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The Impact of Financial Institution Quality and Financial Stability on Trade-Adjusted Carbon Emissions: The Moderating Role of Green Innovation and Environmental Taxes

Magdalena Radulescu [1,2,3], Ayşe Meriç Yazıcı [4], Ayşegül Toy [5], Mesut Öztırak [6] and Mesut Dogan [7,*]

[1] National University of Science and Technology Politehnica Bucharest, Pitesti University Center, 110040 Pitesti, Romania; magdalena.radulescu@upit.ro
[2] Institute of Doctoral and Post-Doctoral Studies, University Lucian Blaga of Sibiu, 550024 Sibiu, Romania
[3] UNEC Research Methods Application Center, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku 1001, Azerbaijan
[4] Department of International Trade and Business, Istanbul Gelisim University, 34310 Istanbul, Turkey; ayazici@gelisim.edu.tr
[5] Department of Finance and Banking, Sivas Cumhuriyet University, 58140 Sivas, Turkey; atoy@cumhuriyet.edu.tr
[6] Department of Aviation Management, Istanbul Medipol University, 34815 Istanbul, Turkey; mesut.oztirak@medipol.edu.tr
[7] Department of Finance, Banking and Insurance, Bilecik Seyh Edebali University, 11230 Bilecik, Turkey
* Correspondence: mesut.dogan@bilecik.edu.tr

Abstract: This study analyzes the impact of financial institution quality (FIQ) and financial stability (FSI) on trade-adjusted carbon emissions (TAE) in G7 countries from 2000 to 2022. It also examines whether green innovation (GI) and environmental taxes (ET) moderate this relationship. In the study, long-term coefficient estimations were conducted using the Seemingly Unrelated Regressions (SUR), Panel-Corrected Standard Errors (PCSE), and Driscoll-Kraay standard error estimator methods. The results show that GI, ET, FIQ and FSI variables have a negative and significant effect on TAE. Green innovation and environmental taxes reduce carbon emissions, while strong financial institutions and stable financial systems enhance environmental performance by supporting sustainable investments. The Dumitrescu-Hurlin (D-H) causality test results indicate a unidirectional causal relationship between these variables to carbon emissions. These results highlight the significance of integrating environmental policies with financial systems and promoting GI for sustainable development.

Keywords: trade-adjusted carbon emissions; green innovation; financial institution quality; financial stability

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1. Introduction

Environmental deterioration poses a major challenge worldwide, drawing significant attention from governments due to its impact on global warming and its potential to disrupt the global carbon cycle [1,2]. Recently, interest in GI has increased significantly due to its capacity to contribute to the elimination of environmental problems [3,4]. GI can contribute to reducing environmental costs, promoting environmentally-friendly (E-F) technologies, and supporting efforts to mitigate environmental degradation [5]. Additionally, GI can aid in reducing emissions and waste, as well as fostering the use of cleaner technologies [6].

An environmental tax (ET) is one probable remedy to the issue of greenhouse gas (GHG) emissions [7–9]. An ET can fully or partially correct environmental issues by improving incentives for alternative behaviors [10]. In other words, CO_2 concentration may potentially decline as the ET rate increases [11]. While there are various methods to reduce carbon emissions (CO_2), ETs can contribute to this process by supporting the use of clean energy and reducing energy consumption [12]. Many studies have found that CO_2 can be significantly minimized by ETs [13–15]. Nevertheless, ref. [16] argued that an optimal tax level existed to minimize CO_2 and that ETs will be more effective in reducing CO_2 when lower-cost advanced technologies are used.

The financial sector substantially aids in ensuring economic stability while driving growth [17]. Although it contributes significantly to economic expansion and stability in each country, one must also consider its possible adverse environmental consequences [18,19]. Financial development (FD) can help to reduce financial risks and borrowing costs, improving information symmetry between lenders and borrowers, promoting availability of financial capital, and encouraging the adoption of advanced technologies and energy-efficient products [20]. Moreover, the expansion of the financial sector can stimulate industrial growth by boosting the availability of investment resources and broadening the production base. Financial institutions and market efficiency can stimulate industrial growth and help create new infrastructure facilities, which in turn can positively affect energy consumption [21].

Financial institutions (FI) have taken their place among the main actors by helping to accomplish the targets of sustainable development goals. For example, the banking sector can contribute significantly to a country's sustainability performance by employing innovative technologies such as online banking, green banking, and blockchain, and supporting a range of E-F projects [22,23]. The efficiency and sophistication of FI and markets encourage the expenditure of renewable energy (RE) and can assist to reducing CO_2 [24]. Conversely, while stronger FI can facilitate access to credit, which in turn may support industrial activities that contribute to CO_2, this relationship is indirect. The increase in CO_2 is primarily a result of industrial processes, not directly caused by financial access [25]. However, when financial markets encourage investment in environmentally friendly (E-F) sectors, they can help promote environmental quality (EQ) and contribute to addressing sustainable development (SD) challenges [26].

The structure and efficiency of the financial system hold a vital position in SD and environmental policies. FI quality can contribute to increasing environmental investments and reducing CO_2 by enhancing investor confidence and providing long-term financing for sustainable projects [27]. High-quality FI encourage firms to engage in green projects through transparent regulations and risk management mechanisms [28]. In particular, studies have found that strong FI significantly contribute to CO_2 reductions in developed countries [29]. Meanwhile, financial stability (FS) is a crucial factor in ensuring the sustainable growth of the economy. During periods of financial instability, firms tend to focus on short-term profit-oriented investments, whereas in countries with higher FS, there is an increased tendency toward long-term sustainable investments [30]. This difference is particularly impactful in financing RE projects and facilitating the transition to a low-carbon economy [31]. Therefore, maintaining FS can facilitate the support of environmentally friendly projects, thereby contributing to the reduction of CO_2.

This study aims to analyze the impact of financial FIQ and FS on TAE in G7 countries. Global economies are striving to integrate environmental policies with financial systems to achieve SD and carbon neutrality. In this context, how the strength of FI and market stability contribute to environmental sustainability is an important area of research. Strong FI can encourage environmentally friendly investments, finance low-carbon projects, and support sustainable growth. However, when determining the impact of financial systems on CO_2, the role of GI and ET in shaping this relationship should also be considered. In the study, long-term analyses were conducted using SUR, PCSE, and Driscoll-Kraay estimation methods using G7 country data between 2000 and 2022 to identify these relationships.

The G7 countries are the largest actors in the global economic system and are also responsible for a significant portion of CO_2 worldwide. These countries have a decisive role in environmental transformation with their strong financial systems, advanced institutional structures and increasing commitments to sustainability policies. The FS and institutional quality of the G7 countries are critical to the effective implementation of green financing policies, the encouragement of low-carbon investments and the achievement of sustainable economic growth. In addition, since these countries are in a leading position in global markets, the findings obtained here can also be a guide for other developed and developing economies. Therefore, conducting this study within the scope of the G7 countries is of significant value in terms of understanding the effects of financial systems on environmental sustainability and developing applicable strategies for policy makers.

The study aims to fill the gaps identified in the literature at four different points. (i) The research on the impact of FIQ and FS on TAE is quite limited. While much of the existing literature has primarily focused on the relationship between FD and CO_2, the role of FS and institutional quality in promoting sustainability has not been sufficiently explored. This study seeks to fill this important gap by providing empirical analyses that evaluate the environmental impacts of financial systems. (ii) While GI is a critical factor in reducing CO_2, its moderating role in the relationship between financial systems and environmental sustainability (ES) has been largely overlooked in most studies. This research offers a new perspective by examining how green technologies and innovative investments, together with FS and institutional quality, shape CO_2 from the standpoint of environmental policy and technological development. (iii) The study provides significant implications for promoting sustainable investments within banks and FI. Maintaining FS and fostering strong FI can support the expansion of green financing mechanisms and increase loans that contribute to the transition to a low-carbon economy. Moreover, it underscores the need for banks and investors to develop effective risk management strategies for sustainable projects. (iv) Finally, the study offers concrete recommendations for policymakers, particularly in G7 countries, by demonstrating the impact of ET and financial regulations CO_2. It suggests that promoting green finance instruments and strengthening sustainable funds could assist in diminishing CO_2.

This study comprises five sections. After the introduction, Section 2 reviews the literature on FIQ, FS, GI, and CO_2, offering a comparative analysis. Section 3 outlines the study's variables, and methods. Section 4 presents and discusses the estimation results in relation to the literature. The final section provides a general evaluation, policy recommendations, and strategic insights for enhancing financial systems' role in SD.

2. Literature Review

Climate change and increasing fossil fuel consumption have brought the relationship between ES and economic growth to the forefront, and in this context, the effects of factors such as GI, ET, FD and institutional quality on EQ have become the focus of academic studies. While [32] draws attention to the role of green finance in the transition to a low-carbon economy, financial market efficiency and how environmental disclosures affect risk perception in markets are also increasingly discussed [33–36]. According to these studies, environmental disclosures and green finance can contribute to market stability by reducing investor uncertainty.

2.1. Green Innovation and EQ

Lately, there has been a rising volume of studies addressing the impact of GI on ES [37] found a bidirectional relationship between air pollution and innovation, while ref. [38] found that fossil fuel-based patents were not effective in reducing CO_2, but green patents significantly reduced CO_2. Similarly, ref. [39] found a long-term link between energy intensity innovation and RE use, and ref. [40] showed that GI was effective in reducing CO_2 using Chinese data. However, ref. [41] found that there are different views in the literature, arguing that GI increases environmental efficiency but does not directly reduce CE.

Studies on the contribution of GI in minimizing environmental pollution also reveal different results. Refs. [6,42] stated that GI saves energy and reduces waste and CO_2, while ref. [43] emphasized that innovation is critical in reducing CO_2. This view has also been supported by [44–46]. Refs. [47,48] have shown that R&D investments in environmental technologies contribute to SD by increasing the competitiveness of companies.

Technological innovation and financial technologies have great potential in terms of increasing ES. Ref. [49] argue that fintech increases environmental performance and service efficiency, while ref. [50] stated that financial depth should be expanded for ES. Ref. [51] The link between technological innovation and ES was examined and the impact of environmentally friendly technologies on ecological performance was highlighted [52,53] found that fintech improves environmental performance through green financing and investment.

The impact of R&D investments, GI and RE R&D activities on reducing trade-related CO_2 in developed countries has been examined [54]. They found that higher investments in environmental R&D and GI significantly contribute to reducing TAE. Their study emphasized the importance of integrating RE technologies and innovative practices to mitigate the environmental impacts of trade in developed economies. Similarly, ref. [55] investigated the impact of technological innovation on TAE, highlighting that technological advancements, particularly in clean energy technologies, play a key role in reducing CO_2 associated with international trade. Both studies underline the pivotal role of innovation and R&D in addressing the environmental challenges posed by trade. As a result, the following hypothesis has been developed:

H1: *Green innovation has a positive impact on ES.*

2.2. Environmental Taxes and EQ

There is also no consensus in the literature on the relationship between ET and CO_2. While refs. [56–58] argue that strict ET policies reduce CO_2 and direct companies to more sustainable production methods, refs. [59–61] have similarly shown that ETs are effective in reducing GHG. On the other hand, some studies have indicated that ETs can negatively affect EQ [62]. Refs. [63,64] argued that ETs can encourage technological development to combat high CO_2.

The influence of ET on EQ and CO_2 has been widely examined in academic research. For example, ref. [65] has shown that ET reduce CO_2 in Türkiye. Similarly, ref. [66] a study has shown that ET are effective in reducing CO_2, while the use of RE improves EQ. Additionally, ref. [67] emphasized the significance of GI, energy efficiency, and ET in mitigating CO_2 within advanced economies, highlighting their role as essential instruments for ES. Furthermore, ref. [68] explored the effects of environmental innovation and ET on achieving carbon neutrality in E7 economies, demonstrating their substantial contribution to reducing CO_2.

Another important study by [69] found that ET and stricter environmental policies reduced CO_2 in seven developing economies. These findings show that ET are effective not only in developed countries but also in developing economies in limiting CO_2. Furthermore, ref. [70] suggested in their study on Turkey that ET have a nonlinear effect on ecological footprint and CO_2 and that ET could improve environmental indicators in the long term. Finally, ref. [71] found that environmental tax reforms in resource-based cities in China promoted carbon reduction, emphasizing that ET are an effective policy tool for limiting CO_2. These studies emphasize the vital importance of ET in promoting ES and their considerable impact on various economies.

The relationship between ET and TAE has become an important research topic in recent years. Ref. [72] found that ET, combined with energy efficiency, contribute to SD and contribute substantially to the reduction of TAE. Similarly, ref. [73] highlighted the restrictive impact of ET on TAE, emphasizing that these taxes are an effective policy tool for controlling CO_2. Additionally, ref. [74] demonstrated that RE and fiscal policies, in conjunction with environmental policy stringency, reduce TAE, with ET playing a crucial role in this process. Ref. [75] examined the effect of environmental R&D and international trade on TAE, finding that environmental R&D investments help reduce CO_2 associated with trade. This finding highlights the potential of trade to reduce environmental impacts and the important role of environmental R&D. In their study, ref. [76] showed that TAE capture environmental mishandling more effectively in the world's most complex economies, and environmental tax policies are effective in reducing CO_2. These studies demonstrate that ET, when combined with RE policies and environmental R&D, can help reduce TAE and serve as a vital tool for SD. As a result, the following hypothesis has been developed:

H2: *Environmental taxes have a positive impact on ES.*

2.3. Financial Institution Quality and EQ

The effects of institutional structures and financial developments on EQ are increasingly being studied [77–83]. Refs. [84–86] showed that good governance and strong institutions reduce CO_2, while [87,88] argued that countries with high institutional quality reduce environmental costs and promote SD. However, refs. [89,90] argued that institutional structures can lead to environmental degradation. The role of financial systems on environmental performance has also become increasingly important. Ref. [24] showed that developed financial markets reduce CO_2 by increasing RE investments, and similar results were supported by [91,92]. However, some studies suggest that FD can increase CO_2 [92–94].

The impact of FIQ on ES has been increasingly investigated in the literature. Ref. [95], in his study of Belt and Road Initiative (B&R) countries, examined the effects of environmental R&D investments and international trade on trade-driven CO_2. The study found that environmental R&D plays a crucial role in reducing the environmental impacts of trade, and the adoption of eco-friendly technologies in emerging economies is effective in limiting trade-related CO_2. It has also been stated that international trade has the capacity to promote ES, but this should be supported by environmentally friendly innovation and R&D investments [96]. Global studies have shown that improving institutional quality reduces CO_2 and increases ES [97]. It has been found that institutional quality plays an important role in reducing CO_2 in Sub-Saharan African countries, but low levels of FD limit this effect.

Similarly, ref. [98] assessed the impact of FI on ES in Africa, finding that countries with strong financial structures have increased eco-friendly investments and reduced CO_2. Ref. [99] examined the impact of institutional quality on natural resource use, RE, and FD on ecological footprints in China, showing that high-quality FI can implement ES policies more effectively. Ref. [100] investigated how institutional quality mediates the relationship between FD and EQ, revealing that in countries with low institutional quality, FD may have adverse effects on the environment, but strong FI can counterbalance these negative impacts. In summary, the existing literature shows that high institutional quality promotes sustainable finance and reduces $CO_2$by enhancing ES. However, the effectiveness of institutional structures and the level of economic development of countries are significant factors determining the strength of this relationship. In this context, our study aims to contribute to the literature by analyzing the impact of FIQ and FSI on CO_2 in G7 countries and the role of GI. As a result, the following hypothesis has been developed:

H3: *Financial institution quality has a positive impact on ES.*

2.4. Financial Stability and EQ

The impact of FS on EQ, particularly CO_2, ecological footprint, and other environmental indicators, has been explored in several studies. Ref. [101] examined the relationship between FS and CO_2 in E-7 countries, finding that FS, along with economic growth and trade, plays a significant role in limiting CO_2 and enhancing ES. Similarly, ref. [102] highlighted how FS plays an important role in achieving environmental goals by contributing to sustainable environmental practices by supporting RE investments and technological innovation [103] a study examining the asymmetric effects of FS on ecological degradation in Norway showed that FS promotes ES, but financial crises can have negative effects on the environment. This finding highlights the importance of FS in implementing effective environmental policies. Similarly, ref. [104] noted the role of FS in reducing environmental degradation and noted that green economic policies can help mitigate the negative effects of climate change while improving EQ.

Moreover, ref. [105] investigated the role of FS in addressing climate risks and mitigating climate change. Their findings suggest that FS fosters green economic recovery, contributing to the reduction of CO_2. Additionally, ref. [106] analyzed the Asia-Pacific Economic Cooperation (APEC) countries and demonstrated that FS, in combination with RE investments, serves an important function in lessening CO_2 and promoting ES.

Furthermore, refs. [107] emphasize the importance of FS in improving EQ. Studies have shown that FS, combined with investments in RE and clean technologies, plays an important role in reducing CO_2 and increasing ES. These studies argue that FS is an effective factor in achieving environmental goals and significantly encourages the adoption of environmentally friendly practices. In conclusion, the studies reviewed collectively highlight that FS is a crucial factor in improving EQ. FS not only supports investments in RE and green technologies but also ensures the successful implementation of environmental policies aimed at reducing CO_2 and mitigating environmental degradation. As a result, the following hypothesis has been developed:

H4: *Financial stability has a positive impact on ES.*

3. Methodology

3.1. Dataset

This study aims to analyze the impact of FIQ and FS on TAE in G-7 countries over the period 2000–2022, while examining the moderating role of GI. As global economies strive for SD and carbon neutrality, understanding how financial systems influence environmental outcomes becomes crucial. Given that G-7 countries are among the world's largest economies and major contributors to global CO_2, their financial structure and stability play a significant role in shaping environmental policies. Strong FI can enhance sustainable investment flows, regulate environmentally harmful activities, and promote green finance, while FS ensures long-term support for low-carbon economic transitions.

This study investigates whether high-quality FI and stable financial markets contribute to reducing CO_2 when trade adjustments are considered. Furthermore, the research explores how GI moderates these relationships, assessing whether technological advancements in cleaner production, energy efficiency, and eco-friendly investments amplify the positive impact of FD on carbon mitigation. By employing data from 2000 to 2022, the study provides empirical insights into how financial and environmental policies can be integrated to enhance sustainability.

In this study, TAE were used as the dependent variable in line with literature. TAE is an indicator used to more accurately assess the true environmental impact of a country by taking into account emission transfers resulting from trade [75,76,108–112]. Ref. [75], in their study examining the relationship between environmental R&D and TAE, stated that TAE more accurately reflects a country's environmental impact associated with international trade. Instead of considering only domestic production, TAE accounts for the environmental burdens a country transfers to others through trade, providing a more realistic assessment of environmental impacts. Similarly, ref. [112] argued that TAE offers a more comprehensive evaluation compared to production-based emissions. While production-based emissions rely solely on domestic production activities, TAE considers the environmental effects of imports and exports, allowing for a more precise measurement of a country's environmental footprint. Ref. [109] emphasized that TAE provides a broader assessment by taking into account the environmental impacts of international trade. Ref. [74] highlighted that TAE more accurately reflects the effects of environmental policies and energy strategies, demonstrating that environmental policies are shaped not only at the local level but also by the influence of global trade. These studies indicate that TAE not only encompasses production- and consumption-based emissions but also more accurately accounts for a country's global environmental impact through trade. Therefore, TAE is considered a more appropriate and accurate tool for comprehensively examining the environmental impacts of trade compared to other CO_2 measurement methods.

The first independent variable used in the study is the quality of FI. This variable was measured with "The average non-performing loan of banks in a country" in line with the literature [113]. FSI was created as the second independent variable. FS expresses the resilience of the financial system to shocks and its capacity to prevent serious contractions in economic activity [114]. The FSI, created using various indicators, became more widespread by being adopted by the IMF and ECB in 2008 and 2010 [103,112,113].

In this study, an index was created with eight different variables using financial strength, FD and financial fragility indicators. Financial strength indicators include liquidity (liquid assets/deposit ratio), profitability (return on assets—ROA) and capital adequacy (capital/asset ratio, risk-weighted capital adequacy—CRAR). FD indicators are M3 monetary expansion, domestic credit to GDP and stock market capitalization. The current account balance was used as the financial fragility indicator. After all variables were standardized, the FSI was created using the Principal Component Analysis (PCA) method [101,113]. This index evaluates the FS levels of G-7 countries and provides an important indicator for policy makers and economic experts.

Firstly, we constructed a comprehensive Aggregate FSI for G7 countries by utilizing annual data spanning from 2000 to 2022. This index has been constructed to comprehensively assess the financial stability levels of these economies. Similar to the methodology employed by Nasreen [113] and Safi et al. [101], the Aggregate FSI is derived from the aggregation of three key sub-indices: financial sector development, soundness and vulnerability. These sub-indices incorporate various macroeconomic and financial indicators to evaluate the resilience and fragility of the financial system. For empirical analysis, the variance equal weighting method was used to compute the AFSI. Additionally, to test the robustness of the results, the AFSI was also calculated using the Principal Component Analysis (PCA) method. Both approaches yielded similar findings, reinforcing the reliability of the methodology applied in assessing FS.

FSI is calculated using the PCA technique. PCA is a method that transforms multiple correlated variables into fewer independent components and tries to minimize data loss during this transformation. This approach analyzes the joint movement of the variables that make up the index, identifies the first component that explains the maximum variance, and calculates the index based on this component; the index is calculated using the following formula:

$$\text{FSI} = \text{X}_{a(i)} \quad (1)$$

Here, a represents the weight vector of the individual indicators, while X_i denotes the values of the variables used in constructing the index. The weight coefficients determine the contribution of each variable to the common movement, with variables having the greatest impact carrying more weight in the formation of the index. In this study, the correlation coefficient between the indices calculated with the variance-equal weighted method and PCA was analyzed in order to evaluate the reliability of the results. The correlation coefficients range from 0.84 to 0.95, which confirms the robustness of the results.

As a result, the summary of the variables used in the study is shown in Table 1. In addition, following the empirical studies conducted by [54,103,104], the logarithmic regression model is used to estimate the relationships in question as follows:

$$TAE_{i,t} = \beta_0 + \beta_1 GI_{i,t} + \beta_2 ET_{i,t} + \beta_3 FIQ_{i,t} + \beta_4 FSI_{i,t} + \varepsilon_{i,t} \quad (2)$$

Table 1. Summary of Variables.

Variables	**Symbol**	**Measure**	**Source**	**Studies Using the Variables**
Trade-adjusted carbon emissions	TAE	Consumption emissions in Mt CO_2	Global Carbon Atlas (2022)	[54,72].
Green Innovation	GI	Green Innovation, Development of environment-related technologies, % all technologies	OECD	[67,114].
Environment tax	ET	Environment related tax, % of GDP	OECD	[74,76].
Financial Institution Quality	FIQ	The average non-performing loan of banks in a country	The Global Economy	[110].
Financial Stability Index	FSI	An index developed using PCA analysis	Authors own calculation	[101,113].

Figure 1 presents the conceptual causality model proposed in the study. The model includes TAE as the dependent variable, while the independent variables are GI, ET, FIQ, and FSI. The hypotheses (H1, H2, H3, H4) test the impact of these variables on TAE.

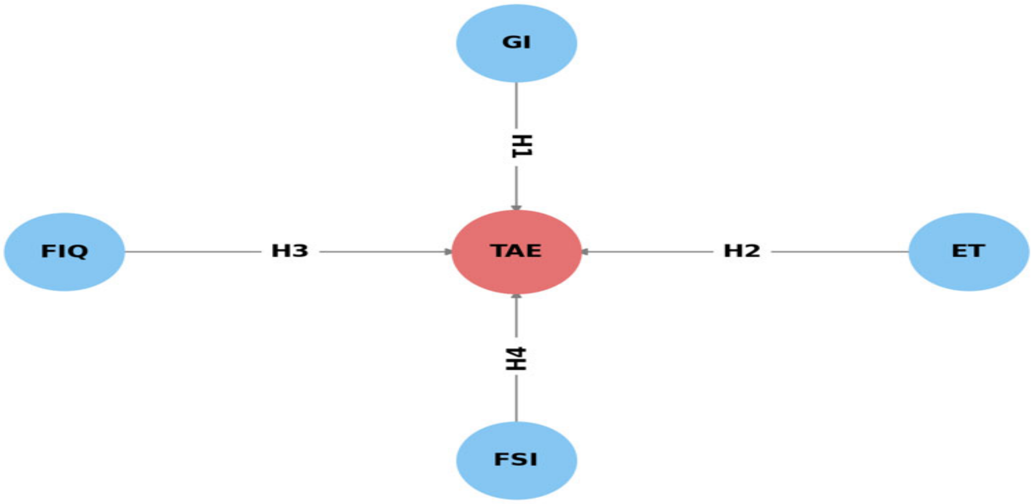

Figure 1. Conceptual Causality Model Based on Hypotheses.

3.2. Method

In the study, cross-sectional dependency (CSD) was primarily examined. In this context, LM test [115] and Scaled LM (CD_{LM}) test [116] were used. However, these tests may give deviant results under certain conditions. Ref. [117] developed the deviant corrected LM test ($\mathrm{LM_{adj}}$) by adding variance and mean corrections to the test statistics in order to eliminate this deviation. The relevant equations are calculated as shown in Equations (3)–(6).

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}{}^{2} \quad (3)$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\hat{\rho}_{ij}{}^{2}-1\right)} \quad (4)$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=1+1}^{N}\hat{\rho}_{ij}\right) \quad (5)$$

$$LM_{adj} = \left(\frac{2}{N(N-1)}\right)^{1/2}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2}\frac{(T-K-1)\hat{\rho}_{ij}-\hat{\mu}_{Tij}}{\upsilon_{Tij}} \sim N(0,1) \quad (6)$$

After examining the CSD, slope homogeneity (SH) is evaluated with [118] Δ tests. However, in cases of heteroskedasticity and serial correlation, [119] Δ tests are preferred. The relevant calculations are shown in Equations (7)–(10).

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC}-k}{\sqrt{2k}}\right) \quad (7)$$

$$S_{HAC} = \sum_{i=1}^{N}T(\hat{\beta}_i-\hat{\beta})'\left(\hat{O}_{iT}V_{iT}^{-1}\hat{O}_{iT}\right)(\hat{\beta}_i-\hat{\beta}) \quad (8)$$

$$\hat{\beta} = \left(\sum_{i=1}^{N}T\hat{O}_{iT}V_{iT}^{-1}\hat{O}_{iT}\right)^{-1}\sum_{i=1}^{N}\hat{O}_{iT}\hat{V}_{iT}^{-1}X_i'M_Ty_i \quad (9)$$

$$\hat{V}_{iT} = \hat{\Gamma}_i(0)+\sum_{j=1}^{T-1}K\left(\frac{j}{M_{iT}}\right)\left[\hat{\Gamma}_i(j)+\hat{\Gamma}_i(j)'\right] \quad (10)$$

In this study, we employed the Cross-Sectionally Augmented ADF (CADF) and Cross-Sectionally Augmented IPS (CIPS) panel unit root tests, as introduced by [120], following the assessment of CSD. CADF unit root test and its calculation methods and CIPS statistic are calculated in Equations (11)–(15):

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{11}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{12}$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_t + \varepsilon_{it} \tag{13}$$

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum\nolimits_{j=0}^{p} d_{i,j} \Delta \overline{y}_{t-j} + \sum\nolimits_{j=0}^{p} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{14}$$

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{15}$$

An appropriate panel cointegration test should be selected to detect the long-term relationship between the variables. In this study, the tests developed by [121–123] were used. In addition, the long-run relationship between the variables was also analysed with the [124] cointegration test. Ref. [124] test consists of four basic test statistics based on structural dynamics: G_t ve G_a group statistics and P_t ve P_a panel statistics. When calculating the group statistics, error correction coefficients are evaluated separately for each horizontal cross-section. The relevant cointegration equation is shown in Equation (16).

$$\Delta Y_{it} = \delta_i d_t + \alpha_i Y_{i,t-1} + \gamma_i X_{i,t-1} + \sum_{j=1}^{pi} \alpha_{ij} \Delta Y_{i,t-1} + \sum_{j=-qi}^{pi} \gamma_{ij} \Delta X_{i,t-1} + \varepsilon_{it} \tag{16}$$

In this study, long-run elasticity coefficients are estimated by Seemingly Unrelated Regressions (SUR) method and [125] method. SUR and Driscoll and Kraay model are chosen as the most appropriate estimators since they solve the endogeneity problem, take heterogeneity and inter-unit correlation into account, and the cross-sectional dimension is smaller than the time dimension [126]. The formulas for the SUR model are shown in Equations (17)–(20).

$$\begin{array}{c} y_1 = x_1 \beta_1 + u_1 \\ y_2 = x_2 \beta_2 + u_2 \\ \vdots \; \vdots \; \vdots \\ y_M = x_M \beta_M + u_M \end{array} \tag{17}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} X_1 \; 0 & \ldots & 0 \\ 0 \; X_2 & \ldots & 0 \\ \vdots \; \vdots & \ddots & \vdots \\ 0 \; 0 & \ldots & X_M \end{bmatrix} + \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_M \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_M \end{bmatrix} \tag{18}$$

$$\sum = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \ldots & \sigma_{1M} \\ \sigma_{21} & \sigma_{22} & \ldots & \sigma_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{M1} & \sigma_{M2} & \ldots & \sigma_{MM} \end{bmatrix} \tag{19}$$

$$\hat{\beta} = \left[x' \Omega^{-1} x\right]^{-1} x' \Omega^{-1} y = \left[x' \left(\Sigma^{-1} \otimes I\right) x\right]^{-1} x' \left(\Sigma^{-1} \otimes I\right) y \tag{20}$$

The study also utilises the PCSE method developed by [127]. This estimator allows for consistent estimation of parameters under heteroskedastic, autocorrelated and inter-unit correlated error terms using Driscoll-Kraay pooled ECM. The relevant calculations are shown in Equations (21)–(23):

$$y_{it} = x_{it} \beta + \varepsilon_{it} \tag{21}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \quad (22)$$

$$\sum[\varepsilon\varepsilon'] = \Omega = \begin{bmatrix} \sigma_{11} I_{11} & \sigma_{12} I_{12} & \cdots & \sigma_{1m} I_{1m} \\ \sigma_{21} I_{21} & \sigma_{22} I_{22} & \cdots & \sigma_{2m} I_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1} I_{m1} & \sigma_{m2} I_{m2} & \cdots & \sigma_{mm} I_{mm} \end{bmatrix} \quad (23)$$

In the final part of the study, the panel causality test suggested by [128] was used and applied according to the formula specified in Equation (24).

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \quad (24)$$

In Equation (23), $X_{i,t}$ and $y_{i,t}$ represent the stationary variables for each unit at time period t.

4. Empirical Findings

In this section, TAE, GI, ET, FIQ and FSI variables are analyzed. Firstly, the horizontal CSD of these variables is tested, and then their stationarity status is analyzed by applying unit root tests. Finally, the long and short run relationships between the variables are evaluated and empirical findings are presented.

The results of all tests reveal significant CSD among the variables (Table 2). Additionally, Bias-Corrected Scaled LM the and Pesaran Scaled LM tests are significant for all variables, indicating the influence of common shocks across the units. The Pesaran CD test results further confirm that the variables in the panel data set are interrelated. Similarly, the CSD test results in Table 3 suggest CSD in the long-run models at the 1% significance level. This implies that common shocks or interdependencies between units must be considered in the model.

Table 2. CDS test results for Variables.

Variables	TAE	GI	ET	FIQ	FSI
Breush-Pagan LM	195.58 *	138.12 *	896.74 *	241.995 *	94.563 *
Pesaran scaled LM	19.86 *	5.508 *	86.904 *	17.829 *	3.772 *
Bias-corected scaled LM	25.29 *	5.29 *	86.614 *	17.539 *	3.482 *
Pesaran CD	4.35 *	5.95 *	31.034 *	4.443 *	5.779 *

Note: * denotes significance at 1% level.

Table 3. CSD test results for long-run models.

Tests	Model
LM	20.55 *
LM adj *	23.36 *
LM CD *	5.19 *

Note: * denotes significance at 1% level.

The SH test results presented in Table 4 indicate the presence of slope heterogeneity in the panel data model. In the analysis using the HAC-based delta tests developed by [122], the null hypothesis H_0 is rejected, i.e., there is no homogeneous structure among the variables. This result reveals that the panel data set has a heterogeneous structure and heterogeneous panel models should be preferred in the analysis.

Table 4. Testing for SH.

	Model
$\tilde{\Delta}$	3.85 *
$\tilde{\Delta}_{adj}$	3.27 *

Note: * denotes significance at 1% level.

In this study, the stationarity of the series for the G7 countries is analyzed with CADF and CIPS tests developed by [120]. The results presented in Table 5 indicate that the series are non-stationary in their level form but achieve stationarity after taking their first differences. CADF and CIPS test statistics are statistically significant at 1% and 5% significance levels, especially at first differences. This indicates that the analyzed variables contain unit root and have I(1) process.

Table 5. Findings of CIPS and CADF analysis.

Variables	**CADF**		**CIPS**	
	Level	First Difference	Level	First Difference
TAE	−0.98	−2.85 ***	−1.39	−4.84 ***
GI	−0.89	−2.28 **	−1.08	−4.71 ***
ET	−0.87	−2.97 ***	−2.25 **	−5.08 ***
FIQ	−0.95	−2.18 **	−1.24	−5.76 ***
FSI	−1.32	−2.75 ***	−2.09 **	−4.63 ***

Note: *** and ** denote significance at 1% and 5% level, respectively.

Various panel cointegration tests, accounting for cross-sectional dependence, were applied to analyze the sustained linkage among variables. The results confirm cointegration, with multiple test statistics significant at the 1% level, indicating a stable equilibrium relationship. Additionally, the ECM cointegration test proposed by [124] was used. Table 6 results confirm cointegration, with all Pedroni and Kao test statistics significant at the 1% level. The ECM test results presented in Table 7 show that all test statistics are significant at the 1% level with the data obtained from [124] and the null hypothesis (H0) is rejected. This result supports the existence of a cointegration relationship that exhibits long-term co-movement between the variables. In general, the findings reveal the existence of a stable long-term relationship between the independent and dependent variables and that the model effectively captures the long-term dynamics. In other words, despite the effects of external shocks, the variables follow a common equilibrium path over time and exhibit a consistent movement in the long run.

Table 6. Cointegration test results.

Pedroni	
Modified P-P t	−6.84 *
P-P t	−7.58 *
ADF t	−9.52 *
Kao	
Modified D-F t	−7.12 *
D-F t	−8.89 *
ADF t	−6.37 *
Unadjusted M-D-F t	−12.35 *
Un- ADF t	−9.75 *

Table 6. *Cont.*

Westerlund	
V-Ratio	−2.72 *

Note: * denotes significance at 1% level.

Table 7. Westerlund (2007) test results [124].

Statistic	Value	Z-Value
G_t	−4.85	−6.18 *
G_a	−12.12	−5.36 *
P_t	−10.89	−6.31 *
P_a	−14.24	−5.52 *

Note: * denotes significance at 1% level.

In the study, PCSE, Driscoll-Kraay and SUR methods were used to estimate the elasticity coefficients in Table 8. The study analyses the long-run relationships between the TAE dependent variable and the GI, ET, FIQ and FSI independent variables. The analyses are based on data from G7 countries for the period 2000–2022. The results show that all independent variables have statistically significant and negative effects on TAE.

Table 8. Long Run Estimator Results.

Variables	SUR	PCSE	D-K
	Coefficients	Coefficients	Coefficients
GI	−0.27 *	−0.32 *	−0.29 *
ET	−0.07 *	−0.11 *	−0.09 *
FIQ	−0.13 *	−0.09 *	−0.14 *
FSI	−0.12 *	−0.14 *	−0.13 *
Constant	−1.27 *	−2.18 *	−1.75 *
Wald $\chi 2$	189.55	162.81	159.37
P	0.000	0.000	0.000
Obs.	161		

Note: * denotes significance at 1% level.

- This suggests that GI contributes to lowering TAE. Consistent with these results, previous studies in the literature have also highlighted the role of GI in enhancing ES and mitigating CO_2. For instance, ref. [129] emphasized that green patents significantly contribute to reducing CO_2, while [114] found that GI plays a crucial role in decreasing CO_2 in the Chinese economy. The results of this study reinforce the argument that GI is a vital instrument in facilitating the transition to a low-carbon economy, underscoring the necessity of promoting environmentally friendly technological advancements.
- It is found that ET have a negative and significant effect on TAE. This finding supports that ET are an effective policy instrument in reducing CO_2. Ref. [59] find that a 1% increase in per capita environmental tax revenues in OECD countries reduces CO_2 by 0.033%. Moreover, ref. [130] show that one-euro increase in energy taxes leads to a 0.73% reduction in CO_2 from fossil fuel use.
- It shows that FIQ has a negative and significant effect on TAE. This suggests that improving the quality of FI can reduce CO_2. Ref. [84] stated that good governance and strong institutions reduce CO_2. Similarly, ref. [85] argue that countries with high institutional quality reduce environmental costs and promote SD.

- It reveals that FSI has a negative and significant effect on TAE. This suggests that increased FS can reduce CO_2. Ref. [24] show that improved financial markets reduce CO_2 by increasing RE investments. Similarly, ref. [21] stated that FD improves environmental performance.

In conclusion, the findings of the study show that GI, ET, FIQ, and FS are important factors contributing to the reduction in TAE. These findings align with existing studies in the literature and highlight the need for policymakers to consider these factors as part of their efforts to reduce CO_2.

The D-H panel causality test results in Table 9 show that TAE are affected by various economic and financial variables, but not directly by these variables. There is a unidirectional causality from GI, ET, FIQ and FSI to CO_2. These findings suggest that environmental policies, the quality of FI, and FS may play a significant role in contributing to the reduction of CO_2. In particular, GI is found to be determinant in reducing CO_2. This result supports that the diffusion of environmentally friendly technologies and sustainable production methods can reduce the carbon footprint. Similarly, ET also emerge as an important policy instrument affecting CO_2. This suggests that regulations such as carbon tax may direct firms towards more sustainable production methods. In terms of financial variables, FIQ and FS have a significant and unidirectional effect on CO_2. This finding suggests that strong FI and a stable economic structure can increase ES by supporting green investments.

Table 9. D-H panel causality test results.

	W-bar	Z-bar	p
TAE $\nrightarrow$ GI	1.21	0.81	0.605
GI $\nrightarrow$ TAE	2.77	4.05	0.000
TAE $\nrightarrow$ ET	0.98	0.74	0.752
ET $\nrightarrow$ TAE	2.21	2.65	0.029
TAE $\nrightarrow$ FIQ	0.65	0.52	0.865
FIQ $\nrightarrow$ TAE	2.84	4.77	0.000
TAE $\nrightarrow$ FSI	1.08	1.22	0.358
FSI $\nrightarrow$ TAE	2.96	5.69	0.000

Note: The maximum lag length is taken as 1.

5. Conclusions and Discussion

This study examines the effects of FIQ and FS on TAE in G7 countries between 2000 and 2022, and analyzes the moderating role of GI in this relationship. In the study, long-term coefficient estimates are made with SUR, PCSE and Driscoll-Kraay methods, while the causal relationships between the variables are evaluated with D-H panel causality test. As a result of the analyses, all the developed hypotheses have been accepted. The findings reveal that GI, ET, FIQ and FS contribute greatly to reducing CO_2. While GI accelerates sustainable transformation in the sector by encouraging the use of clean energy, ET stand out as an effective policy tool that directs firms to environmentally friendly production methods. Carbon taxes and incentives do not directly reduce CO_2; rather, they play a key factor in mitigating CO_2 by encouraging investments in RE. Strong FI accelerate the transition to a low-carbon economy by supporting sustainable financing mechanisms that take environmental risks into account. Maintaining FS increases the effectiveness of environmental policies by creating a secure environment for RE investments. In conclusion, the integration of environmental policies and financial regulations plays a critical role in reducing CO_2 and promoting SD.

Strong FI and stable financial systems play a critical role for the success of SD and policies to reduce CO_2. Improving the quality of FI can incentivise green investments, provide sustainable projects with access to lower-cost financing and expand lending for environmentally friendly technologies. Supporting FI with regulatory frameworks will contribute to the development of credit mechanisms that take into account environmental and social risks. Moreover, ensuring FS will allow for sustainable financing of long-term low-carbon investments, mitigating the negative impacts of economic uncertainties on green transformation. Policymakers should strengthen sustainable financing policies and develop strategies such as mainstreaming green bonds, implementing stress tests that incorporate environmental risks, and enhancing the banking sector's compliance with sustainable finance principles. In addition, mechanisms that encourage GI can accelerate the transition to a low-carbon economy as well as ensure FS. In this context, advanced financial infrastructures and sustainability-oriented financial policies should be considered as effective tools to reduce CO_2 and achieve environmental goals. The results also emphasize the importance of FS in global efforts to reduce CO_2. In large economies such as the G7 countries, reducing uncertainties in financial markets and providing support for long-term environmental investments can promote SD. However, the interactions between GI and FS need to be investigated more comprehensively.

This study highlights the critical role of FIQ and FS in shaping environmental outcomes, specifically TAE. The findings contribute to the growing body of literature on the intersection of finance and sustainability, demonstrating that financial systems, particularly strong FI and stable markets, play a significant role in enhancing environmental performance. The study draws attention to the critical role of GI in the transition to a low-carbon economy and argues that technological developments and innovative solutions are indispensable in reducing CO_2. The unidirectional causal link between these financial elements and CO_2 suggests that strengthening financial infrastructure and disseminating green technologies can reduce CO_2 in line with the theoretical framework combining environmental and financial performance. From a policy and practice perspective, the results suggest that strengthening FI and ensuring FS are key to promoting SD and reducing CO_2. Policymakers should consider implementing regulations that support green investments, such as incentives for RE projects, and strengthening the resilience of financial systems against environmental risks. Supporting GI should be considered as an important way to accelerate the spread of sustainable technologies and practices in industries. In addition, ET are an effective mechanism to direct businesses to more environmentally friendly production methods and can contribute to reducing CO_2. In conclusion, the integration of environmental policies with financial regulations, alongside incentives for GI, will be crucial in achieving long-term sustainability and addressing climate change.

Future research could explore the impact of financial systems on ES in greater detail, particularly in across developing economies, where financial infrastructure may differ significantly from developed nations. In line with the findings of this study, future investigations could focus on understanding how specific financial policies and regulations—such as green bonds, sustainable financing mechanisms, and environmental risk assessments—can effectively promote green investments. In addition, analyzing the impact of FI in the transition to a low-carbon economy and how FS can contribute to long-term ES goals under various economic conditions can be considered as an important research area.

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