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The Impact of Nuclear Energy on Environmental, Economic, and Agricultural Dynamics: New Evidence for More Sustainability

Gökhan AKAR [1]
Hikmet AKYOL [2]
Tufan SARITAŞ [3]

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Abstract

The extremes caused by climate change threaten the economic and agricultural future of nations. This research examined the impact of NE (nuclear energy) on CO_2, GDP and Agro-Production Indices (API) for 24 developed and developing countries. The results of the research showed that the variables are cointegrated in the long run. The estimated results of FMOLS and AMG revealed that the use of NE reduces CO_2 and increases environmental quality. In this context, our results show that NE contributes to environmental, economic and agricultural sustainability. We found that oil consumption negatively affects all API, and renewable energy (RE) consumption negatively affects agricultural and food production indices. Causality analyses showed that NE policies are compatible with environmental and RE policies. Therefore, the use of NE can play a crucial role in the transition to clean energy in research countries and in the adaptation of the agricultural sector to RE sources. In these countries, it is important to encourage policies that will reduce the dependence of the agricultural sector on fossil fuel consumption and reduce costs in the transition to clean energy sources in terms of food security and sustainable agriculture practices. The integration of nuclear energy into the agricultural sector can contribute to reducing input costs in the agricultural sector and reducing fluctuations and volatilities in food prices. In addition, the continuity of energy supply, technological innovation and infrastructure investments provided by nuclear energy can play a key role in the transition to clean energy and the achievement of the sustainable development goals of countries.

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[1] Assoc. Prof. Dr., Karamanoğlu Mehmetbey University, Faculty of Economics and Administrative Sciences, Department of Economics, Turkiye, gakar@kmu.edu.tr, http://orcid.org/0000-0001-8401-4052.

[2] Assoc. Prof. Dr., Gümüşhane University, Turkiye, hikmetakyol76@gmail.com, http://orcid.org/0000-0001-9119-7416

[3] Assoc. Prof. Dr. Karamanoğlu Mehmetbey University, Faculty of Economics and Administrative Sciences, Department of Economics, Turkiye tufansaritas@kmu.edu.tr, http://orcid.org/ 0000-0003-1728-2377 (Corresponding author)

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1. Introduction

The widespread adoption of industrial production processes during the Industrial Revolution significantly increased the demand for energy, which was largely met by fossil fuels (Pirani, 2018; Yang et al, 2021). The gradual growth of mass production has led to an increase in greenhouse gas (GHG) emissions due to fossil fuel consumption and energy demand. The International Energy Agency (IEA, 2025) reported that Total energy-related CO_2 emissions increased by 0.8% in 2024, reaching an all-time high of 37.8 Gt CO_2. According to the organization, this increase contributed to a record high of 422.5 ppm in atmospheric CO_2 concentrations in 2024, which is approximately 3 ppm higher than in 2023 and 50% above pre-industrial levels. This process, which has been developing since the industrial revolution, has led us to face the fact that increasing GHG emissions cause an increase in global warming, and the importance of RE among alternative sources to reduce GHG emissions has increased (Respitawulan and Rahayu, 2019; Attanayake et al., 2024; Yi and Chen, 2024; Lin, 2025). The European Environment Agency (EEA, 2025) reported that in 2024, 25.4% of the final energy consumed in the European Union was obtained from renewable sources. According to the organization, this is about one percentage point higher than in 2023. Since the oil crisis in the 1970s, the importance of alternative energy sources to replace oil has taken an important place on the agenda, and when the difficulties of oil and natural gas supply from unstable geographical regions are added to this situation, the importance of RE comes to light. In fact, the energy demand needed to make GDP sustainable becomes more stable with the use of NE. In addition to this contribution to energy security, NE also offers countries several opportunities, such as minimizing the price volatility associated with oil imports (Yoo and Jung, 2005).

According to the International Energy Agency (IEA, 2022), NE sources meet 10% of global electricity production. In this respect, nuclear power is the second largest source of low-emission energy after hydropower on a worldwide scale (IEA 2023). Therefore, the use of NE can play an important role in the transition to REsources, achieving net-zero emission targets, and combating climate change (Wang et al. 2023). NE can contribute to the reduction of CO_2 and help meet national and regional CO_2 emission targets (Addo 2023). According to the Food and Agriculture Organization of the United Nations (FAO, 2021), nuclear technology offers some innovative options for improving agricultural practices. The International Atomic Energy Agency (IAEA, 2024), which cooperates with FAO on this issue, stated that these technologies offer competitive and unique solutions to ensure food safety and increase environmental quality. As it is known, with basic policies such as protecting the environment, practices that increase the efficiency of natural resources, and sustainable economy, the idea of leaving a usable world for future generations is tried to be implemented (Razzaq et al., 2021). In agricultural production, energy consumption has a very important place in terms of sustainability. In addition, NE is seen as a suitable alternative energy source as an energy source with a lower cost against high oil prices. In this context, electrical energy provided by NE can be used as an important energy source in agricultural production. However, the ecological damage caused by nuclear power plants, especially to their immediate surroundings, also leads to some negativity on agricultural production in these regions. The issue that needs to be discussed and investigated here is to make a comparison between the damage caused by NE production to the environment and the damage caused by fossil fuel consumption to the environment and to determine energy policies accordingly.

This research investigated the environmental, economic, and agricultural outputs of NE. For this purpose, nuclear and RE in developed and developing countries and their impact on CO_2, GDP, and agro-industrial production was tested using heterogeneous panel data analysis estimators. Today, many countries use RE sources widely, while countries that use NE are more limited. For this reason, 24 countries were selected from the basket of countries using NE while selecting the research sample. However, since methods that consider cross-sectional dependency were used in the analysis, it was considered whether the periodic data of the variables were missing while selecting the sample. The study will contribute to existing literature in this respect. In addition, this contribution is intended to guide the prejudice against the use of NE or the belief that NE reduces CO_2 in line with the empirical literature that affects it to be placed on more solid ground in empirical findings. In the study, using a large panel data set and up-to-date techniques, the effects of NE use and oil and RE on CO_2, API, and GDP were revealed. In this respect, the study differs significantly from the empirical literature. Moreover, a wide range of policy implications and recommendations are presented for policymakers, researchers, and market participants. Analyzing the role of NE use, fossil and RE in supporting agricultural sustainability makes the study unique. In this context, the role of nuclear energy use in terms of ensuring agri-food security, economic and agricultural sustainability has been examined in the context of fossil fuel use and renewable energy consumption. Second, the causality relationship between NE use, oil and renewable energy, growth, gross fixed capital accumulation and GDP were tested. In this context, the causality between growth, investment, agriculture and energy policies implemented in the research countries and the role of nuclear energy use in the transition to clean energy were discussed. In this direction, the connection and compatibility of different energy policies with each other and with development policies have been revealed. The rest of the research is as follows: Empirical studies are included in the literature section. In the third part, information about the data set and method is given. The last section contains the results of the analysis and the discussion.

2. Literature Review

The use of fossil fuels to meet the expansion of energy demand that occurred after the Industrial Revolution has led to an increase in greenhouse gas emissions (Azam et al., 2021b). In this context, the increase in concerns about global warming and climate change, especially in recent years, has revealed the necessity of reducing CO_2 from energy production (Saidi and Omri, 2020). This is because energy consumption can affect environmental quality depending on the energy source used (Goh and Ang, 2018; Pao and Chen, 2019; Adams and Nsiah, 2019; Lau et al., 2019; Azam et al., 2021a). Accordingly, nuclear and RE sources can be an important part of environmental protection as they can contribute to the reduction of CO_2 (Luqman et al., 2019). In this context, there are many studies in the literature to investigate the question of whether renewable and NE consumption contributes to the reduction of CO_2. For example, Saidi and Omri (2020) concluded that nuclear and RE is effective in reducing CO_2 in their study in which they examined the 1990-2018 data for 15 OECD countries with the panel data estimation method. Vo et al. (2020), Hassan et al. (2020) came to a similar conclusion. On the other hand, Sovacool et al. (2020), analyzing the period 1990-2014 for 123 selected countries, find that NE does not reduce CO_2. On the other hand, Fell et al. (2022) found that NE and RE are effective in reducing CO_2. In addition, Mahmood (2022), in their study for 28 countries with different income levels producing nuclear electricity, found that NE reduces CO_2 in countries other than low-middle income countries. Voumik et al. (2023) reached the same conclusion for BRICS countries. Another study supporting this result was conducted by Sun and Dong (2022). On the other hand, Shafiei and Salim (2014) found the positive impact of RE on the environment for the OECD and Bekun et al. (2019) for EU countries. However, there are also studies in literature that address the causal relationship between variables. For example, Menyah and Wolde-Rufael (2010), with the help of Granger causality test, conclude that there is a unidirectional relationship from NE consumption to CO2 for the US, while there is no causal relationship for renewable energy. In another study, Iwata et al. (2010) found that for France, RE is the cause of CO_2 reduction. On the other hand, Kahia et al. (2019) found that RE has an active role in CO_2 mitigation for 12 MENA countries. Jin and Kim (2018) found a long-term equilibrium relationship between NE, RE and CO_2. Azam et al. (2021b) found that RE and NE expansion contributed to CO2 reduction for the 10 countries with the highest CO_2 in the period 1990-2014. Mahmood et al. (2020) reached a similar conclusion for Pakistan in NE and Apergis (2023) for Uzbekistan in RE. Accordingly, Alfarra and Abu-Hijleh (2012) stated that NE is a preferable option to RE in terms of environment in the UAE sample. For the US, Baek (2016) analyzed the data for the period 1960-2010 with the ARDL approach and concluded that NE and RE contribute to CO2 reduction. This result is supported by studies by Wagner (2021), Danish et al. (2021), Ozgur et al. (2022), Omri and Saadaoui (2023), Pata and Samour (2022).

Some studies examining the relationship between environmental quality and energy have also considered the growth factor. For example, Saidi and Mbarek

(2016) found a bidirectional causality relationship between GDP and RE and that GDP is the cause of CO_2. On the other hand, Apergis and Payne (2014) found a positive cointegration relationship for GDP, CO_2 and RE for 7 selected Central American countries. In another study, Bilgili et al. (2016) found that the EKC hypothesis is valid and RE contributes to CO2 reduction for the data of 17 OECD countries for the period 1977-2010. Jebli et al. (2016) for 25 OECD countries and Nathaniel et al. (2021) for G7 countries confirm the EKC hypothesis. On the other hand, Magazzino et al. (2022) find that RE contributes to CO_2 reduction without harming GDP. When the studies in the literature on the relationship between NE and agro-industrial output are examined, it is seen that agro-industrial complex is emphasized. The increase in energy consumption per capita caused by the ever-increasing world population and prosperity causes the energy demand to grow rapidly. However, because of the increase in the current and future food needs, the agricultural sector has become even more important, and energy production has become a necessity in the agricultural production process. In this context, the use of NE to increase agricultural productivity is an idea that comes to the fore. In this context, the agro-industrial complex based on the application of NE in food production is emphasized (Milller, 1970). Many developing countries have expressed interest in these complexes in order to develop rural areas and speed up the commissioning of NE (Delyannis, 1972). Agro-industrial complexes based on NE are new concepts that can contribute to industrial, agricultural, and overall economic progress (Sefidvash, 1979). This will be especially true for developing countries such as India, which has a strong nuclear base and where agriculture depends mostly on monsoons (Thomas, 1973). The agro-industrial complex is a topic that has been studied over the past few years (Smagulova et al. 2022; Ershov and Bobrovnikova, 2024).

According to the literature reviewed in this direction, as far as we know, there is no empirical study examining the relationship between agro-industrial complexes based on NE. The evidence presented in the studies in the literature shows that nuclear and RE can have an important function in the realization of environmental quality by contributing to the reduction of CO_2. In summary, there is a consensus that the use of cleaner, environmentally friendly energy sources reduce CO_2. In this context, no research has yet been conducted that considers the relationship between the relevant variables in terms of countries using NE. There is no research examining the impact of different energy policies (NE, fossil and RE) on agricultural sustainability in the empirical literature distinguishes our study from others. That there is no research examining the impact of different energy policies (NE, fossil and RE) on agricultural sustainability in the empirical In this context, an important contribution has been made to the empirical literature, and several inferences and recommendations have been made for researchers, policymakers, and market participants. In the study, the effects of NE use on agricultural, environmental, and economic sustainability were determined and contributed to the existing literature.

3. Methodology

This research addressed the environmental, economic, and agricultural performance of NE. In this context, the impact of NE use on CO_2, GDP and API was examined. We analysed the period 1996-2020 for 24 developed and developing countries using NE using panel data analysis estimators. The countries in the sample are shown in Table 1. Within the framework of the research, we received data on the number of agricultural, food, and crop gross production indices per capita (2014-2016 = 100) representing agro-industrial production. In our study, we used real gross domestic product (GDP, USD) data per capita as an indicator of GDP. In the estimated models, the ratio of RE to total final energy consumption, oil consumption (thousand barrels per day), and gross fixed capital accumulation (% of GDP) were included as control variables. Within the scope of the research, we got CO_2, GDP per capita, and RE consumption data from the World Bank and agricultural data from FAO. We compiled the NE use and oil consumption data of the countries from the British Petroleum (BP, 2023) Statistical Review of the World Energy 2022 report.

Table 1. Research countries

Argentina	Hungary	Slovak Republic
Brazil	India	South Africa
Bulgaria	Japan	Spain
China	Korea, Rep.	Switzerland
Czechia	Mexico	Ukraine
Finland	Netherlands	United States
France	Romania	United Kingdom
Germany	Russian Federation	Canada

Source: Edited by researchers.

While selecting countries and variables, we excluded countries with missing or missing data from the sample, considering the data constraints. Within the scope of the study, we used the natural logarithm of all data except RE consumption and gross fixed capital accumulation. The natural logarithm of the variables was taken in order to reduce the measurement differences between the variables, to minimize the normal distribution and variable variance problems, to ensure model fit, and to facilitate interpretation. Since the RE and physical capital accumulation series are proportional data, percentage values were used. Descriptive statistics for the data used in the research and code representations of the variables are presented in Table

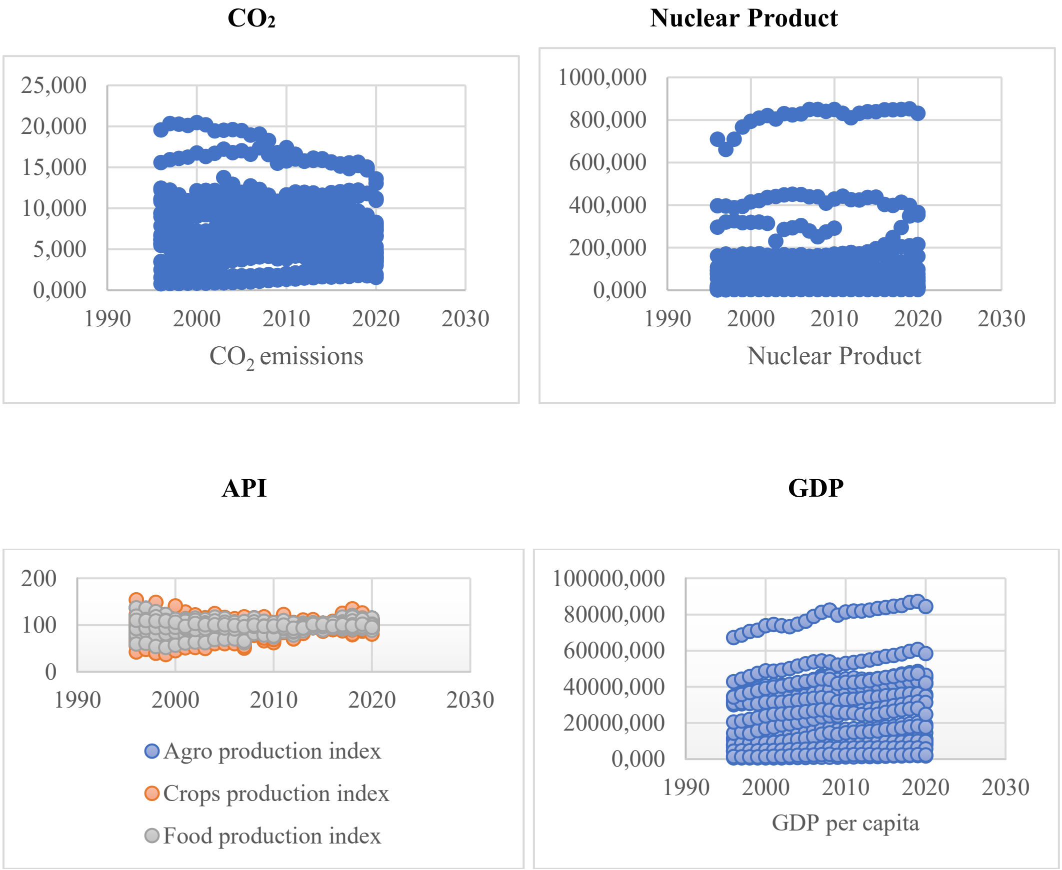
Table 2. Research variables

	Mean	Median	SD	Min.	Max.
LnCO$_2$	1.859	1.900	0.620	-0.239	3.018
LnAGRO	4.544	4.573	0.135	3.946	4.919
LnFOOD	4.543	4.573	0.136	3.946	4.918
LnCROPS	4.524	4.562	0.186	3.611	5.037
LnGDP	9.593	9.612	1.087	6.479	11.375
LnNUC	3.632	3.264	1.391	0.326	6.747
LnOIL	6.842	7.327	1.441	4.200	9.929
RENEW (%)	14.020	10.060	11.963	0.610	50.050
K (% GDP)	23.087	21.995	5.781	4.452	44.518

Source: Authors'own calculations

Figure 1 presents the periodic change graph of CO$_2$, NE, GDP and agricultural production index data of the countries in the research sample. It shows the annual CO$_2$ consumption (metric tons per capita) of the countries. The countries with the highest amount of CO$_2$ per capita in the sample are: Canada, USA, Russia and South Korea, while the countries with the lowest CO$_2$ per capita are India, Brazil and Mexico. The three countries with the highest NE use are the US, China and Russia, while Argentina, Romania and South Africa have lower NE use compared to other countries. It can be said that countries are reducing their NE use in the 2012-2020 period. Figure 1 shows the periodic change graphs of the research variables. In order to clearly show the changes of the variables throughout the period and the effect of global shocks on the series in the research countries, the level values of the series were used in the graphics. As seen in Figure 1, GDP per capita in the sample countries has increased with the increase in wealth around the world. The 2008 Global Crisis and the decline in GDP caused by the COVID-19 pandemic that broke out in 2019 are clearly visible in the graph. According to the graph, while API per capita showed a more heterogeneous distribution in the 1990s, most production levels increased over the period due to increased technological methods and productivity. Czechia, France, Germany, Hungary, the Netherlands, Slovakia, Slovakia, Switzerland and the United Kingdom saw a general decline in their production indices. In 2019, the outbreak of the COVID-19 pandemic in China negatively affected the level of agricultural production in some of the study countries.

Graph 1. Periodic change graph of CO_2, NE, real GDP per capita and API in research countries



Source: Data from FAO (2023), BP (2023) Statistical review of World energy 2022 and World Bank (2023), edited by researchers.

In the study, we estimated the econometric relationship between NE use, CO_2, API and GDP using panel cointegration, regression, and causality tests. While establishing the econometric model of the research, the recent empirical literature was taken as a basis (Jin and Kim 2018; Magazzino et al. 2020; Piłatowska et al. 2020; Sartbayeva et al. 2023). The following is the model function in which the econometric relationship between the variables is shown:

$$Y_{i,t} = f\left(LnNUC_{i,t}, LnOIL_{i,t}, RENEW_{i,t}, LnGDP/K_{i,t}\right) \quad (1)$$

Here, *Y* represents the dependent variables CO_2 emission, agro-industrial production indices, and GDP. *LnNUC*, *LnOIL*, *RENEW*, and *LnGDP/K* show the use of NE, oil consumption, RE use, and GDP or capital stock. In the functional model, i and t represent the unit and time dimension. The following is a linear representation of the model showing the panel data relationship between variables:

Model 1: $LnCO_{2i,t}=\alpha_{i,t}+\beta_1 LnNUC_{i,t}+\beta_2 OIL_{i,t}+\beta_3 RENEW_{i,t}+\beta_4 LnGDP_{i,t}+\mu_{i,t}$ *(2)*

Model 2: $LnAGRO_{2i,t}=\alpha_{i,t}+\beta_1 LnNUC_{i,t}+\beta_2 OIL_{i,t}+\beta_3 RENEW_{i,t}+\beta_4 LnGDP_{i,t}+\mu_{i,t}$ *(3)*

Model 3: $LnFOOD_{2i,t}=\alpha_{i,t}+\beta_1 LnNUC_{i,t}+\beta_2 OIL_{i,t}+\beta_3 RENEW_{i,t}+\beta_4 LnGDP_{i,t}+\mu_{i,t}$ *(4)*

Model 4: $LnCROPS_{2i,t}=\alpha_{i,t}+\beta_1 LnNUC_{i,t}+\beta_2 OIL_{i,t}+\beta_3 RENEW_{i,t}+\beta_4 LnGDP_{i,t}+\mu_{i,t}$ *(5)*

Model 5: $LnGDP_{2i,t}=\alpha_{i,t}+\beta_1 LnNUC_{i,t}+\beta_2 OIL_{i,t}+\beta_3 RENEW_{i,t}+\beta_4 K_{i,t}+\mu_{i,t}$ *(6)*

Here, α represents the constant slope parameter, the β coefficient parameters, and μ denotes the error term. Within the framework of the research, we first tested the existence of cross-sectional dependence (CSD) in series. For this purpose, we used Breusch-Pagan (1980) LM, Pesaran (2004) scaled LM (S-LM), and CD and Pesaran et al. (2008) Bias-corrected scaled LM (BC-LM) tests. The following is the calculation of the Breusch-Pagan (1980) LM Statistic (Pesaran,2004):

$$\lambda_{LM}=T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{ij}^{2} \qquad (7)$$

We examined whether the series used in the study had a CSD problem using the CD test proposed by Pesaran (2004). The CD test produces very robust results in panel data analyses where the number of observations is greater than the time dimension (N>T). In the next stage, we examined the stationarity of the variables using the Pesaran (2007) CADF-CIPS test. We used *the Delta* tests proposed by Swamy (1970) *s* and Pesaran-Yamagata (2008) to test the slope heterogeneity of the models we estimated after testing the stationary of the series. We used the heteroscedasticity and autocorrelation-resistant *Delta HAC test* proposed by Blomquist and Westerlund (2013) to confirm the slope heterogeneity of the predicted model. In the next step, we examined the long-term relationship between the variables using the tests of Kao (1999), Pedroni (1999), Johansen-Fisher, Westerlund (2005), and Gengenbach et al. (2016). We analyzed the estimation of long-run coefficients using the Full Modified Ordinary Least Squares (FMOLS) of Pedroni (1999) and the Mean Group Dynamic Ordinary Least Squares (DOLS-MG) estimators proposed by Pedroni (2004).

While the FMOLS estimator produces reliable results in the estimation of heterogeneous models, it can give deviant results in the presence of CSD. The DOLS-MG estimator is highly reliable under conditions of both CSD and heterogeneity. In the next stage of the research, we examined the causality relationship between NE use and explanatory variables using Dumitrescu and Hurlin (2012), Granger causality test.

4. Findings

Diagnostic tests

In the presence of CSD, traditional panel unit root tests can lose their reliability. For this reason, we first examined whether there was a CSD problem in the series. For this purpose, we used Breusch-Pagan (1980) LM, Pesaran (2004) scaled LM (S-LM) and CD and Pesaran et al. (2008) Bias-corrected scaled LM (BCS-LM) tests. The results of the analysis are presented in Table 3.

Table 3. CSD analysis

	LM	S-LM	BC-LM	CD
$LnCO_2$	3074.786 (0.000)	119.124 (0.000)	118.624 (0.000)	16.980 (0.000)
LnAGRO	22226.648 (0.000)	83.025 (0.000)	82.525 (0.000)	9.330 (0.000)
LnFOOD	2241.462 (0.000)	83.655 (0.000)	83.155 (0.000)	9.584 (0.000)
LnCROPS	1845.144 (0.000)	66.787 (0.000)	66.287 (0.000)	9.258 (0.000)
LnGDP	5533.242 (0.000)	223.763 (0.000)	2223.263 (0.000)	73.999 (0.000)
LnNUC	1624.662 (0.000)	57.402 (0.000)	56.902 (0.000)	9.441 (0.000)
LnOIL	2233.385 (0.000)	83.311 (0.000)	82.811 (0.000)	5.500 (0.000)
RENEW	3760.784 (0.000)	148.322 (0.000)	147.822 (0.000)	24.044 (0.000)
K	1530.571 (0.000)	53.398 (0.000)	52.898 (0.000)	5.592 (0.000)

Source: Authors'own calculations

The test results confirmed CSD in all series. We analyzed the stationary of the series using the Pesaran (2007) CADF-CIPS tests, which are reliable in the presence of CSD. The findings of the unit root analysis are shown in Table 4. All series contain unit roots at the level (I [0]), while their differences are stationary when (I [1]) is taken.

Table 4. Unit root analysis

	CADF		CIPS	
	LEVEL	DIFFERENCE	LEVEL	DIFFERENCE
LnCO$_2$	-0.882	-3.461***	-0.640	-3.404***
LnAGRO	-0.748	-10.652***	-1.645	-3.493***
LnFOOD	-0.912	-10.595***	-1.744	-3.506***
LnCROPS	-2.491***	-12.553***	-1.928	-3.379***
LnGDP	-2.553***	-2.481***	-1.906	-2.193**
LnNUC	-1.321*	-9.125***	-1.443	-3.813***
LnOIL	-1.352	-3.424***	-1.766	-3.453***
RENEW	-0.940	-3.156***	-0.927	-3.054***
K	-2.195***	-3.024***	-2.084	-2.199**

***, ** and * represented significance at the level of $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$.
Source: Authors'own calculations

In the next step, we examined the slope-heterogeneity of the predicted models. For this purpose, we used the Pesaran-Yamagata (2008) and Blomquist-Westerlund (2013) Delta tests and the Swamy (1970) *s* tests. The results of the analysis are presented in Table 5. The results of the Pesaran-Yamagata (2008) Delta and Swamy (1970) S test showed that the predicted models exhibited heterogeneous characteristics. The Blomquist-Westerlund (2013) Delta test results given in Table 1 supported the other test results. In this respect, it has been revealed that all the predicted models have heterogeneous properties.

Table 5. Slope heterogeneity analysis

Delta test	(1)	(2)	(3)	(4)	(5)
Δ	20.700 ^{a} (0.000)	17.573 ^{a} (0.000)	17.570 ^{a} (0.000)	12.122 ^{a} (0.000)	22.773 ^{a} (0.000)
$\Delta_{adj.}$	23.751 ^{a} (0.000)	20.174 ^{a} (0.000)	20.171 ^{a} (0.000)	13.916 ^{a} (0.000)	26.129 ^{a} (0.000)
Delta (HAC)					
Δ	13.747 ^{a} (0.000)	18.578 ^{a} (0.000)	10.715 ^{a} (0.000)	8.382 ^{a} (0.000)	16.420 ^{a} (0.000)
$\Delta_{adj.}$	15.773 ^{a} (0.000)	21.328 ^{a} (0.000)	12.301 ^{a} (0.000)	9.622 ^{a} (0.000)	18.840 ^{a} (0.000)
Swamy *S* chi2	1.1e+05 ^{a} (0.000)	4633.37 ^{a} (0.000)	4360.97 ^{a} (0.000)	4484.50 ^{a} (0.000)	3.6e+05 ^{a} (0.000)

"a" represents significance at the level of $p \leq 0.01$.
The data in parentheses show the p-value values.

Cointegration analysis

In this section, the results of the cointegration test and the estimation of long-run coefficients are presented. It is possible to predict the long-run relationship between series that contains unit roots at the level but becomes stationary when their differences are taken using cointegration tests. The statistics of Fisher-Johansen trace and max-eigen, Kao (1999) ADF and Westerlund (2005) presented in Table 6 were significant for all models. Panel *PP* and *Panel ADF*, which accept that the parameters of the Pedroni (1999) test in Panel (b) are homogeneous, and *Group PP* and *Group ADF* statistics, which argue that the parameters are heterogeneous, are significant for all models except the fifth model. Only *Panel ADF*, *Group ADF*, and *Group PP* were significant for the fifth model. Also, the Panel rho test statistic is only significant for the fourth model. Within the framework of the research, the long-term cointegration relationship between the variables was analyzed using the Gengenbach et al. (2016) test. *The T-bar* statistical value shown in panel (d) was significant for all models except the fifth model. The cointegration test results revealed that there is a long-term cointegration between NE use and explanatory variables.

Table 6. Cointegration analysis

	(1)	(2)	(3)	(4)	(5)
Panel (a): Kao (1999)					
ADF	-2.160^{a} (0.015)	2.689^{a} (0.003)	2.649^{a} (0.004)	3.579^{a} (0.000)	-1.976^{b} (0.024)
Panel (b): Pedroni (1999, 2004)					
Panel *v*	0.389 (0.348)	0.537 (0.295)	0.478 (0.316)	-0.155 (0.561)	-2.251 (0.987)
Panel *rho*	0.843 (0.800)	-2.633^{a} (0.004)	-2.600^{a} (0.004)	-3.344^{a} (0.000)	0.878 (0.810)
Panel *PP*	-2.858^{a} (0.002)	-8.945^{a} (0.000)	-8.804^{a} (0.000)	-11.611^{a} (0.000)	-1.010 (0.156)
Panel *ADF*	-2.697^{a} (0.003)	-8.955^{a} (0.000)	-8.704^{a} (0.000)	-11.617^{a} (0.000)	-2.661^{a} (0.003)
Group *rho*	2.151 (0.984)	0.442 (0.663)	0.393 (0.653)	-0.772 (0.219)	2.162 (0.984)
Group *PP*	-4.892^{a} (0.000)	-8.322^{a} (0.000)	-7.971^{a} (0.000)	-13.029^{a} (0.000)	-3.029^{a} (0.001)
Group *ADF*	-4.202^{a} (0.000)	-7.995^{a} (0.000)	-7.278^{a} (0.000)	-12.289^{a} (0.000)	-4.595^{a} (0.000)
Panel (c): Westerlund (2005)					
Variance ratio	-1.853^{b} (0.031)	-2.211^{a} (0.013)	-2.117^{b} (0.017)	-2.882^{a} (0.002)	2.753^{a} (0.003)
Panel (d): Gengenbach vd. (2016)					
Coef	-1.274	-1.332	-1.324	-1.300	-0.645
T-bar	-3.646^{b}	-3.726^{b}	-3.679^{b}	-3.916^{a}	-2.122
Panel (e): Fisher-Johansen					
Fisher *trace* test					
$r \leq 0$	459.8^{a} (0.000)	547.8^{a} (0.000)	552.3^{a} (0.000)	519.1^{a} (0.000)	505.7^{a} (0.000)
$r \leq 1$	221.9^{a} (0.000)	261.3^{a} (0.000)	257.3^{a} (0.000)	245.1^{a} (0.000)	240.0^{a} (0.000)
$r \leq 2$	115.3^{a} (0.000)	129.0^{a} (0.000)	124.3^{a} (0.000)	125.8^{a} (0.000)	129.8^{a} (0.000)
$r \leq 3$	71.19^{b} (0.016)	91.72^{a} (0.000)	87.34^{a} (0.000)	85.34^{a} (0.000)	86.99^{a} (0.000)
$r \leq 4$	62.68^{c} (0.075)	94.77^{a} (0.000)	96.62^{a} (0.000)	90.92^{a} (0.000)	85.38^{a} (0.000)

Fisher *max-eigen* test					
r≤0	290.4 ^{a} (0.000)	349.3 ^{a} (0.000)	358.9 ^{a} (0.000)	332.5 ^{a} (0.000)	329.8 ^{a} (0.000)
r≤ 1	145.2 ^{a} (0.000)	171.5 ^{a} (0.000)	172.7 ^{a} (0.000)	157.3 ^{a} (0.000)	148.4 ^{a} (0.000)
r≤ 2	82.71 ^{a} (0.001)	77.51 ^{a} (0.004)	76.45 ^{a} (0.005)	79.91 ^{a} (0.002)	82.27 ^{a} (0.001)
r≤3	63.09 ^{c} (0.070)	69.47 ^{b} (0.023)	64.56 ^{b} (0.055)	64.69 ^{b} (0.054)	65.10 ^{b} (0.050)
r≤ 4	62.68 ^{c} (0.075)	94.77 ^{a} (0.000)	96.62 ^{a} (0.000)	90.92 ^{a} (0.000)	85.38 ^{a} (0.000)

a, b and c represent significance at p≤0.01, p≤0.05 and p≤0.10.
The data in parentheses show the p-value values.

Table 7. Estimation of long-run coefficients

Panel (a): FMOLS					
	(1)	(2)	(3)	(4)	(5)
LnNUC	-0.042 ^{a} (0.003)	0.033 (0.114)	0.031 (0.131)	0.071 ^{a} (0.010)	0.104 ^{a} (0.001)
LnOIL	0.432 ^{a} (0.000)	-0.100 (0.180)	-0.099 (0.185)	-0.104 (0.283)	1.078 ^{a} (0.000)
RENEW	-0.026 ^{a} (0.000)	-0.007 ^{a} (0.001)	-0.007 ^{a} (0.002)	-0.002 (0.479)	0.031 ^{a} (0.003)
LnGDP	0.140 ^{a} (0.000)	0.258 ^{a} (0.000)	0.265 ^{a} (0.000)	0.306 ^{a} (0.000)	
K					0.009 ^{b} (0.017)
Panel (b): DOLS-MG					
LnNUC	0.042 [-0.983]	0.364 ^{a} [10.05]	0.370 ^{a} [9.565]	0.590 ^{a} [8.273]	0.241 ^{a} [5.256]
LnOIL	0.096 ^{a} [31.17]	-0.522 ^{a} [-10.8]	-0.528 ^{a} [-10.97]	-0.917 ^{a} [-13.63]	0.352 ^{a} [49.92]
RENEW	-0.034 ^{a} [-26.89]	-0.005 ^{a} [-2.719]	-0.004 ^{b} [-2.401]	0.013 ^{a} [2.794]	0.013 ^{a} [10.82]
LnGDP	0.400 ^{a} [8.078]	0.448 ^{a} [4.69]	0.476 ^{a} [6.207]	0.645 ^{a} [5.089]	
K					0.014 ^{a} [39.34]
Panel (c): AMG					
LnNUC	-0.090 ^{c} (0.070)	0.090 ^{a} (0.003)	0.089 ^{a} (0.003)	0.141 ^{a} (0.005)	-0.012 (0.680)
LnOIL	0.155 ^{a} (0.002)	-0.050 (0.464)	-0.046 (0.503)	-0.090 (0.383)	0.253 ^{a} (0.000)
RENEW	-0.021 ^{a} (0.000)	0.006 (0.130)	0.006 (0.135)	0.013 (0.119)	-0.004 (0.159)
LnGDP	0.485 ^{a} (0.000)	0.300 ^{a} (0.000)	0.298 ^{a} (0.000)	0.382 ^{a} (0.000)	
K					0.008 ^{a} (0.000)

a, b and c represent significance at p≤0.01, p≤0.05 and p≤0.10.
Data in parentheses show p-value and t-statistic values.

In the next step, we used FMOLS, DOLS-MG and AMG estimators to estimate the long-run coefficients. The estimation results are presented in Table 7. The estimated results of FMOLS and AMG showed that the impact of NE use on CO_2 was negative. Using NE has reduced CO_2 and increased environmental quality. In this respect, the results showed that NE can play an important role in reducing CO_2 and energy supply (Pilatowska et al.2020). The effect of NE use on agricultural and food production indices is insignificant according to the FMOLS forecast results, while it is positive according to the DOLS-MG and AMG estimation results. All estimations have shown that the use of NE supports the crop production index. The impact of NE use on GDP is positive, according to the FMOLS and DOLS-MG estimation results. The analysis showed that the use of NE contributes to increasing the level of agricultural production, food security and economic development. The estimation results showed that RE reduces CO_2 and increases environmental quality. Similarly, the estimation results of FMOLS and DOLS-MG showed that RE contributes to GDP. However, the effect of RE on agricultural and food production indices was negative according to the results of FMOLS and DOLS-MG estimations, and its effect on the crop production index was positive according to the DOLS-MG estimation result. Our results have contributed to the literature showing the effect of RE on agricultural indices in the long term. The impact of oil consumption on environmental degradation and GDP is positive, according to all forecaster results. The results of the DOLS-MG estimation showed that oil consumption had a negative effect on API.

Causality analysis

In the next stage of the research, we analyzed the causality relationship between the variables using the Dumitrescu-Hurlin (2012) test. The results of the analysis are presented in Table 8. Our results showed that there is a bidirectional Granger causality between GDP, NE, RE and oil consumption and CO_2 emissions. Similarly, a bidirectional Granger causality was determined between the agricultural production index and the food production index and GDP, NE, RE and oil consumption. There is bidirectional Granger causality between NE, RE and oil consumption and the crop gross production index, while there is one-way Granger causality from GDP to the crop gross production index. The results of the analysis showed that there is a bidirectional Granger causality between GDP and RE, oil consumption and physical capital accumulation, and a one-way Granger causality from GDP to NE. There is a bidirectional Granger causality between RE and NE, oil consumption and physical capital accumulation, and a one-way Granger causality from NE to physical capital accumulation. Similarly, according to our results, there is a one-way Granger causality from oil consumption to NE and from physical capital accumulation to oil consumption.

Tablo 8. Dumitrescu-Hurlin causality analysis

	LnCO$_2$	LnAGRO	LnFOOD	LnCROPS	LnGDP	LnNUC	LnOIL	RENEW	K
	W-stat.	W-stat	W-stat	W-stat	W-stat	W-stat	W-stat	W-stat	W-stat
LnCO$_2$	1.000				2.083***	1.678*	4.716***	3.388***	
LnAGRO		1.000			2.066***	1.733*	2.669***	2.023***	
LnFOOD			1.000		1.942**	1.712*	2.682***	2.047***	
LnCROPS				1.000	1.502	2.254***	2.399***	1.938**	
LnGDP	3.651***	5.182***	5.365***	5.742***	1.000	4.149***	4.578***	2.966***	2.143 ***
LnNUC	1.842**	2.695***	2.768***	3.273***	1.469	1.000	1.488	2.052***	1.885 **
LnOIL	2.050***	3.735***	3.732***	3.904***	1.709*	2.296***	1.000	2.475***	1.136
RENEW	4.740***	3.491***	3.434***	3.994***	2.978***	2.164***	5.398***	1.000	1.910 **
K					2.819***	1.644	2.278***	2.371***	1.000

****, ** and * represented significance at the level of $p \leq 0.01$, $p \leq 0.05$ and $p \leq 0.10$.
While determining the lag length, Akaike, Schwarz and Hannan-Quinn information criteria are taken into account, and the second lag is chosen as the appropriate lag.

5. Conclusion and policy implications

The transformation of global climate change into a crisis requiring urgent solutions has placed the relationship between economic development, energy consumption and environmental sustainability at the center of the agenda. Both climate change and the COVID-19 Pandemic have shown that food security and the sustainability of agricultural resources are critical for the entire world. Therefore, the role of clean energy in the relationship between economic development, agriculture and environmental degradation is a topic of wide debate. In this paper, we examine the effects of NE use on CO$_2$, GDP and API using recent panel data techniques. Our estimation results show that the long-term use of NE is cointegrated with CO$_2$, GDP and agricultural API. The findings suggest that NE improves environmental quality. In this respect, our findings support the studies of Saidi and Omri (2020), Vo et al. (2020), Hassan et al. (2020), Fell et al. (2022), Mahmood (2022) and Voumik et al. (2023). On the other hand, our results differ from the findings of Sovacool et al. (2020). Moreover, NE has a positive impact on agricultural and food production indices and GDP. Our analysis shows that the use of NE not only promotes agricultural and economic development but also contributes to improving environmental quality. In this context, our findings provide evidence that NE can play an important role in both agricultural, economic and environmental sustainability. On the other hand, the results of the analysis show that GDP is positively correlated with other variables. In the next stage of the study, the causality relationship between the variables is estimated using the Dumitrescu-Hurlin (2012) test. Our results showed that there is a bidirectional Granger causality between GDP, NE, RE and oil consumption and CO$_2$ emissions. Our results showed that the energy policies and environmental policies implemented in the research countries are integrated and compatible with each other. Similarly, a bidirectional Granger causality was determined between the agricultural production index and the food production index and GDP, NE, RE and oil consumption. There is bidirectional Granger causality between NE, RE and oil consumption and the crop gross production index, while there is one-way Granger causality from GDP to the crop gross production index. Our findings revealed that development and energy policies are an important determinant of agricultural policies and are compatible with each other. The results of the analysis showed that there is a bidirectional Granger causality between GDP and RE, oil consumption and physical capital accumulation, and a one-way Granger causality from GDP to NE. There is a bidirectional Granger causality between RE and NE, oil consumption and physical capital accumulation, and a one-way Granger causality from NE to physical capital accumulation. Similarly, according to our results, there is a one-way Granger causality from oil consumption to NE and from physical capital accumulation to oil consumption.

When the results of the study are evaluated, we can draw the following conclusions for policy makers, practitioners and researchers:

- The results of the research showed that the use of NE has an important role in both improving environmental quality and promoting economic development. In this respect, it is important to quickly transition from traditional energy sources to clean energy sources in research countries.
- Our results show that NE policies are in harmony with environmental and RE policies. For this reason, NE can play a critical role in the transition to RE sources for research countries.
- On the other hand, the use of NE has a positive effect on all agricultural indices. In this respect, NE can make important contributions to protecting the agricultural sector from the high costs of fossil fuel consumption and the effects of global fluctuations in research countries. In these countries, policies that will speed up the adaptation of the agricultural sector to RE are important.
- The findings reveal that GDP is consistent with agricultural and food production policies.
- Our evidence suggests that GDP is a major driver of environmental degradation. In addition, we have determined that environmental policies are an important determinant of growth policies. In this respect, growth policies that encourage environmentally friendly production patterns and less carbon-intensive sectors are important to limit the environmental costs of economic development.

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