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DOES RENEWABLE ENERGY MATTER IN THE EFFECT OF ECONOMIC GLOBALIZATION ON ENVIRONMENTAL SUSTAINABILITY? EVIDENCE FROM THE PSTR APPROACH

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ABSTRACT: The environmental effects of economic globalization have gained increasing scholarly attention. This study examines the impact of economic globalization on environmental sustainability using two models that incorporate renewable energy consumption and production dynamics. The analysis covers the five top-performing countries in the 2022 Global Green Economy Index along with Türkiye, using annual data from 1976 to 2021. A Panel Smooth Transition Regression model is applied to capture nonlinear interactions. Results indicate a three-regime nonlinear relationship in the consumption model and a two-regime structure in the production model. In both models, economic globalization exerts pressure on environmental sustainability. However, when renewable energy shifts to a high-consumption or high-production regime, this adverse effect diminishes. These findings suggest that renewable energy mitigates the environmental impact of globalization. Additionally, the Dumitrescu-Hurlin panel causality test confirms both the direct and indirect effects of globalization on ecological footprint via renewable energy. The study highlights the critical role of renewable energy in the globalization–environment nexus and offers policy recommendations for achieving sustainability goals.

KEYWORDS: economic globalization, ecological footprint, renewable energy, environmental sustainability, panel smooth transition regression

Introduction

Globalization stands out as one of the defining terms of modern society for humanity spread all over the world. It has become one of the focal points of humanity's attention, especially with the increasing economic, political, and social integration as a result of technological developments. Although the growing global economy, forms of global governance, and globally integrated social and environmental developments are often referred to as globalization, there is no single agreed definition of globalization (Dreher et al., 2008). However, it can be explained simply as a multifaceted process that refers to the transcendence of economic, cultural, political, and environmental boundaries and intensified interactions between different societies. Definitions in the literature, on the other hand, emphasize the wider scope of globalization. For instance, Held et al. (2000) define globalization as the widening, deepening, and acceleration of interconnectedness between countries in all aspects of modern life. Scholte (2000), instead, considers it as the intensification of interactions between countries in many areas, from economic relations to social life. This intensification process is accelerated by the increase in cross-border connections by creating a global network system of production, trade, finance, and information flows (Dreher et al., 2008).

According to Held and McGrew (2007), although the beginnings of globalization date back to antiquity, globalization in the modern sense originates from the period of geographical discoveries in the 15th century. During this period, a stronger network of interaction between communities was established through intercontinental trade activities. Especially in the post-Industrial Revolution period, this interaction continued to increase, and the foundations of a new global economic order were laid with the development of industrial societies. In the 20th century, international organizations such as the World Trade Organization (WTO), the United Nations (UN), the International Monetary Fund (IMF), etc., established after World War II, encouraged the strengthening of global cooperation and the increase in international trade. Meanwhile, globalization accelerated as multinational corporations dominated the world economy. Advances in communication technologies and the post-Cold War spread of capitalist market economies further fueled this momentum. Friedman (2005) defines the post-Cold War era with the metaphor of "the world flattening" and refers to this new wave of globalization as a process that transcends economic, social, and cultural differences.

According to the WTO, international trade has increased 45-fold from 1950 to 2024 (World Trade Organization, 2025). There is a strong belief that this pace of economic globalization is one of the main causes of today's environmental problems. The argument basically argues that the trade that grows through globalization causes economic expansion, which in turn causes environmental deterioration (Copeland, 2009). However, Frankel (2003) states that, in the modern era, nations are concerned about their own prosperity rather than the quality of the environment. In this respect, if policymakers only focus on environmental measures, they will unintentionally weaken national economies. Consequently, environmental concerns will completely lose their priority for nations whose prosperity level and standard of living have been lost. Therefore, the goals of environmental quality and economic growth should be balanced against each other. The question "How can these two objectives be balanced against each other?" inspired this study. Hence, while examining the nexus between environmental sustainability and economic globalization, the study utilizes a nonlinear Panel Smooth Transition Regression (PSTR) approach to determine the role of renewable energy in this nexus.

This paper contributes to the literature in three ways. First, the nonlinear PSTR approach was used to capture the nonlinear dynamics between the variables in question. Depending on the value of the transition variable, this method separates the series into homogenous regimes and enables different interpretations for each regime. Secondly, renewable energy was chosen as a transition variable in two separate models in both consumption and production contexts, and the findings were compared. Considering that economic variables are commonly employed as transition variables in the literature on threshold models, this choice was an innovative approach to better understand the environmental impacts of the energy sector. Finally, in this paper, almost all of the countries chosen have the highest scores in the Global Green Economy Index (GGEI) 2022 Report. Thus, it is believed that the findings of the study will serve as a helpful guide for policymakers aiming to improve their countries' environmental performance.

The next section presents the literature review on the nexus between globalization and the environment. Section 3 summarizes the theoretical background of econometric methodology and the

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data. Section 4 presents the empirical results, and Section 5 provides a discussion. The last section contains concluding remarks and policy recommendations.

An overview of the literature

Globalization is an important term that has been discussed in the international literature for many years. As the relevant literature has expanded, more complex dynamics have arisen. Since globalization is a multidimensional process, researchers have started to focus on studies that consider its economic, social, and political dimensions separately. Early studies in this field, such as Dreher (2006), have focused especially on the effects of economic globalization on the economic performance and social structures of countries. The author suggested that globalization is strongly associated with economic growth and that economic globalization mostly promoted growth in his study covering 123 countries. He also argued that social globalization has a positive effect on growth, even if to a lesser extent, and that political globalization has no effect on growth.

Negative impacts on environment

Recently, the environmental impacts of globalization have also been a subject of interest for researchers. Some of these researchers claim that globalization causes environmental pollution (Adebayo, 2022; Anser et al., 2021; Phong, 2019; Shabbir Alam et al., 2023; Shabir, 2024; Shahbaz et al., 2018; Sharif et al., 2019; Xu et al., 2018; Sibt-e-Ali et al., 2024). For instance, Leitão (2013) conducted the first study to consider the globalization index as an explanatory variable. According to the empirical findings, globalization causes CO_2 emissions by intensively increasing production. Phong (2019) analyzed the period 1971-2014 for five selected Asian countries. He concluded that globalization causes pollution, and economic globalization has the most impact. Xu et al. (2018) considered economic, social and political globalization as explanatory variables in addition to general globalization. The empirical findings revealed that only economic globalization leads to higher emissions for the case of Saudi Arabia. Abbass et al. (2025) confirmed these results with findings obtained using the AMG method from their research that covered Next-11 countries. Zhang and Liu (2024) examined the impact of globalization on the environment using PSTR analysis over the period 1992–2021, in the Yellow River Basin in China. According to the empirical findings, economic globalization means that emissions continue to increase; however, the rapid development of the tertiary industry alleviates the negative influence of the economy on CO_2 emissions. Suki et al. (2020) also obtained the same result in their study for the case of Malaysia, covering the period from 1970 to 2018.

On the other hand, among the studies focusing on the nexus between globalization and the environment, Figge et al. (2017) is the first to consider the ecological footprint as a measure of environmental sustainability. The study covering 183 countries revealed that globalization significantly increases the pressure on the environment. Ahmed et al. (2019) showed that globalization has no significant impact on ecological footprint but on ecological carbon footprint. Furthermore, Bilgili et al. (2020) demonstrated that economic and social globalization leads to worsening environmental degradation in Türkiye using nonlinear Markov regime-switching models. On the other hand, Rudolph and Figge (2017) found that economic globalization increases the ecological footprint, but social globalization decreases it using annual data for 146 countries over the period 1981-2009. Also, Ahmad et al. (2022) as well as Bekun and Ozturk (2025) demonstrated that economic integration has caused an increase in the ecological footprint for E7 countries. Finally, Lu and Wang (2024) examined how economic globalization affected the ecological footprint of the top ten Asian nations noted for technological innovation between 1999 and 2018. Results reveal that increased economic globalization harms the environment and necessitates additional resources. These studies have emphasized the importance of implementing sustainable development policies to mitigate the harms of economic globalization on environmental sustainability.

Positive impacts on the environment

All of the studies mentioned above have pointed to the negative impact of economic globalization on environment quality. However, there are also studies in the literature that suggest that globaliza-

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tion contributes to environmental sustainability (Lawal et al., 2023; Haseeb et al., 2018; Leitão, 2014; Lu et al., 2024; Lv & Xu, 2018; Phong et al., 2018; Wang et al., 2021; You and Lv, 2018; Idroes et al., 2024). For instance, Destek and Ozsoy (2015) analyzed the nexus between economic globalization and emissions for the case of Türkiye. They showed economic globalization has mitigated environmental degradation. Likewise, Lv and Xu (2018) asserted that economic globalization has a positive impact on environmental sustainability for 15 selected developing countries over the period 1970-2012. Moreover, Karaduman (2022) showed that economic globalization has reduced the ecological footprint in the Next Eleven (N-11) countries. Therefore, this meant that economic integration could contribute to protecting the environment. More recently, Lu et al. (2024) for BRICS-T countries and Ximei et al. (2025) for APEC countries supported the result that economic globalization contributes to the improvement of environmental conditions through their empirical findings using the ARDL method. Okere et al. (2024) examined this nexus for the North Africa region, and Villanthenkodath and Pal (2023) for India and they also found same results. All of these studies have obtained results showing that globalization has a positive environmental impact.

In summary, the literature has shown that economic globalization in particular has a complex and often detrimental impact on environmental sustainability. Accordingly, economic globalization integrates markets, encourages economic growth through enhanced trade, and often causes pollution through increased industrial activity as well as excessive resource consumption. In other words, the focus of economic globalization on production and consumption further increases CO_2 emissions (Audi et al., 2025; Du et al., 2025). There are many studies showing that this situation is more intense, especially in developing economies (Ahmad et al., 2022; Bilgili et al., 2020). Moreover, some recent studies revealed that the harmful effects of economic integration on the environment can be avoided or eliminated through the use of renewable energies (Adebayo et al., 2024; Çetin et al., 2023; Pata, 2021; Wang et al., 2024). These findings indicated that economic integration needs to be balanced with sustainable energy policies to tackle the negative environmental impacts of economic globalization.

Research methods and data

Data

This paper examined the nexus between environmental sustainability and economic globalization in the context of renewable energy in two different perspectives, namely consumption and production models, and made a comparative evaluation of the findings. For this purpose, environmental sustainability was represented by the ecological footprint, while economic globalization was represented by the economic dimension of the KOF Globalization Index, and they were considered as dependent and independent variables, respectively. There were some reasons for the choice of these variables determined within the scope of the research. First of all, the Ecological Footprint variable allowed us to understand the ecological deficit or ecological reserve status worldwide and was an important indicator in terms of environmental sustainability. The KOF Globalization Index, introduced to the literature by Dreher (2006), comprehensively handles the economic dimension of globalization with financial and trade indicators, which have equal shares in both the de jure and de facto context. While renewable energy consumption was used as the transition variable in the first model, renewable energy production was preferred in the second model. Thus, it has been discussed how renewable energy causes changes in the environmental impacts of economic integration, depending on the dynamics of consumption and production.

In addition, the countries that scored highest on the GGEI 2022 Report – Sweden, Switzerland, Norway, France, and Denmark – and Türkiye were also included in the study. The inclusion of Türkiye allowed for a broader cross-country comparison between countries with advanced environmental policies and a developing economy undergoing an energy transition. This contrast helped assess whether the globalization–environment relationship was consistent across different levels of environmental maturity and development. Although this choice makes the model structure heterogeneous, the PSTR approach can capture potential differences in slope coefficients or regime shifts among countries through preliminary tests such as the remaining heterogeneity test, explicitly accounting for heterogeneity and nonlinearities. Annual data of these countries over the period 1976-2021 were used for the analysis. We believe that this large period, which corresponds to almost half a century,

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has strengthened our research's findings. Accordingly, data on the Ecological Footprint variable used in this study were gathered from the Global Footprint Network, while data on the Economic Globalization Index were taken from the KOF Swiss Economic Institute. Finally, renewable energy data was obtained from the International Energy Agency. Table 1 shows the descriptions of the variables.

Table 1. Descriptions of the variables

Variables	Symbol	Description	Unit	Source
Ecological Footprint	EF	Measures the demand pressure on the biocapacity provided by nature.	Global hectares per capita	GFN
Economic Globalization Index	EGI	Composed of the de jure and de facto measurement of international trade and financial transactions.	Index	KOF
Renewable Energy Consumption	lnREC	Natural logarithm of total consumption	Petajoule (PJ)	IEA
Renewable Energy Production	lnREP	Natural logarithm of total production	Petajoule (PJ)	IEA

Methodology

The notion of linearity in econometric analysis, in its simplest form, states that an increase in the independent variable causes a constant change in the dependent variable. Linear regression models, which offer the opportunity to define the relationships between variables in a simple and clear way, are widely preferred due to their theoretical simplicity and practical convenience (Wooldridge, 2010). However, these methods are insufficient to provide estimates that are accurate, especially in panel data analyses, given the differences between individuals and seasonal effects (Hsiao, 2003).

The Panel Threshold Regression (PTR) model introduced by Hansen (1999) aims to estimate such nonlinear structures. This approach checks for the presence of a certain threshold and, if present, determines the behaviours above or below the threshold. However, the disadvantage of the PTR model is that it is based on the assumption that the transition between regimes is sharp. Gonzalez et al. (2005), on the other hand, suggested that the transition between regimes is smooth rather than sudden and thus they developed the PSTR model in order to obtain estimates that are closer to reality.

Based on the value of the transition variable, the PSTR model separates the panel's data into homogenous regimes. It means that the values of the regression coefficients could vary depending on the regime. Accordingly, a PSTR model with a single transition function (two regimes) is as given in the following Equation (1):

$$y_{it} = \mu_i + \beta_0' x_{it} + \beta_1' x_{it} g(q_{it}; \gamma, c) + u_{it} \quad i = 1, \dots, N; \quad t = 1, \dots, T \tag{1}$$

In Equation (1), x_{it} refers to a k-dimensional vector of independent variables, while y_{it} scales the dependent variable. In addition, μ_i denotes fixed individual effects, and u_{it} denotes residuals. As a continuous function of q_{it}, the transition function $g(q_{it};\gamma,c)$ allows values between 0 and 1. It is also defined in the form of a logistic function as in Equation (2) below:

$$g(q_{it}; \gamma, c) = \left(1 + exp\left(-\gamma \prod_{j=1}^{m} (q_{it} - c_j) \right) \right)^{-1} \quad \gamma > 0; \; c_1 < c_2 < \cdots < c_m \tag{2}$$

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In Equation (2), q_{it} is the transition variable, $c=(c_1,...,c_m)'$ is the m-dimensional vector of the location (threshold) parameter, and the slope parameter γ of the transition function determines the smoothness of the transition. If the value of γ is high, the transition is completed in a short time, while for small values, the transition is slower. The transition function turns into an indicator function if $(\gamma\to\infty)$, taking the value 1 when $q_{it}>c$ and 0 otherwise. As in the PTR model, switching from one regime to another is rather rapid in this instance. Hence, the PTR approach is used for analyzing the model. Finally, as $(\gamma\to0)$, the transition function $g(q_{it};\gamma,c)$ becomes equal to a constant. In other words, the model becomes a linear panel regression model with fixed effects (González et al., 2005).

On the other hand, the transition variable's value influences the transition function's value. Therefore, it would not be wrong to define the regression coefficient for the ith individual at time t as $\beta_0 x_{it}+\beta_1 x_{it}\, g(q_{it};\gamma,c)$. Accordingly, the parameters in the extreme regimes depend on the extreme values 0 and 1 of the transition function. In this respect, the coefficient estimates are equal to β_0 and $\beta_0+\beta_1$ for the first regime and for the second regime, respectively. However, it is the weighted average of the β_0 and β_1 estimates, when the transition function equal to a value between 0 and 1. As a result, in this approach, rather than directly interpreting the coefficients, it is preferred that the interpretation of their signs. Therefore, the influence of the independent variable on the dependent variable can be stated to be positive or negative (Fouquau et al., 2009).

Additionally, the PSTR model may have more than two regimes. In such a case, it can be extended as in Equation (3):

$$y_{it} = \mu_i + \beta_0' x_{it} + \sum_{j=1}^{r} \beta_j' x_{it} g_j\left(q_{it}^{(j)}; \gamma_j, c_j\right) + u_{it}. \tag{3}$$

The process of building the PSTR model consists of specification, evaluation, and estimation. The specification process involves testing linearity, selecting the transition variable q_{it}, and determining the optimal form of the transition function when linearity is rejected, i.e., selecting the appropriate value of m in Equation (2). Also, the transition variable can be determined using the linearity test. All potential transition variables are subjected to the test for this purpose, and the one that most strongly rejects linearity is chosen to serve as the transition variable. In the evaluation step, the remaining heterogeneity needs to be tested, and hence the number of regimes, i.e., the value of r in Equation (3), needs to be determined. At the last step, parameter estimation is conducted using the NLS method (González et al., 2005).

Finally, to ensure the chosen variables in the nonlinear PSTR framework are reliable and to verify the presence of causal relationships, we employed the Dumitrescu–Hurlin (2012) panel Granger non-causality test, which is an extended version of Granger's (1969) method. Indeed, understanding the nature of the causal links between the model factors might be useful for policymakers in implementing appropriate environmental policies. Considering the issues of heterogeneity and cross-sectional dependency, this causality method is effective for correctly determining the nature of the cause-effect relationship between variables.

Results of the research

Based on Equation (1), in order to measure the impact of the economic globalization on environmental performance in the context of renewable energy, the consumption model (A) and production model (B) were constructed as in Equations (4) and (5):

$$Model\ A: \quad EF_{it} = \mu_i + \beta_0 EGI_{it} + \beta_1 EGI_{it} g(lnREC_{it}; \gamma, c) + u_{it}. \tag{4}$$

$$Model\ B: \quad EF_{it} = \mu_i + \beta_0 EGI_{it} + \beta_1 EGI_{it} g(lnREP_{it}; \gamma, c) + u_{it}. \tag{5}$$

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In Equations (4) and (5), EF represents the ecological footprint, which is a measure of environmental performance, while EGI represents the level of economic globalization. The transition variables were defined as renewable energy consumption for models A and as renewable energy production for model B. Figure 1 presents an overview of our estimation procedure.

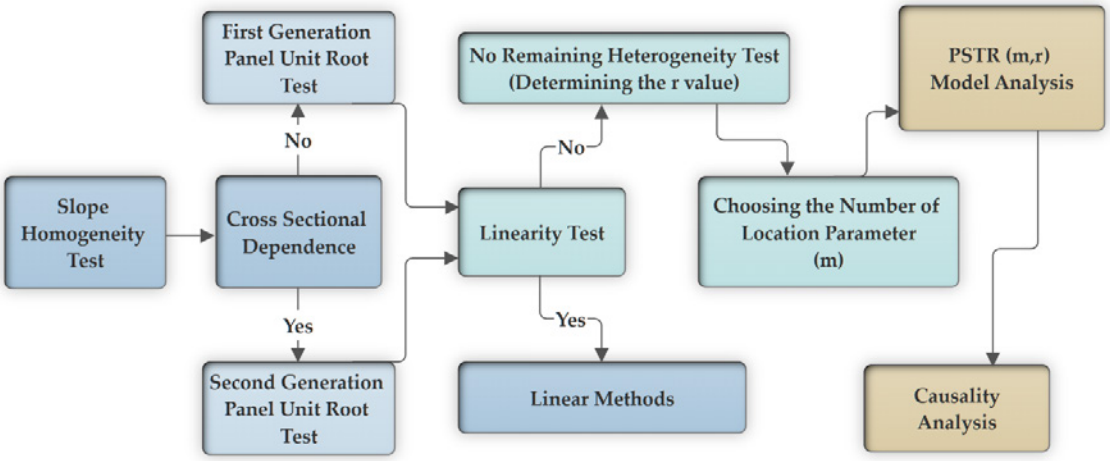


Figure 1. The methodology flow implemented in the current research.

Since it is necessary to test for both the presence of cross-section dependence and the unit root for all panel series, the Breusch-Pagan CD_{LM} (1980) test was used as the first step of the analysis phase to investigate the existence of cross-section dependence. According to the results presented in Table 2, for all series and the models, the null hypothesis stating that the cross-section independence was rejected. Table 2 also provides the Δ and Δ_{adj} slope homogeneity tests by Pesaran and Yamagata (2008). The null hypothesis that the slope coefficients are homogenous was rejected based on the calculated values. Consequently, it is concluded that the panel includes cross-sectional dependence and was heterogeneous in slopes.

Table 2. Panel specification test results

Cross-section dependency test	Model A		Model B	
Variables	Statistics	p-values	Statistics	p-values
EF	263.7976	0.000	263.7976	0.000
EGI	628.5305	0.000	628.5305	0.000
lnREC	437.0801	0.000	-	-
lnREP	-	-	499.5031	0.000
MODEL	96.49	0.000	84.32	0.000
Slope homogeneity tests				
	Δ	p-values	Δ	p-values
Δ Test	16.690	0.000	23.298	0.000
Δ_{adj} Test	17.466	0.000	24.382	0.000

Secondly, due to the presence of cross-section dependence, the CIPS test developed by Pesaran (2007), one of the second-generation panel unit root tests that takes into account cross-section dependence, was applied to investigate the stationarity of the series. A comparison of the test statistics with the critical values given in Table 3 indicates that the existence of unit root was rejected at a 5% significance level for all variables and both models. Thus, it is concluded that all variables are stationary in level.

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Table 3. CIPS unit root test results

	Model A		Model B	
Variables	C	C&T	C	C&T
EF	-2.949***	-3.716***	-2.949***	-3.716***
EGI	-2.958***	-3.224***	-2.958***	-3.224***
lnREC	-2.347**	-2.950**	-	-
lnREP	-	-	-2.825***	-2.932**
Critical Values				
	1%	5%	10%	
C	-2.55	-2.33	-2.21	
C&T	-3.06	-2.84	-2.73	

***, **, and * denote 1%, 5%, and 10% significance, respectively.

Following the conclusion that the series were appropriate for PSTR analysis, the linearity test was conducted first. It should be determined whether there was a linear relationship between the variables. In other words, the presence of more than one regime should be tested with the linearity test. The null hypothesis states for the linearity, while the alternative hypothesis is for the nonlinearity with at least two regimes. The findings of the analysis presented in Table 4 suggest that the null hypothesis of linearity is strongly rejected for both models A and B.

Table 4. Linearity test results

H_0: Linear model (r=0)	Model A		Model B	
H_1: PSTR model with at least two regimes (r≥1)	m=1 Statistics	m=2 Statistics	m=1 Statistics	m=2 Statistics
Wald Test (LM)	67.978 [0.000]	71.833 [0.000]	50.031 [0.000]	53.318 [0.000]
Fisher Test (LM_F)	87.905 [0.000]	47.146 [0.000]	59.558 [0.000]	32.084 [0.000]
Likelihood Ratio Test (LRT)	78.041 [0.000]	83.203 [0.000]	55.201 [0.000]	59.245 [0.000]

[ ] are p-values.

As previously explained, if we reject the linearity, we need to determine the number of regimes. In order to decide the number of regimes, the analysis would be repeated until the null hypothesis could not be rejected. No remaining heterogeneity test was conducted for both m levels and models A and B, and the results are given in Table 5. Firstly, the two-regime PSTR model was tested against the PSTR model with at least three regimes. Empirical findings obtained for model B show that the PSTR model with one transition function could not be rejected at the 5% significance level for both m values. On the contrary, model A results indicate that the two-regime PSTR model was rejected at all significance levels. In the second phase, the null hypothesis that suggested the PSTR model with two transition functions was not rejected for both m values at all levels of significance. Thus, it could be concluded that there was a three-regime nonlinear relationship between variables for model A, while there was a two-regime for model B.

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Table 5. No remaining heterogeneity test results

H_0: PSTR model with two regimes (r=1)	Model A		Model B	
H_1: PSTR model with at least three regimes (r≥2)	m=1 Statistics	m=2 Statistics	m=1 Statistics	m=2 Statistics
Wald Test (LM)	8.476 [0.004]	33.517 [0.000]	3.100 [0.078]	3.461 [0.177]
Fisher Test (LM_F)	8.459 [0.004]	18.384 [0.000]	3.033 [0.083]	1.689 [0.187]
Likelihood Ratio Test (LRT)	8.609 [0.003]	35.734 [0.000]	3.118 [0.077]	3.483 [0.175]
H_0: PSTR model with three regimes (r=2) H_1: PSTR model with at least four regimes (r≥3)				
Wald Test (LM)	0.361 [0.548]	2.140 [0.343]	-	-
Fisher Test (LM_F)	0.349 [0.555]	1.035 [0.357]	-	-
Likelihood Ratio Test (LRT)	0.361 [0.548]	2.148 [0.342]	-	-

[ ] are p-values.

Following Colletaz and Hurlin (2006), we used the Sum of Residual Squares (RSS), Akaike Information Criterion (AIC), and Bayes Information Criterion (BIC) to decide the number of threshold parameters. Table 6 shows the contains the RSS, AIC, and BIC values.

Table 6. Selecting the number of optimal location parameter

	Model A		Model B	
	m=1	m=2	m=1	m=2
RSS	84.508	89.165	106.818	108.067
AIC	-1.081	-1.050	-0.902	-0.879
BIC	-0.963	-0.958	-0.850	-0.814

When the values obtained for both m levels were compared, it was seen that the *m*=1 level was appropriate for both models A and B. Hence, the model with one location parameter and two transition functions was determined as the optimal model. In this regard, PSTR (1, 2) was found to be the optimal model for model A, whereas PSTR (1, 1) was for model B. The findings of PSTR analysis are presented in Table 7.

Findings obtained from Model A indicate that the estimated coefficients are statistically significant. The slope parameter (γ) was 6.6017 for the first transition function and 4.9812 for the second transition function. The low values of the slope parameter estimates of the transition functions implied that the transition between regimes was slow. The threshold values dividing the regimes were found to be 43 PJ for the first transition and 322 PJ for the second transition. According to empirical results, the increase in the degree of economic globalization has caused a negative impact on environmental pollution by increasing the per capita ecological footprint (β_0=0.0334) in the first regime, where the renewable energy consumption was lower than 43 PJ. In the second regime, where consumption was between 43 PJ and 322 PJ, this economic globalization-induced pressure on the ecological footprint has continued ($\beta_0+\beta_1$=0.0046). On the other hand, for the third regime, where the level of renewable energy consumption exceeded 322 PJ, the sign of the estimated coefficient has turned out to be negative ($\beta_0+\beta_1+\beta_2$=-0.0290). In other words, in the high-consumption regime, the pressure caused by economic globalization on the ecological footprint was lost.

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Table 7. PSTR model estimation results

	Model A: PSTR (1, 2)		Model B: PSTR (1, 1)	
	Coefficients	Statistics[a]	Coefficients	Statistics[a]
EGI	0.0334***	5.2869	0.0872***	6.1006
	-0.0288***	-12.7106	-0.1007***	-8.3946
	-0.0336***	-7.9703	-	-
Threshold values (c)	3.7590 (43 PJ)		5.4439 (231 PJ)	
	5.7746 (322 PJ)		-	
Slope parameters (γ)	6.6017		1.8728	
	4.9812		-	

***, **, and * denote 1%, 5%, and 10% significance, respectively. [a] Indicates t-statistics corrected for the heteroskedasticity of the estimated coefficients (Newey-West HAC).

In terms of Model B, the results demonstrated that the coefficients were statistically significant and the slope parameter of the transition function (γ) was 1.8728. The threshold value dividing the two regimes was found to be 231 PJ. While the sign of the estimated coefficient was positive in the first regime (β_0=0.0872), it was found to be negative in the second regime, where production exceeds this threshold level ($\beta_0+\beta_1$=-0.0135). In other words, while economic globalization caused environmental degradation in the first regime, where production was low, it turned into a factor that contributed to environmental sustainability in the second regime, where production was high. In sum, our findings obtained from both models A and B support each other. Thereby, it could be said that even though economic globalization was a factor that reduced environmental quality, this impact could be reversed through incentives for renewable energy, thus contributing to environmental sustainability.

Table 8. Dumitrescu-Hurlin (2012) Panel Granger Non-Causality Test Results

	W-bar	Z-bar	p-value	Conclusion
EGI does not Granger cause EF	3.8384	4.9162***	0.0000	EGI → EF
EF does not Granger cause EGI	1.5140	0.8902	0.3733	
EGI does not Granger cause lnREC	3.0976	3.6331***	0.0003	EGI → REC
lnREC does not Granger cause EGI	0.9351	-0.1125	0.9104	
EGI does not Granger cause lnREP	4.7588	6.5104***	0.0000	EGI → REP
lnREP does not Granger cause EGI	1.2886	0.4998	0.6172	
lnREP does not Granger cause EF	4.4611	5.9949***	0.0000	REP → EF
EF does not Granger cause lnREP	1.8021	1.3893	0.1647	
lnREC does not Granger cause EF	5.3583	7.5488***	0.0000	REC ↔ EF
EF does not Granger cause lnREC	2.4675	2.5418**	0.0110	

***, **, and * denote 1%, 5%, and 10% significance, respectively.

To assess the robustness of our findings, we also investigated the causal relationship between the variables. Empirical findings from the Dumitrescu-Hurlin panel Granger non-causality test developed for heterogeneous panels are presented in Table 8. Based on the results, there is a unidirectional causal relationship from EGI to all other variables and from REP to EF. Moreover, we found a bidirectional Granger causality relationship between REC and EF. These empirical links justify the adoption of a PSTR model to further explore the nonlinear regime-dependent dynamics among these variables.

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Discussion/Limitation and future research

Figure 2 shows the regimes in which the renewable energy consumption and production levels of the countries are located on a yearly basis with reference to the determined thresholds. In general, renewable energy consumption and production levels have been observed to have an increasing trend, with the exception of Türkiye's consumption levels. In terms of consumption, Switzerland, Norway, and Denmark exceeded the 43 PJ threshold and moved from a low to a moderate consumption regime; Sweden has reached the threshold of a high consumption regime, and France is in a high consumption regime. Türkiye, on the other hand, experienced fluctuations around the second threshold until the 2000s but then fell into the moderate consumption regime and showed a falling trend. This shows that fossil fuels still play an important role in energy demand, which increases with industrialization and economic growth. Türkiye can hasten the transition back to the high consumption regime by developing policies that promote renewable energy. In terms of production, Denmark and Switzerland were initially in the low production regime. However, Switzerland moved to the high production regime in 2012. This can be explained by the fact that these countries do not need large-scale investments in renewable energy production due to their populations. However, they can strengthen their position in the global energy market by investing in technologies that will increase energy storage capacity. Sweden, Norway, France, and Türkiye are in the high production regime. Especially Türkiye has experienced a jump in production after 2014. In order for this jump to be sustainable, energy export strategies can be reinforced by prioritizing infrastructure investments and modernization of energy distribution systems.

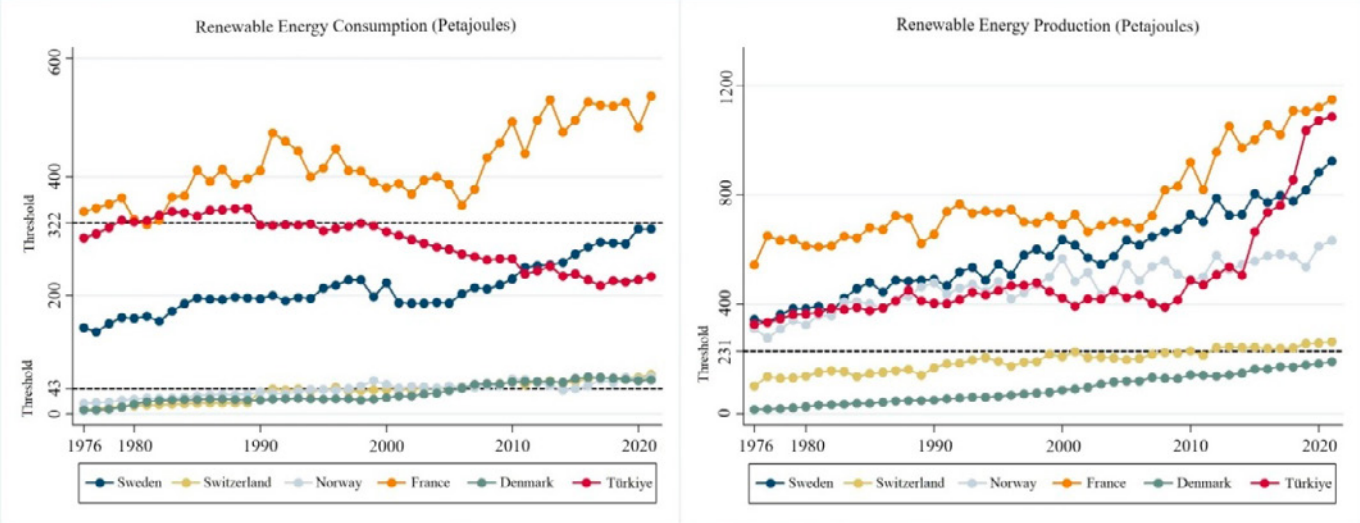


Figure 2. Evolution of renewable energy consumption and production levels across regimes

Figure 3 presents the spatial distribution of REC and REP regimes for six countries in 2021. In terms of renewable energy consumption, all countries are positioned within the moderate consumption regime, while France stands out by achieving the high consumption regime. Regarding renewable energy production, all countries have crossed the high production threshold, while Denmark remains in the low production regime. These findings underline the heterogeneity in renewable energy dynamics among environmentally advanced countries and emphasize the importance of policy and infrastructural differences in shaping renewable energy targets.

Table 7 provides the parameter estimates of both consumption and production models together. All coefficient estimates were found to be statistically significant. However, as mentioned in the previous section, coefficient estimates cannot be directly interpreted but signs in PSTR models. In this respect, it is possible to say that the economic globalization increases the ecological footprint in the first regime for both models. Results clearly show that the most obvious difference between the consumption and production models is the number of regimes. While the consumption model has three regimes, the production model has two. This result implies that renewable energy consumption affects the relationship between economic globalization and ecological footprint in a multiphase pro-

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cess. There are several possible reasons for this result, since renewable energy consumption and renewable energy production have different dynamics. Firstly, consumption is directly influenced by consumer behavior, government policies, and incentives. For instance, transfer expenditures or incentives can lead to an increase in renewable energy consumption and thus to considerable environmental improvements. Moreover, renewable energy consumption is shaped by factors like technology, market prices, and public awareness. This explains why the consumption model has more phases than the production model.

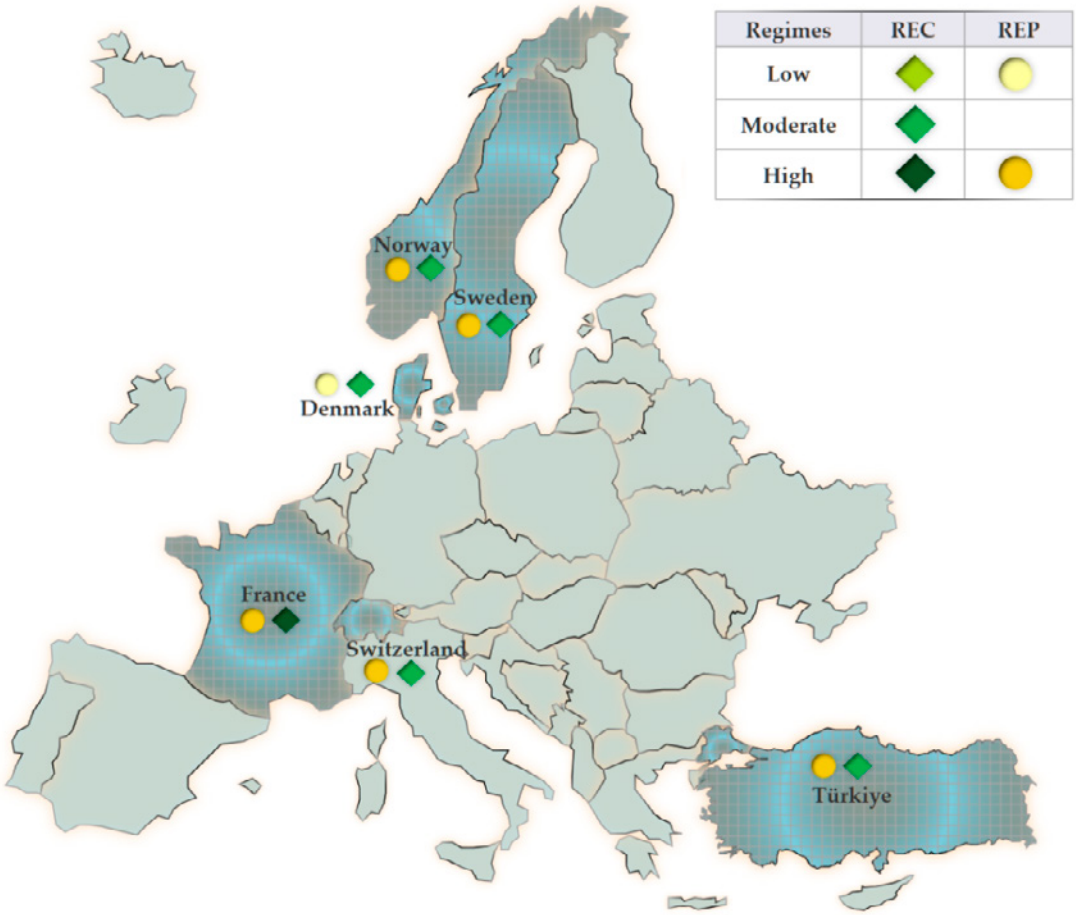


Figure 3. Renewable energy consumption and production regimes of sample countries in 2021

When the threshold values, which are the defining points in transitions between regimes, are examined, it is seen that the first transition for the consumption model has occurred at 43 PJ. In the second regime, where this threshold is exceeded, the pressure of economic globalization on the ecological footprint continues even though it decreases. As can be seen in Figure 1, France is the only country that has exceeded the second threshold of 322 PJ and has switched to the third regime and maintained its current situation. In this high consumption regime, economic globalization becomes a factor that decreases the ecological footprint and thus contributes to environmental improvement. In the renewable energy production model, there is a one-threshold and two-regime relationship, and the threshold value is found as 231 PJ. Consistent with the consumption model, economic globalization has a damaging effect on the environment in the low production regime, while it has environmental benefits for countries with higher production than the threshold. Considering the beneficial effect of this clear and single phase, taking actions to increase renewable energy production would be a highly effective strategy for environmental sustainability.

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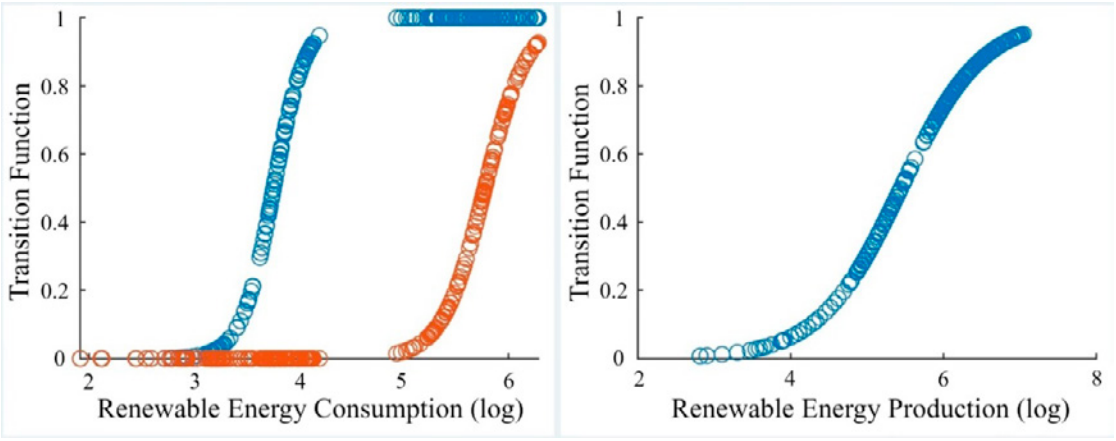


Figure 4. Comparison of transition functions plotted against transition variables

It is observed that the slope parameter estimates of the transition functions of both consumption and production models take very low values. Based on this, it can be said that the transition between regimes is smooth. Nevertheless, since the slope parameter takes a smaller value in the production model, it can be said that the transition occurs more slowly than in the consumption model. Figure 4, where the transition functions plotted against the transition variables for both models are shown together, supports this conclusion. Moreover, this result is consistent with the nature of renewable energy production processes. This is because infrastructures such as wind farms, solar panels, and hydroelectric power plants must be built for generation. These infrastructures are capital-intensive and time-consuming projects that require planning and investment. For instance, the generation sector is constrained by regulatory rules, long construction periods, and time-consuming technological developments. On the other hand, the consumption model transitions faster than the production model. This is due to the easier adoption of energy-efficient technologies and the direct impact of policies and incentives on consumer behavior. In addition, the fact that renewable energy consumption directly reduces dependence on fossil fuels and decreases carbon emissions will increase the speed of transition between regimes. Beyond reducing fossil fuel dependence and lowering carbon emissions, renewable energy contributes to environmental sustainability through additional mechanisms. It enhances energy efficiency by enabling cleaner and more decentralized systems, particularly through the integration of solar, wind, and smart grid technologies. Moreover, investments in renewable energy often stimulate innovation in green technologies, creating a positive feedback loop that supports ecological modernization. These mechanisms collectively demonstrate how renewable energy acts not only as an energy source but also as a systemic catalyst for transforming the environmental impacts of economic globalization. As a result, the slower transition in the renewable energy production model can be explained by the time it takes to build generation capacity, regulatory and financial barriers, and the adoption of generation technologies over time. Conversely, in the renewable energy consumption model, environmental impacts are expected to be seen faster with the rapid implementation of incentives and policies and rapid adoption by consumers. A better understanding of these dynamics will help to develop strategies to effectively increase both renewable energy consumption and production to achieve environmental sustainability.

Additionally, the findings we obtained from the causality analysis also support these mechanisms. Figure 5 illustrates the dynamic causal structure among the variables based on the results of the Dumitrescu–Hurlin panel non-causality test. The visual form makes it easy to see how economic globalization impacts the environment, both directly and indirectly. Economic globalization causes ecological footprints through both direct and indirect pathways, particularly via renewable energy consumption and production. These results suggest that renewable energy serves not only as a mediator but also as a transmission mechanism through which globalization exerts its environmental impact. Furthermore, the bidirectional causality between ecological footprint and renewable energy consumption suggests that environmental degradation can influence energy behavior. This may occur through policy changes or shifts in societal preferences. These findings reinforce the importance of integrating renewable energy policies into broader economic globalization strategies to achieve sustainable environmental outcomes.

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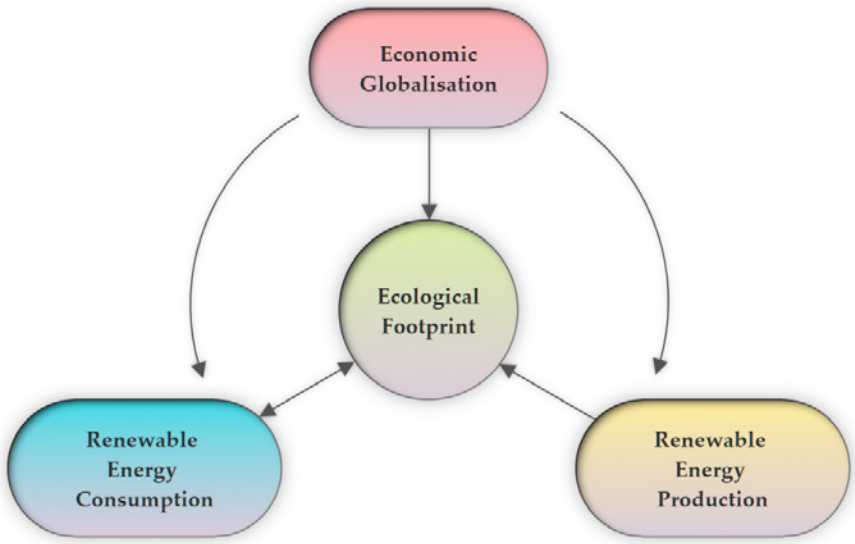


Figure 5. Schematic representation of the causality relationships

The study contributes to the literature by combining long-run panel data with a nonlinear modeling strategy, offering nuanced insights into the globalization–environment nexus. While additional variables such as technological development, environmental innovation, or policy instruments were considered, they were excluded to maintain methodological consistency and data stationarity. The PSTR model was selected for its ability to capture nonlinear and regime-dependent relationships in panels while accommodating cross-country heterogeneity. This ability makes the PSTR model more suitable than other techniques for analyzing threshold effects of renewable energy within the globalization–environment nexus. In addition to model justification, it is also important to address potential econometric considerations such as endogeneity. As a precaution against potential endogeneity, country fixed effects were incorporated into the model to account for time-invariant heterogeneity. Moreover, the use of long-term panel data helps mitigate risks of reverse causality and short-term shocks that could bias the estimates. While the PSTR model does not explicitly address endogeneity, its structure combined with the data design limits such concerns to a considerable extent, and further exploration of advanced endogeneity treatments can be considered a valuable direction for future research. In this context, the chosen variables allow for a focused nonlinear analysis using the PSTR approach, capturing cross-country heterogeneity and threshold effects without compromising empirical robustness. Future research may explore more complex dynamics by incorporating multiple transition variables or conducting sector-specific investigations, provided data and methodological compatibility are ensured.

Conclusions and policy implications

This study provides empirical evidence on the relationship between economic globalization and environmental sustainability, with a particular focus on the mediating role of renewable energy. Using the PSTR approach, the nonlinear dynamics between the variables were modeled for six countries, including the top five performers in the 2022 GGEI report and Türkiye. Two separate models were constructed by employing renewable energy consumption and renewable energy production as transition variables, and findings obtained from both models were compared. Annual data for the period 1976–2021 were used to ensure the long-term relevance of the analysis.

The empirical results consistently indicate that economic globalization harms environmental sustainability. However, once renewable energy consumption or production exceeds a certain threshold, the impact of globalization turns positive, supporting the hypothesis that renewable energy acts as a key moderator in this relationship. In addition, the Dumitrescu-Hurlin panel non-causality test

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results suggested the existence of both direct and indirect effects of economic globalization on the environmental footprint via renewable energy. These findings highlight that investments in renewable energy not only reduce ecological pressure but also transform global economic integration into an environmentally beneficial process.

Based on the findings of the study, several recommendations for environmental sustainability policies have been developed. Firstly, it is important to coordinate environmental policies at national and international scales in order to manage the environmental impacts of economic globalization. Policymakers can reduce the environmental costs of economic activities by including provisions that promote environmental sustainability in trade agreements. However, the implementation of such provisions requires strong institutional frameworks and cross-border monitoring mechanisms, which may involve high coordination costs but can yield long-term global benefits.

It would also be useful to strengthen international cooperation to manage and export energy surpluses to meet the growing global demand for energy from green sources. In particular, pioneer countries in the field of green economy, such as Switzerland and Denmark, have stayed in a low production regime. This may be due to low energy demand stemming from low population. However, it would be beneficial for such countries to establish international renewable energy cooperation in order to manage and export their energy surplus. Although such cooperation may face technical and geopolitical challenges, it could reduce energy waste and strengthen regional energy security.

In addition, it is important for countries with high production capacity, such as Türkiye, to invest in storage infrastructure and make plans for energy exports. For this purpose, infrastructure projects can be accelerated through public-private sector cooperation. While such investments may require significant public funding and long-term planning, they also present opportunities for job creation and technology transfer.

Moreover, for countries like Sweden, where production and consumption are balanced, making long-term plans would be helpful in preserving energy independence. On the other hand, incentive policies for both the public and private sectors should be implemented to increase renewable energy consumption. For instance, expanding the use of resources such as solar and wind energy can mitigate environmental impacts by reducing fossil fuel dependency in energy production. However, these technologies often require substantial initial capital investment and regulatory support, which should be planned according to the fiscal capacity of each country.

Furthermore, technologies that increase energy efficiency should be encouraged in order to control the environmental impacts of increasing energy consumption. Additionally, environmental education and awareness campaigns can help people reduce their negative impact on the environment. Re-transforming consumption habits will be an important step in promoting environmental sustainability, especially in developing countries. Sustainable production and consumption activities can contribute to the conservation of natural resources and the reduction of ecological footprints.

While these policy measures are promising, their feasibility depends on each country's institutional capacity, fiscal resources, and technological infrastructure. For instance, Denmark's success in wind energy expansion reflects early investment in grid integration, while Switzerland's focus on hydropower showcases the role of resource endowments. In contrast, Türkiye's growing energy demand highlights the importance of balancing industrialization with sustainability through large-scale storage projects and regional energy trade. Implementing such policies may involve substantial upfront costs, regulatory reforms, and coordination among multiple stakeholders. Overcoming these barriers will require phased implementation, international financing mechanisms (such as green bonds or climate funds), and knowledge transfer from frontrunner countries. These steps can make renewable energy-centered strategies both realistic and effective in reducing ecological pressures associated with globalization.

Consequently, it is a fact that climate change caused by environmental degradation has become a global crisis. This study has shown that international economic integration, which is a natural consequence of the industrial and technological progress of the modern world, has increased the severity of this crisis. However, it would not be wrong to say that this pressure arising from international economic integration will be eliminated with the investments to be made in the field of renewable energy. In this respect, the use of economic models based on renewable energy in particular will support the reaching of long-term environmental goals.

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The contribution of the authors

Conceptualization, M.E. and Ç.D.T.; software, M.E.; validation, M.E. and Ç.D.T.; formal analysis, M.E.; investigation, M.E.; resources, M.E.; data curation, M.E.; visualization, M.E.; supervision, Ç.D.T.; methodology, M.E.; writing – original draft preparation, M.E.; writing – review and editing, Ç.D.T.

The authors have read and agreed to the published version of the manuscript.

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