies, production structures, or low system flexibility.

Based on the conducted research, several important recommendations can be formulated for decision-makers shaping agricultural and general economic policy. Above all, the process of implementing renewable energy solutions in agriculture should be better integrated with the production system to avoid indirectly increasing $CO_2$ emissions. Attention should be paid to equipment parameters and billing systems that reward the use of renewable energy sources. This also requires increasing the flexibility of the entire energy production system, including from other sources. Improving agricultural productivity does not automatically lead to reduced emissions. Additional environmental regulations are necessary to leverage these effects to reduce greenhouse gas emissions. Regulations should guide technological changes aimed specifically at reducing emissions, as market mechanisms alone do not provide this at the current stage of transformation and the advancement of renewable energy technologies.

National strategies for reducing emissions in agriculture should be individualized, which means taking into account local income, structural, technological, and production conditions. It is impossible to apply a one-size-fits-all policy in this area, not only to all countries but also to smaller areas within a country.

The presented research has certain limitations, primarily related to the time horizon. Analysis of the variables used indicated that they do not exhibit a stable, long-term equilibrium relationship, which prevented their long-term examination. Furthermore, the ARDL models used are sensitive to sample length and lag selection, and Granger causality tests only allow for the identification of statistical relationships, not true economic causality.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| ARDL | Autoregressive Distributed Lag |
| Agri | Agriculture |
| $CO_2$ | Carbon dioxide |
| RE | Renewable energy |
| REC | Renewable energy consumption |
| OP | Openness of the economy |
| LP | Labor productivity |
| FI | Factor income |

## Appendix A

**Table A1.** Main Relationships Between $CO_2$ Emissions and Renewable Energy in Research Result.

| Authors | Countries | Period | Methodology | Main Results |
|---|---|---|---|---|
| [54] | 94 middle-income countries | 2000–2015 | two-step generalized method of moments (GMM) regression | There is a negative relationship between renewable energy production, the added value of agricultural production and $CO_2$ emissions per capita. |
| [41] | Turkey | 1970–2017 | bootstrap ARDL, fully modified OLS, and dynamic ordinary least squares long-run estimators | Agriculture, renewable energy production and economic globalization increase environmental pollution. |
| [59] | 38 sub-Saharan African countries | 2000–2019 | The differentiated-generalized method of moments (GMM) | Renewable energy use can reduce $CO_2$ emissions, while agriculture increases emissions. |
| [53] | BRIC countries | 1971–2016 | Fourier-ADL cointegration test, TY causality test | Globalization increases pollution indicators, while renewable energy production reduces environmental pressure (China). Furthermore, globalization increases $CO_2$ emissions, while renewable energy production improves environmental quality in Brazil. Casualty: Agri <=> environmental degradation; globalization → ecological footprint and $CO_2$ emissions; RE → ecological indicators. |
| [41] | Marocco | 1980–2013 | ARDL, Granger causality test | Economic growth, agricultural production and agricultural land use contribute to increased renewable energy, while falling $CO_2$ emissions increase renewable energy consumption. Short-term casuality: agricultural value added → RE, agricultural land use → RE. |
| [52] | Somalia | 1990–2020 | ARDL, DOLS | In the long term, the added value of agriculture and the use of renewable energy significantly reduce both the ecological footprint and $CO_2$ emissions. In the short term, the added value of agriculture temporarily increases the ecological footprint and $CO_2$ emissions. Urbanization increases both the ecological footprint and $CO_2$ emissions in the short and long term. |
| [60] | 12 MENA countries | 1975–2008 | Panel cointegration, FMOLS, DOLS, Granger causality test | $CO_2$ influences renewable energy consumption (FMOLS, DOLS). Casuality: short-term: RE → $CO_2$; long-term: causality running from GDP → RE; $CO_2$ → RE. |

**Table A1.** *Cont.*

| Authors | Countries | Period | Methodology | Main Results |
|---|---|---|---|---|
| [51] | 6 South Asian countries | 1991–2019 | FE, RE and dynamic panels | Agriculture, fertilizers, non-renewable energy, tourism, GDP growth and government spending in selected regions increase $CO_2$ emissions, while the use of clean energy reduces emission levels. |
| [49] | 13 developed and developing Asia Pacific countries | 2005–2017 | Panel cointegration, Granger causality test | Long-term casuality: RE → $CO_2$ and Population → $CO_2$. Short-term casuality: Agri → GDP; economic development, population, and clean energy increase $CO_2$ emissions. |
| [61] | Tunisia | 1980–2011 | VECM, Granger causality | Short-term casuality: agri value added <=> $CO_2$ emissions and between agri value added <=> trade, NRE → agri value added, RE → $CO_2$. Long-term estimates indicate that non-renewable energy, agri value added increases $CO_2$ emissions, while renewable energy reduces $CO_2$ emissions. |
| [62] | BRICS-M-A countries | 1999–2021 | Panel VAR/GMM, Granger causality analysis | Strong impact of delayed $CO_2$ on RE, $CO_2$ delayed by 2 periods reduces RE, and green technology supports REC without directly reducing $CO_2$ emissions. REC does not Granger Cause $CO_2$ and $CO_2$ does not Granger Cause REC. |
| [63] | South Africa | 1990–2021 | ARDL, FMOLS, DOLS, CCR, Granger Causality Tests | Growth in the agricultural sector leads to deterioration of the environment; Lack of causality for: $CO_2$ → Agriculture GDP; Agriculture GDP → $CO_2$; $CO_2$ → Renewable Energy Renewable Energy → $CO_2$; Renewable Energy → Agriculture GDP; Agriculture GDP → Renewable Energy. |

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