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Re-Imagining Trade Policy and Energy Efficiency: Groundbreaking Pathways to Strengthen Environmental Sustainability in South Korea

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Abstract: This study explores the long-term interplay between trade policy, energy efficiency, and carbon dioxide (CO_2) emissions in South Korea, using data spanning from 1985 to 2023. By applying the Fourier autoregressive distributed lag (FARDL) model, the analysis reveals that while trade liberalization initially leads to a 0.23% increase in CO_2 emissions for each 1% rise in trade openness—driven by the energy demands of industrial expansion—integrating energy efficiency standards within trade agreements helps mitigate these effects over time; this results in a 0.26% reduction in emissions for every 1% improvement in energy efficiency. The study also highlights the dual role of foreign direct investment (FDI), which contributes to a short-term 0.08% rise in emissions but significantly reduces carbon intensity in the long term by facilitating the adoption of cleaner technologies. These findings underscore the importance of innovation and FDI in decoupling economic growth from environmental degradation. The study advocates for the incorporation of energy efficiency measures into trade agreements and the prioritization of green technologies, recommending strategies that could enable South Korea to reduce its CO_2 emissions by up to 40% by 2030. This research positions South Korea as a key actor in achieving global climate goals while maintaining economic competitiveness, offering valuable insights into the balance between sustainable development and industrial growth.

Keywords: trade policy; energy efficiency; carbon dioxide emissions; foreign direct investment; environmental sustainability

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1. Introduction

Addressing climate change has become increasingly urgent, particularly in highly industrialized nations such as South Korea, where balancing rapid economic growth with environmental sustainability poses substantial challenges. As one of the world's major exporters and industrial leaders, South Korea relies heavily on energy-intensive sectors such as petrochemicals, steel, and electronics, contributing to high per capita CO_2 emissions. This reliance on carbon-intensive industries underscores the need for policy interventions that can effectively decouple economic growth from environmental degradation, a challenge that becomes more critical as global climate commitments intensify. Trade policy and energy efficiency are pivotal mechanisms in this context. While South Korea's trade liberalization has facilitated industrial expansion and bolstered economic growth, it has simultaneously intensified CO_2 emissions due to the increased energy demands in sectors that are highly carbon-intensive. As documented in the research by Sebri and Ben-Salha [1] and Zafar et al. [2], trade openness, although beneficial for economic growth, often comes at the cost of heightened emissions. However, incorporating energy efficiency standards into trade agreements presents a viable strategy to mitigate these negative externalities. By adopting stringent environmental regulations and promoting energy-efficient technologies, South Korea can lower the carbon intensity of its exports, aligning trade policies with both domestic and global sustainability goals. Furthermore, the role of green technology innovation is crucial in addressing South Korea's environmental challenges. Recent studies emphasize the potential of renewable energy systems, carbon capture technologies, and advanced energy management innovations to significantly reduce CO_2 emissions (Gielen et al. [3]; Mikulčić et al. [4]). Technological advancements, supported by robust policy frameworks, are vital in accelerating South Korea's transition towards a low-carbon economy. In addition, foreign direct investment (FDI) serves as a critical avenue for emissions reduction, as it facilitates the transfer of cleaner technologies and sustainable practices, contributing to the decoupling of industrial growth from environmental harm. Nasir et al. [5] and Essandoh et al. [6] have highlighted the importance of FDI in promoting the adoption of energy-efficient practices across sectors.

South Korea's commitment to reducing CO_2 emissions by 40% by 2030, compared to 2018 levels, underscores the pressing need for a swift transition to a low-carbon economy. While the Korean Emissions Trading System provides a crucial policy foundation for incentivizing emissions reductions, a more comprehensive integration of environmental principles into trade and industrial strategies is vital to achieve the nation's ambitious climate goals. This study offers critical insights by quantifying the long-term impacts of trade policy, energy efficiency, and foreign direct investment on CO_2 emissions, providing evidence to inform sustainable development pathways for South Korea. Utilizing the advanced Fourier autoregressive distributed lag (FARDL) methodology, which accounts for both short- and long-term effects and adjusts for structural breaks and non-linearities, the research highlights the immediate rise in CO_2 emissions driven by trade liberalization, particularly in energy-intensive industries. Over time, however, the inclusion of energy efficiency standards within trade agreements mitigates these impacts, leading to a net decrease in emissions. The study further emphasizes the significant role of FDI and advancements in green technology in reducing carbon intensity, showcasing the importance of aligning trade policies with environmental sustainability goals. The findings offer robust empirical support for the promotion of energy-efficient technologies and environmentally conscious trade policies as pivotal elements in South Korea's journey toward a low-carbon future. These results contribute to the broader discourse on the interactions between trade, energy policy, and environmental sustainability, providing valuable guidance for policymakers seeking to balance economic growth with climate change mitigation efforts.

This study offers four significant contributions to the literature, particularly in the realm of environmental sustainability within South Korea. First, while existing research has explored the relationship between trade liberalization and CO_2 emissions, this study innovates by quantitatively analyzing the short- and long-term effects of trade policy, energy efficiency, and foreign direct investment using the Fourier autoregressive distributed lag model. This methodological advancement addresses limitations of traditional models, offering a more detailed understanding of the dynamic interactions between these variables, and accounting for structural breaks and non-linear patterns often overlooked in previous studies. Second, while much of the existing scholarship focuses on economic growth and industrialization as primary drivers of emissions, this study introduces energy efficiency as a central factor. The findings reveal that energy efficiency plays a dual role: in the short term, it mitigates the negative externalities associated with trade expansion, while over the long term, it decouples economic growth from carbon emissions. This contribution stands out as earlier studies, such as Rahman et al. [7] and Chikezie Ekwueme et al. [8], have not adequately considered the cumulative impact of energy efficiency on emissions reduction over time. Third, this study broadens the conversation on FDI by highlighting its divergent short- and long-term impacts on emissions in South Korea. Initially, FDI is associated with increased emissions due to higher industrial activity but, over time, it supports the adoption of cleaner, more energy-efficient technologies. This analysis deepens the insights provided by Lee and Zhao [9] and Khan et al. [10], who primarily focus on the economic advantages of FDI without fully addressing its environmental consequences. Lastly, the research offers a comprehensive policy framework that aligns trade policy with environmental sustainability objectives, recommending the integration of energy efficiency and green technology innovation into South Korea's trade agreements. This forward-thinking policy perspective fills a gap in the literature, as prior research has tended to focus on technological adoption within national borders without sufficiently exploring the global dimensions of trade and sustainability. By underscoring the role of international collaboration, this study sets a new standard for future research in environmental economics and policy development.

The structure of this paper is outlined as follows: Section 2 provides a thorough review of the relevant literature that underpins the research. Section 3 introduces the methodology, including the formulation of variables and model specification. Section 4 presents an in-depth analysis of the empirical results, offering a detailed interpretation of the findings. Finally, Section 5 summarizes the study's conclusions, highlighting key insights and their broader implications for policy and future research directions.

2. Literature Review

The interaction between trade policy and environmental sustainability has gained increasing attention in the global conversation on climate change mitigation, particularly in the context of highly industrialized nations such as South Korea. Central to this discourse is the Environmental Kuznets Curve hypothesis, which posits that economic growth initially intensifies environmental degradation before improving once a certain level of income is reached. Recent studies, such as those by Zeeshan et al. [11] and Zhu et al. [12], offer compelling evidence supporting this hypothesis, illustrating that, while trade liberalization promotes economic growth, it also leads to a short-term rise in CO_2 emissions, driven by the energy demands of industrial expansion. Nevertheless, as highlighted by Sajeev and Kaur [13] and Jiang et al. [14], trade openness alone cannot explain the complexities of environmental outcomes. The incorporation of energy efficiency standards and the promotion of green technologies, as noted by Corrocher and Mancusi [15] and Shahzad et al. [16], have become critical components of South Korea's trade agreements, providing a viable pathway to mitigate the environmental costs associated with industrial growth. These interventions are essential, not only for reducing carbon emissions but also for facilitating the transition to a more sustainable growth model. This study extends the existing literature by quantifying the role of energy efficiency in reducing carbon emissions, while also emphasizing the critical function of foreign direct investment in accelerating the adoption of cleaner technologies. Through a detailed examination of these factors, the study sheds light on how FDI can be strategically leveraged to support South Korea's broader sustainability goals, offering valuable insights for policymakers aiming to balance economic development with environmental stewardship.

Green technology innovation and improvements in energy efficiency are essential elements in the long-term decoupling of economic growth from environmental degradation. These components are integral to addressing the global challenge of reducing CO_2 emissions while maintaining robust economic performance. Razmjoo et al. [17] and Madejski et al. [18] underscore the transformative potential of renewable energy systems and carbon capture technologies in achieving significant emissions reductions. In the case of South Korea, energy efficiency has emerged as a crucial factor in moderating the carbon intensity of its export-oriented economy. Oryani et al. [19] and Ding and Lee [20] have demonstrated that the incorporation of energy efficiency standards within trade agreements has led to a substantial decline in energy consumption per unit of output in key industrial sectors, particularly in carbon-intensive industries such as steel and petrochemicals. This shift has been pivotal in reducing the environmental footprint of these sectors, which have traditionally been major contributors to the nation's CO_2 emissions. However, much of the existing literature, including research by Sonnenschein and Mundaca [21] and Ha and Byrne [22], has tended to focus on the immediate impacts of energy efficiency improvements, often neglecting their cumulative, long-term effects. This study addresses this oversight by providing empirical evidence that demonstrates how sustained advancements in energy efficiency and green technology can significantly reduce emissions over time. The results highlight that, while the short-term gains are measurable, it is the long-term commitment to energy innovation that drives meaningful environmental progress. Such findings underscore the importance of a forward-looking policy framework that prioritizes continuous investments in energy efficiency and innovation, especially in industrialized nations like South Korea. Moreover, foreign direct investment plays a critical role in facilitating this transition toward sustainability. Dos Santos Gaspar et al. [23] and Apostu and Gigauri [24] emphasize the capacity of FDI to act as a conduit for the transfer of cleaner, more efficient technologies across borders. By enabling access to advanced technological innovations, FDI supports the adoption of energy-efficient practices in industries that are otherwise slow to innovate due to financial or technical constraints. This study further demonstrates that FDI not only promotes industrial growth but also reinforces sustainable development by enhancing the capacity of domestic industries to integrate cleaner technologies. The synergistic effects of FDI, energy efficiency, and green technology create a comprehensive pathway toward achieving the dual objectives of economic growth and environmental sustainability, offering a model for policymakers to optimize trade and investment strategies in alignment with global climate goals.

Although energy efficiency and green technologies have demonstrated clear positive impacts on environmental sustainability, the role of foreign direct investment in this context remains a subject of ongoing debate within the literature. FDI, while a catalyst for industrial growth, often leads to an initial increase in CO_2 emissions, as industrial expansion drives higher energy consumption. This phenomenon is well documented by Nepal et al. [25] and Tariq et al. [26], who note that the influx of foreign capital typically stimulates energy-intensive production in the early stages of industrial development. However, the long-term effects of FDI tell a more nuanced story. Over time, FDI plays a pivotal role in facilitating the transfer of advanced energy-efficient technologies and practices, as evidenced by Huan and Qamruzzaman [27] and Amara et al. [28]. These studies suggest that, while FDI may initially contribute to environmental degradation, its ultimate impact is a net reduction in emissions as industries adopt cleaner technologies and more efficient energy management systems. This research extends the existing literature by examining the divergent temporal impacts of FDI, providing fresh insights into how foreign investment contributes to emissions reduction. The analysis reveals that FDI not only drives industrial growth but also supports South Korea's long-term environmental goals by enabling the adoption of advanced energy management practices. By facilitating the integration of green technologies, FDI becomes a critical tool for decoupling economic growth from environmental harm. This finding aligns with the broader understanding of FDI's dual role, which initially exacerbates emissions but ultimately mitigates them through technological innovation and transfer. Additionally, the results underscore the necessity of aligning FDI flows with South Korea's overarching sustainability objectives. Policies that incentivize investments in green technologies are vital for ensuring that FDI serves as a driver of both economic and environmental progress. This perspective echoes the recommendations of Kim and Seok [29] and Ghorbal et al. [30], who emphasize the importance of strategically channeling FDI into sectors that prioritize sustainability. Thus, the study not only contributes to the theoretical understanding of FDI's environmental implications but also offers actionable policy guidance for aligning foreign investments with national and global climate objectives.

In comparison to previous research, this study makes notable contributions by providing a more refined understanding of the dynamic relationship between trade policy, energy efficiency, and carbon emissions. Earlier studies, including those by Park and Hong [31], Salman et al. [32], and Khan et al. [33], have extensively examined the roles of economic growth and urbanization in contributing to rising emissions. However, these studies have not sufficiently addressed the mitigating effects that energy efficiency can exert over time. This research fills that gap by employing a robust methodological framework, specifically the Fourier autoregressive distributed lag model, to capture both short- and long-term impacts of trade policy and energy efficiency on carbon emissions in South Korea.

The results present compelling evidence that, while trade liberalization initially leads to higher emissions, the integration of energy efficiency standards into trade agreements can progressively reverse this upward trend.

3. Variables and Model

3.1. Variables

Independent variable: Carbon dioxide emissions serve as a critical indicator of South Korea's environmental sustainability, closely linked to the country's industrial composition, energy consumption patterns, and policy frameworks. As a highly industrialized nation with significant reliance on fossil fuels, South Korea has experienced elevated levels of greenhouse gas emissions, positioning CO_2 emissions as a prominent measure of its environmental impact. Studies by He [34], Li and He [35], and Wang et al. [36] emphasize the strong relationship between CO_2 emissions, energy use, and economic growth in South Korea. The nation's rapid urbanization and industrial expansion have driven emissions upward, although recent investments in green technologies and energy-efficient practices have begun to temper this trajectory. Despite these advancements, South Korea remains among the world's leading CO_2 emitters, highlighting the urgency of transitioning to a low-carbon economy to meet international climate objectives. The government's commitment to reducing CO_2 emissions by 40% by 2030, relative to 2018 levels, underscores the centrality of CO_2 as a metric for both environmental performance and policy direction. Initiatives such as the Korean Emissions Trading System reinforce the pivotal role of CO_2 emissions in guiding South Korea's sustainable development strategy (Adebayo et al. [37]). Consequently, CO_2 emissions are not only a key indicator of environmental sustainability but also serve as a fundamental variable in assessing the broader economic–environmental nexus in academic research. Their inclusion in this analysis reflects the country's ongoing efforts to balance robust economic growth with stringent environmental responsibilities.

Core variable: Trade policy and energy efficiency are key determinants of South Korea's carbon dioxide emissions, particularly due to the country's position as a heavily industrialized and export-driven economy. Recent authoritative studies highlight that South Korea's liberal trade policies, while driving economic growth, have also led to elevated CO_2 emissions. This is largely due to the energy-intensive nature of key industries such as steel and petrochemicals (Koc and Bulus [38]; Adebayo et al. [39]; He [40]). The expansion of exports, facilitated by trade liberalization, has resulted in increased energy consumption and, consequently, higher emissions. However, evidence also suggests that the incorporation of energy efficiency measures within trade policies can counteract this upward trend in emissions. For example, Moon and Min [41] and Nam and Jin [42] demonstrate that advancements in energy efficiency, spurred by domestic regulations and international environmental agreements, have reduced the energy intensity of South Korea's exports. This shift has facilitated a partial decoupling of economic growth from CO_2 emissions, marking an important step towards sustainability. Further, the adoption of cutting-edge technologies and the implementation of stringent energy efficiency standards—promoted through various trade agreements—have enabled South Korean industries to lower CO_2 emissions per unit of output (Lee [43]; Raihan [44]; Cho et al. [45]). Thus, while trade expansion has traditionally been linked to higher emissions, these findings underscore the positive impact of integrating energy efficiency into trade frameworks. Moving forward, the alignment of trade policies with robust energy efficiency standards will be crucial to South Korea's pursuit of long-term carbon reduction goals and sustainable economic growth.

Control variable: Economic growth, urbanization, industrialization, foreign direct investment, and green technology innovation are pivotal drivers of South Korea's CO_2 emissions. Historically, economic growth has been linked to higher energy consumption, particularly in energy-intensive manufacturing sectors, leading to increased CO_2 emissions (Kim [46]; Song et al. [47]). The process of urbanization further intensifies energy demand, as expanding infrastructure, housing, and transportation needs contribute significantly to the country's emission profile (Shafique et al. [48]). Similarly, industrialization, a cornerstone of South Korea's economic strategy, exacerbates emissions, with sectors like petrochemicals and steel production heavily reliant on fossil fuels (Yun and Jeong [49]; Xu et al. [50]). On the other hand, FDI exerts a more nuanced influence. While FDI often boosts industrial output and energy use, it also facilitates the transfer of cleaner, more energy-efficient technologies, which can mitigate CO_2 emissions over time (Kim [46]). Finally, green technology innovation plays a crucial role in reducing emissions. Innovations in renewable energy, energy efficiency, and carbon capture are progressively decoupling economic growth from emissions, indicating a shift toward a more sustainable future (Jung et al. [51]). Together, these factors form a complex landscape that influences both the short-term rise in emissions and long-term mitigation strategies in South Korea. To provide a clearer understanding of the variables analyzed in this paper, Table 1 summarizes the essential characteristics of each variable.

Table 1. Description of variables.

Variable	Form	Definition	Source
Carbon dioxide emissions	CO_2	Metric tons per capita in log	World Bank
Trade policy	tp	Trade policy index	FRED Economic Database
energy efficiency	ee	GDP/energy consumption	World Bank
Economic growth	eg	GDP (constant 2015 USD, and unit: billion USD) in log	World Bank
Urbanization	ur	Share of the urban population in the total population	World Bank
Industrialization	in	Ratio of industry to GDP	World Bank
Foreign direct investment	fdi	Foreign direct investment, net inflows (% of GDP)	World Bank
Green technology innovation	gt	Values for patents (% of total) in environment-related technologies	Organization for Economic Cooperation and Development

3.2. Model

In analyzing the long-term interaction between trade policy, energy efficiency, and carbon dioxide emissions in South Korea, it is critical to account for both the economic and environmental dimensions that have underpinned the country's development trajectory. South Korea's export-oriented industrialization, heavily dependent on energy-intensive sectors such as manufacturing and petrochemicals, has historically contributed to rising CO_2 emissions (Hong et al. [52]). Nevertheless, recent empirical research indicates that advancements in energy efficiency, catalyzed by domestic regulatory frameworks and international trade agreements, have the potential to alleviate the environmental pressures associated with industrial growth (Kim and Tromp [53]). The integration of energy efficiency measures within trade policies is particularly important for decoupling economic growth from environmental degradation. This suggests that increased trade openness, when aligned with robust energy efficiency standards, can support long-term reductions in CO_2 emissions (Hille and Lambernd [54]; Wenlong et al. [55]). Building on these insights, this paper introduces a long-term empirical model to quantify the effects of trade policy and energy efficiency on CO_2 emissions, offering a comprehensive framework for understanding the pathways to sustainable economic growth. The baseline model is outlined as follows:

$$CO_{2,t} = a_0 + a_1 tp_t + a_2 ee_t + a_3 eg_t + a_4 ur_t + a_5 in_t + a_6 fdi_t + a_7 gt_t + \epsilon_t. \tag{1}$$

In Equation (1), t represents the time variable, denoting the year under consideration. a_0 refers to the constant term, which captures the baseline level of the dependent variable when all other explanatory variables are zero. The terms $[a_1, a_7]$ correspond to the coefficients to be estimated, reflecting the magnitude and direction of the relationships between the independent variables and the dependent variable. Finally, ϵ denotes the white noise error term, which accounts for the random variability not explained by the model, ensuring that the residuals are normally distributed with a mean of zero. This formulation allows for the precise estimation of the impact of key variables on the outcome while maintaining statistical rigor.

In addition, this study employs the innovative Fourier autoregressive distributed lag methodology to achieve its research objectives. The following section provides a detailed discussion of this approach. Traditional methods for testing cointegration, such as the Engle and Granger [56] two-step procedure and the Johansen and Juselius [57] test, are widely recognized in the literature. However, these techniques are constrained by certain limitations, particularly the requirement for all variables to be integrated at the same order. To address these issues, Pesaran et al. [58] introduced the autoregressive distributed lag (ARDL) model, which offers greater flexibility by allowing variables of mixed orders of integration (i.e., $I(0)$ or $I(1)$). The ARDL model also addresses challenges such as serial correlation and endogeneity, providing more reliable and robust estimates. Moreover, it distinguishes between short- and long-run dynamics, enabling the formulation of policies that are tailored to different time horizons. The ARDL framework, therefore, offers a comprehensive approach to understanding both short- and long-term relationships between variables, as demonstrated in the following formal model specification.

$$\begin{gathered}\Delta CO_{2,t} = b_0 + \sum_{i=0}^{n1} b_{1i}\Delta CO_{2,t-i} + \sum_{i=0}^{n2} b_{2i}\Delta tp_{t-i} + \sum_{i=0}^{n3} b_{3i}\Delta ee_{t-i} + \\ \sum_{i=0}^{n4} b_{4i}\Delta eg_{t-i} + \sum_{i=0}^{n5} b_{5i}\Delta ur_{t-i} + \sum_{i=0}^{n6} b_{6i}\Delta in_{t-i} + \sum_{i=0}^{n7} b_{7i}\Delta fdi_{t-i} + \\ \sum_{i=0}^{n8} b_{8i}\Delta gt_{t-i} + b_9 CO_{2,t-1} + b_{10} tp_{t-1} + b_{11} ee_{t-1} + b_{12} eg_{t-1} + b_{13} ur_{t-1} + \\ b_{14} in_{t-1} + b_{15} fdi_{t-1} + b_{16} gt_{t-1} + ect_{t-1} + \epsilon_t.\end{gathered} \tag{2}$$

Equation (2) illustrates the ARDL model with an unrestricted intercept and no trend. In this formulation, b_0 represents the intercept, while the coefficients $[b_{1i}, b_{8i}]$ correspond to short-run estimates and $[b_9, b_{16}]$ reflect the long-run estimates. The terms $[n1, n8]$ denote the lag orders, and ϵ_t represents the disturbance term. To assess cointegration, two standard tests are applied within the ARDL framework: firstly, an F-test (or bounds test) on the long-run coefficients, testing the null hypothesis that $b_9 = b_{10} = b_{11} = b_{12} = b_{13} = b_{14} = b_{15} = b_{16} = 0$, and secondly, a *t*-test on the lagged dependent variable, specifically testing $b_9 = 0$. The null hypothesis H_0 in both cases posits no cointegrating relationship, whereas the alternative hypothesis H_1 asserts the presence of cointegration. Cointegration is confirmed if the F- and *t*-test statistics exceed the critical values for the upper bound, corresponding to an $I(1)$ series. However, one limitation of the ARDL approach is its inability to account for structural breaks, which can lead to biased results (Enders and Lee [59]; Gil-Alana and Yaya [60]; Cai and Omay [61]). To address this issue, the Fourier transformation is incorporated into the ARDL model, enhancing its ability to handle structural breaks without requiring prior knowledge of the timing, frequency, or form of the breaks. Unlike structural break dummies, the Fourier transformation efficiently captures these breaks while maintaining strong power and size properties due to its reduced number of parameters. The model incorporating the Fourier transformation, known as FARDL, is formulated as follows:

$$\begin{gathered}\Delta CO_{2,t} = b_0 + \sum_{i=0}^{n1} b_{1i}\Delta CO_{2,t-i} + \sum_{i=0}^{n2} b_{2i}\Delta tp_{t-i} + \sum_{i=0}^{n3} b_{3i}\Delta ee_{t-i} + \\ \sum_{i=0}^{n4} b_{4i}\Delta eg_{t-i} + \sum_{i=0}^{n5} b_{5i}\Delta ur_{t-i} + \sum_{i=0}^{n6} b_{6i}\Delta in_{t-i} + \sum_{i=0}^{n7} b_{7i}\Delta fdi_{t-i} + \\ \sum_{i=0}^{n8} b_{8i}\Delta gt_{t-i} + b_9 CO_{2,t-1} + b_{10} tp_{t-1} + b_{11} ee_{t-1} + b_{12} eg_{t-1} + b_{13} ur_{t-1} + \\ b_{14} in_{t-1} + b_{15} fdi_{t-1} + b_{16} gt_{t-1} + F_1 \sin\left(\frac{2\pi kt}{T}\right) + F_2 \cos\left(\frac{2\pi kt}{T}\right) + ect_{t-1} + \epsilon_t.\end{gathered} \tag{3}$$

Equation (3) introduces two key components of the Fourier transformation: F_1 and F_2, which represent the amplitude and displacement, respectively. In this context, the term π is the mathematical constant (approximately 3.14), while k denotes the frequency parameter associated with the Fourier series. The variable t captures the time trend, and T refers to the total sample size. The Fourier transformation enhances the model by allowing for smooth, periodic shifts in the data, which can capture underlying cyclical patterns and structural changes without relying on predefined breakpoints. This approach is particularly advantageous in econometric models where abrupt shifts in the underlying data-generating process might bias traditional estimates. The inclusion of Fourier terms in ARDL models has been shown to improve model flexibility and fit by capturing non-linearities that might otherwise be overlooked (Wu et al. [62]; Alper et al. [63]; Syed et al. [64]). Moreover, this method allows the identification of structural breaks without the need for prior assumptions about their timing, thus offering a more nuanced approach to understanding long-run relationships in the presence of such breaks.

4. Results and Discussion

4.1. Basic Statistical Analysis

This section presents the empirical results of the analysis. In time series econometrics, testing for unit roots or stationarity is a critical preliminary step to avoid spurious regression results and to ensure the selection of the appropriate estimation method. Accordingly, before proceeding with the estimation of the FARDL model, unit root tests were conducted to determine the order of integration for each variable. Traditional unit root tests, such as the augmented Dickey–Fuller (ADF) test and the Phillips–Perron (PP) test, are commonly employed in this context. However, these conventional methods do not account for structural breaks, which can lead to misleading conclusions in the presence of such breaks. To address this limitation and enhance the robustness of the analysis, the Fourier-ADF and Fourier-LM tests were utilized. These tests incorporate Fourier transformations, which effectively capture structural breaks by identifying smooth shifts in the data without requiring prior knowledge of the breakpoints. The use of Fourier-based unit root tests allows for a more reliable assessment of stationarity, accommodating potential non-linearities and discontinuities in the data. As a result, this approach yields more robust and accurate empirical findings. The results from the Fourier-ADF and Fourier-LM tests, presented in Table 2, provide a comprehensive overview of the stationarity properties of the variables under investigation, ensuring a solid foundation for subsequent model estimation and policy analysis.

Table 2. Results of unit root test.

Variable	Fourier-ADF Test		Fourier-LM Test	
	I(0)	I(1)	I(0)	I(1)
CO_2	0.137	−5.796 ***	−4.489 **	−6.357 ***
tp	−2.652	−6.771 ***	−1.635	−6.856 ***
ee	−1.972	−6.132 ***	−1.838	−6.538 ***
eg	−0.723	−5.856 ***	−4.502 **	−5.924 ***
ur	−1.745	−5.003 ***	−1.136	−5.399 ***
in	−1.593	−6.782 ***	−4.131 **	−6.898 ***
fdi	−2.474	−5.515 ***	−1.098	−6.146 ***
gt	−1.041	−5.619 ***	−1.283	−6.395 ***

Note: ** 5% significance level. *** 1% significance level.

The null hypothesis H_0 for both the Fourier-LM and Fourier-ADF tests posits the presence of a unit root, while the alternative hypothesis H_1 suggests stationarity. As shown in Table 2, the results indicate that H_0 cannot be rejected at the level $I(0)$ for either test, signifying that the dataset exhibits non-stationarity at levels. However, upon differencing the data, H_0 is rejected at $I(1)$, confirming that the variables become stationary after the first difference. This finding implies that the series is integrated of order one, $I(1)$, and thus suitable for further analysis using the FARDL framework. The decision to employ the FARDL approach in this study is particularly justified by its ability to account for structural breaks, a feature that traditional cointegration methods often overlook. As highlighted in the methodology, the FARDL method outperforms conventional approaches by incorporating Fourier terms, which capture smooth structural shifts without prior knowledge of their timing. This flexibility is crucial for improving the robustness of the empirical results, especially in the context of time series data with potential breaks. The results of the FARDL bounds testing, as summarized in Table 3, provide further evidence of the long-run relationships between the variables under study, offering insights into the dynamic interactions that govern the model. This methodology enhances the reliability of the analysis, ensuring that both short- and long-term impacts are appropriately captured, even in the presence of structural changes.

Table 3. Results of cointegration test.

Method	Statistical Value	Lower Critical Value	Upper Critical Value
t-statistical test	−7.742 ***	−2.58	−4.23
F-statistical test	21.218 ***	3.07	4.44

Note: *** 1% significance level.

As presented in Table 3, the results from both the F-test and *t*-test indicate that the respective test statistics exceed the critical values for the upper bound. Consequently, the null hypothesis of no cointegration is decisively rejected. This suggests the existence of a stable long-run relationship among the variables under consideration in this study. The rejection of the null hypothesis confirms that the variables are cointegrated, signifying that despite short-term fluctuations, they tend to move together in the long run. Following this, the analysis proceeds to examine the long-run and short-run dynamics as estimated by the FARDL model. The FARDL approach allows for a detailed decomposition of the long-term equilibrium relationships and short-term adjustments, enabling a more nuanced understanding of the interactions between the variables. The subsequent section presents the estimated coefficients for both the long-run and short-run relationships, offering insights into the extent and direction of the effects, as well as the speed of adjustment toward long-run equilibrium. These findings provide a robust basis for policy recommendations, as they illuminate the differential impacts of the considered variables over various time horizons.

4.2. Long- and Short-Run Effect Test Analysis

To extend the analysis from the cointegration results to a more granular examination of the long- and short-run dynamics, it is critical to assess the implications of the FARDL model across different time horizons. The results of the cointegration tests have confirmed a robust long-term relationship between the key variables, indicating that despite temporary deviations, these variables converge towards a stable long-run equilibrium. In this context, the subsequent examination of short-run dynamics will provide valuable insights into the immediate, transient effects of trade policy, energy efficiency, and other influencing factors on CO_2 emissions. Conversely, the long-run estimates will capture the enduring, equilibrium adjustments that unfold over time. Table 4 offers a detailed presentation of these findings, facilitating a comprehensive understanding of how the determinants impact CO_2 emissions over both short and long durations. These results highlight not only the elasticity of CO_2 emissions in the short term but also the broader, sustained effects of the key variables in shaping South Korea's long-term environmental outcomes.

As demonstrated in Table 4, short-term effects of South Korea's trade policy are marked by increased industrial activity, particularly in energy-intensive sectors such as manufacturing and petrochemicals, which leads to a rise in CO_2 emissions. This outcome is largely attributable to the rapid expansion of production capacities and heightened energy consumption facilitated by trade liberalization (Li et al. [65]; Chen et al. [66]). The opening of markets and greater export activity, in the absence of strict environmental regulations, tends to elevate emissions, as highlighted by Hu et al. [67] and Wang et al. [68]. These studies observe that the initial phases of trade liberalization contribute significantly to CO_2 emissions as industries scale up to meet growing international demand. In contrast, over the long term, the relationship between trade policy and CO_2 emissions shifts as energy efficiency measures and technological advancements are gradually integrated. The adoption of environmental standards within trade agreements, alongside innovations in green technologies, plays a critical role in reducing the carbon intensity of production. Nathaniel et al. [69] and Işık et al. [70] provide evidence supporting this, demonstrating that trade policies, when aligned with environmental regulations, can reduce the energy intensity of exports and result in declining CO_2 emissions over time. This aligns with the findings of the FARDL model in this study, which shows a negative long-term impact of trade policy on CO_2 emissions. The primary distinction between this study and prior research lies in the treatment of the transitional phase. While earlier studies acknowledge the initial rise in emissions due to trade liberalization, this study offers a more detailed perspective by emphasizing the long-term mitigating effects of energy efficiency. Both studies converge on the conclusion that trade policies can have differing impacts across time horizons, with short-term increases in emissions ultimately offset by long-term reductions driven by technological progress and regulatory improvements.

Table 4. Results of long- and short-run effect test analysis.

Variable	Long-Run Effect	Variable	Short-Run Effect
tp	−0.093 *** (−6.239)	Δtp	0.229 *** (5.714)
ee	−0.259 *** (−3.689)	Δee	−0.147 *** (−3.916)
eg	0.359 *** (8.524)	Δeg	0.533 *** (8.866)
ur	0.199 ** (2.205)	Δur	0.258 *** (2.834)
in	0.306 ** (2.129)	Δin	0.447 *** (3.738)
fdi	−0.108 ** (−2.273)	Δfdi	0.075 ** (2.215)
gt	−0.117 *** (−3.228)	Δgt	−0.032 *** (−3.662)
Diagnostics test			
Statistical test	Value	Statistical test	Value
ect	−0.181 ***	Ramsey RESET test	0.152
F_1	0.052 ***	ARCH test	0.292
F_2	0.079 ***	Jarque–Bera test	0.381
LM test	0.217	CUSUM and CUSUM of squares test	Stable

Note: *** 1% significance level. ** 5% significance level. *t*-statistics in the parentheses.

In the short term, energy efficiency has a negative effect on South Korea's CO_2 emissions, primarily by reducing the energy intensity of production processes, particularly within energy-demanding industries such as manufacturing. The immediate reductions in emissions stem from the adoption of more efficient technologies, improved energy management systems, and the optimization of industrial operations. These early gains, although relatively moderate due to the gradual integration of new practices and technologies, contribute to lower CO_2 emissions even as industrial output continues to grow. This is consistent with findings from Steren et al. [71] and Hossain et al. [72], who emphasize the short-term advantages of energy efficiency measures, although their full potential may only be realized as these innovations become more widely implemented. In the long run, the impact of energy efficiency on CO_2 emissions is even more substantial. Sustained investment in energy-efficient technologies, along with advancements in renewable energy, leads to a more pronounced decoupling of economic growth from carbon emissions. The compounding effects of technological innovation, policy support, and broader adoption of green practices significantly enhance the reduction of emissions over time. This is corroborated by Misila et al. [73] and Nam and Jin [42], who highlight the importance of energy efficiency as a key driver of long-term emissions reduction, particularly when combined with advancements in clean technologies and supportive regulatory frameworks. The primary distinction between the findings of this study and those of previous literature lies in the more granular differentiation between short- and long-term effects. While existing studies acknowledge the overall role of energy efficiency in reducing emissions, this study offers a more comprehensive perspective by clearly delineating the time horizons over which these impacts manifest. Nonetheless, the conclusion remains consistent across studies: the long-term benefits of energy efficiency are significantly greater than the short-term reductions, especially when underpinned by continuous technological innovation and policy interventions.

In the short term, South Korea's rapid economic growth, urbanization, and industrialization contribute significantly to increasing CO_2 emissions, primarily due to the country's dependence on energy-intensive industries and urban infrastructure expansion. Economic growth in particular drives a higher demand for energy across critical sectors, such as manufacturing, transportation, and construction, leading to increased consumption of fossil fuels and, consequently, higher emissions. Similarly, urbanization, characterized by the growth of cities and rising demand for services like housing and transportation, exacerbates energy use, further elevating emissions. Industrialization, especially in sectors like steel, petrochemicals, and electronics, plays a crucial role in driving emissions due to the high carbon intensity of these industries (Park et al. [74]; Tan et al. [75]). Over the long term, the positive relationship between CO_2 emissions, economic growth, urbanization, and industrialization gradually weakens. This is due to several factors, including structural shifts toward a service-based economy, improvements in energy efficiency, and an increasing reliance on renewable energy. As the economy evolves, technological advancements and policy measures, such as the Korean Emissions Trading System, mitigate the environmental impact of these factors. Although economic activities still contribute to emissions, the long-term effects are less pronounced compared to the short-term impacts. This observation is supported by Brockway et al. [76] and Lamb et al. [77], who find that industrial expansion initially leads to higher emissions, but over time, technological and structural changes reduce these effects.

Foreign direct investment follows a similar trajectory. In the short term, FDI typically results in greater industrial activity and emissions, as foreign capital often flows into energy-intensive sectors that are central to South Korea's economy. The increased production fueled by FDI elevates energy consumption, thereby contributing to higher CO_2 emissions. However, in the long run, FDI has the potential to reduce emissions by facilitating the transfer of cleaner, more energy-efficient technologies. Studies by Hille et al. [78] and Saqib and Dincă [79] highlight the critical role FDI plays in introducing advanced technologies that help reduce the carbon intensity of industrial processes. As these technologies are integrated into South Korea's industrial base, the long-term impact of FDI on CO_2 emissions becomes negative, with emissions decreasing as energy efficiency improves. Green technology innovation exerts a negative influence on CO_2 emissions in both the short and long term. In the short term, the introduction of green technologies, such as renewable energy systems, energy-efficient industrial processes, and carbon capture technologies, begins to lower the carbon intensity of production and consumption. These early effects, although initially modest due to the time required for widespread adoption, contribute to emissions reductions. Over the long term, however, the impact of green technology innovation becomes increasingly significant. As innovation accelerates and these technologies are more widely adopted across industries, the reductions in CO_2 emissions become more substantial. This is consistent with studies by Lee and Woo [80] and Mo [81], which emphasize that sustained innovation in green technologies, particularly when supported by favorable policy frameworks, is crucial to long-term emissions reductions.

When comparing these findings with the existing literature, both convergence and divergence can be observed. The short-term positive relationship between economic growth, urbanization, and industrialization with CO_2 emissions is consistent with studies by Pata [82], Odugbesan and Rjoub [83], and Jiang et al. [84], which underscore the immediate environmental costs associated with rapid industrial expansion and urban development. These studies, like the present analysis, emphasize that the short-term benefits of economic growth in terms of emissions reductions are constrained by the significant energy demands that accompany early-stage industrialization and urbanization. However, this study distinguishes itself by offering a more nuanced perspective on the varying effects of these factors over time, particularly regarding green technology innovation. While prior studies, such as those by Bulus and Koc [85], acknowledge the importance of green technology in reducing long-term emissions, this study extends the discussion by highlighting the compounding effects of continuous technological innovation and integration. It demonstrates that, while the initial impact of green technology on emissions may be limited, its long-term effects are far more substantial, particularly as green technologies become more affordable and widely adopted. Furthermore, the long-term negative impact of FDI on CO_2 emissions, as found in this study, aligns with the findings of Wang and Huang [86], all of which emphasize the importance of FDI in facilitating the transfer of cleaner technologies. However, this study contributes additional depth to the discussion by clearly distinguishing between the short-term and long-term impacts of FDI, noting that while FDI initially increases emissions, its long-term effects can be mitigated through the widespread adoption of energy-efficient technologies. This difference highlights the importance of time horizons when evaluating the environmental impacts of FDI.

In conclusion, this study aligns with much of the existing literature, particularly in recognizing the divergent impacts of economic growth, urbanization, industrialization, FDI, and green technology innovation on CO_2 emissions over different time periods. The analysis presented here, however, offers a more detailed and comprehensive understanding of how these factors evolve over time, providing valuable insights into both short- and long-term pathways to emissions reductions in South Korea. As the country continues to balance economic growth with environmental sustainability, these findings underscore the critical importance of sustained technological innovation, targeted policy interventions, and strategic use of FDI to achieve long-term carbon reduction goals.

4.3. Robustness Test Analysis

To validate the robustness of the empirical findings, this analysis applies three econometric techniques: fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and canonical cointegration regression (CCR). These methods are designed to address potential econometric issues such as endogeneity and serial correlation, thereby ensuring the reliability and accuracy of the long-run coefficient estimates. FMOLS is particularly effective in adjusting for serial correlation and endogeneity, making it well-suited for dealing with small sample sizes and time series that are integrated. DOLS further enhances the robustness by incorporating leads and lags of differenced variables, which corrects for potential biases in ordinary least squares (OLS) and yields consistent estimates in the context of cointegrated relationships. Similarly, CCR transforms the original data before estimation to tackle endogeneity and serial correlation, providing additional robustness to the long-term estimates. By employing these three methods, the study ensures that the estimated long-run relationships, particularly those involving trade policy, energy efficiency, and CO_2 emissions, are rigorously tested and validated. The results obtained from the FMOLS, DOLS, and CCR estimations, as presented in Table 5, confirm the consistency and robustness of the key findings, offering further assurance in the credibility and reliability of the conclusions drawn from the analysis.

As evidenced in Table 5, all estimated coefficients are statistically significant at the 1% level, underscoring the robustness of the results across the FMOLS, DOLS, and CCR models. Notably, the negative coefficients for trade policy and energy efficiency across all models indicate that enhancements in both areas contribute to a reduction in CO_2 emissions, thus improving environmental quality and promoting sustainability in South Korea. These findings are consistent with the baseline results and further confirm that policies designed to liberalize trade, when coupled with improvements in energy efficiency, have a substantial positive impact on reducing emissions. In the case of trade policy, these results suggest that the strategic integration of environmental regulations within trade agreements can play a pivotal role in mitigating the environmental footprint of industrial activities, particularly in sectors that are energy-intensive. Similarly, improvements in energy efficiency contribute directly to emissions reduction by lowering the energy consumption per unit of output across industries. This is particularly relevant for South Korea, where economic growth has traditionally been tied to energy-intensive manufacturing sectors. These findings resonate with previous studies that highlight the dual benefits of trade liberalization and energy efficiency in reducing environmental degradation (Woo et al. [87]; Zhang [88]; Kim and Lin [89]). The consistency of the results across FMOLS, DOLS, and CCR further enhances the credibility of the conclusions, as these methodologies are specifically designed to correct for issues such as endogeneity and serial correlation, ensuring that the estimated relationships reflect true long-term effects. Consequently, the negative coefficients not only corroborate the baseline findings but also provide additional evidence that policies aimed at improving energy efficiency and trade regulation can be key drivers of long-term environmental sustainability in South Korea. Thus, the results offer robust support for policy frameworks that emphasize sustainable trade practices and technological innovation in energy efficiency as essential components of national and global efforts to reduce CO_2 emissions.

Table 5. Results of robustness test analysis.

Variable	FMOLS	DOLS	CCR
tp	−0.126 *** (−7.233)	−0.053 *** (−7.199)	−0.077 *** (−6.887)
ee	−0.292 *** (−4.113)	−0.109 *** (−4.074)	−0.136 *** (−4.254)
cv	Yes	Yes	Yes

Note: *** 1% significance level. *t*-statistics in the parentheses. cv control variable.

5. Conclusions

This study underscores the pivotal influence of trade policy, energy efficiency, and various economic factors in determining South Korea's carbon emissions trajectory. In both the short and long term, improvements in energy efficiency and the adoption of environmentally sustainable trade practices emerge as essential strategies for reducing CO_2 emissions. The analysis demonstrates that, while economic growth, urbanization, and industrialization initially drive up emissions, the deployment of advanced technologies, foreign direct investment, and green innovations significantly offset these effects in the long run. South Korea's robust commitment to environmental sustainability, reinforced by its progressive policies and technological advancements, provides a solid framework for achieving its ambitious carbon reduction objectives. As the nation continues to balance the dual imperatives of economic growth and environmental stewardship, the findings offer compelling support for the adoption of long-term strategies that integrate sustainability into development. By advancing energy efficiency standards and accelerating the adoption of green technology, South Korea is well positioned to become a global leader in the transition toward a low-carbon economy, making a substantial contribution to international efforts to mitigate climate change.

Drawing on the results of this study, several key policy implications and strategic solutions are proposed to advance environmental sustainability while maintaining economic growth. First, it is essential to align trade policies with stringent environmental regulations to reduce the carbon emissions associated with industrial exports. Incorporating energy efficiency standards into trade agreements can significantly lower the carbon intensity of South Korea's manufacturing exports. The Korean Emissions Trading System offers a foundational mechanism to support these efforts, incentivizing industries to adopt cleaner and more sustainable production practices. Second, the government should focus on increasing investments in energy efficiency, particularly within energy-intensive sectors such as petrochemicals, steel, and electronics. Implementing policies that encourage the adoption of state-of-the-art technologies to reduce energy consumption per unit of output is crucial. Offering subsidies or tax incentives to industries meeting enhanced energy efficiency benchmarks can further stimulate innovation and contribute to the overall reduction of CO_2 emissions. Third, promoting innovation in green technologies, including renewable energy and carbon capture systems, should be a key priority. Government funding, research grants, and partnerships with private sector actors are essential for accelerating the development and widespread implementation of these technologies. Such efforts are critical to decoupling economic growth from environmental degradation and achieving substantial long-term reductions in CO_2 emissions. Finally, South Korea should strategically target foreign direct investment that facilitates the transfer of cleaner and more energy-efficient technologies into the domestic market. FDI policies should prioritize partnerships with foreign firms that emphasize sustainability, ensuring that foreign capital not only enhances industrial capacity but also contributes to emissions reductions over time. These policy recommendations offer a comprehensive framework for achieving significant reductions in CO_2 emissions while supporting South Korea's broader economic objectives, ensuring that the country remains competitive globally while pursuing its environmental sustainability goals.

This study presents several limitations that highlight potential directions for future research. First, the analysis relies on national-level data, potentially masking regional disparities in CO_2 emissions across South Korea's industrial and urban areas. Future studies could evaluate region-specific emissions and policy impacts, offering a more detailed understanding of geographic variability in environmental outcomes. Second, while this research employs advanced econometric methods to explore the relationship between trade policy, energy efficiency, and CO_2 emissions, it does not fully consider the effects of global economic fluctuations or geopolitical events on trade dynamics. Future research could integrate the impacts of international market volatility and geopolitical tensions, providing a more comprehensive assessment of South Korea's environmental sustainability in a global context. Third, the study focuses primarily on energy efficiency and trade policy but does not sufficiently examine the role of emerging technologies, such as artificial intelligence and blockchain, in reducing emissions. Further research could assess the potential of these advanced technologies to enhance industrial practices and accelerate emissions reductions. Lastly, although the study addresses the long-term impact of foreign direct investment on CO_2 emissions, further examination of sector-specific FDI and its environmental implications could provide deeper insights. Future research could investigate how directing FDI toward green technology sectors may expedite South Korea's transition to a low-carbon economy, contributing to both national sustainability goals and global climate commitments. These avenues for future inquiry would enrich the understanding of South Korea's environmental challenges and guide more targeted, effective policy interventions.

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