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Investigating the Effect of Green Productivity and CO_2 Emissions Intensity in Developed and Developing CPTPP Countries: An Application of Panel Threshold

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ABSTRACT

Rising CO_2 emissions, a major driver of climate change, demand urgent measures to reduce fossil fuel dependence, adopt clean technologies, and promote sustainable development. This study examines the relationship between green productivity and CO_2 emissions intensity among CPTPP nations from 2001 to 2021 using panel data and econometric models, including panel Autoregressive Distributed Lag (ARDL) tests, panel Fully Modified Ordinary Least Square analysis (FMOLS), and a panel threshold model. The results reveal a U-shaped relationship, aligning with the Jevons Paradox but diverging from the conventional EKC hypothesis. Specifically, green productivity improvements initially result in higher emissions, but they lead to environmental benefits beyond a certain threshold of technology use. These findings highlight the critical need to balance economic growth with environmental protection through enhanced green productivity. The study also underscores that the effectiveness of the green economy varies across countries, emphasizing the importance of tailoring green economic strategies to the unique conditions of developed and developing nations to achieve a win-win outcome for climate health and economic progress.

Keywords: CO_2 Intensity, Green Productivity, U-Shaped Curve, Effectiveness of Green Economy, Win-Win Outcome
JEL Classifications: Q5

1. INTRODUCTION

Carbon dioxide (CO_2) is the most prevalent greenhouse gas (GHG), primarily originating from the burning of fossil fuels for transportation, electricity generation, and industrial activities. It significantly contributes to climate change by disrupting atmospheric temperature regulation. Since 1970, over 89% of the excess heat absorbed by the climate system has been stored in the oceans due to their capacity to absorb CO_2, resulting in ocean warming and acidification (von Schuckmann et al., 2020; Sohail et al., 2023). These changes have far-reaching consequences, including disrupted marine ecosystems, melting ice caps, altered weather patterns that further contribute to extreme weather events, rising sea levels, and threats to biodiversity and human health. The severity of these impacts can be mitigated by the world's emission reduction efforts, underscoring the urgent need for the promotion of green productivity through increased efficiency and sustainable development. Aligning with Sustainable Development Goal 13 (SDG 13), which focuses on climate action, suggests the linkage between CO_2 emissions and green productivity is critical to achieving sustainable development. Green productivity drives the low-carbon transition by promoting economic growth alongside environmental sustainability (Peng et al., 2023).

Two key scenarios emerge from the relationship between CO_2 emissions and green productivity. In the first scenario, prevalent in many developing nations, economic growth relies on an extensive production model that prioritizes higher input usage to increase output (Yang et al., 2022). This production method is resource-inefficient, often heavily reliant on fossil fuels, and characterized by low-technology manufacturing, leading to lower green productivity and consequent increases in CO_2 emissions (Avenyo and Tregenna, 2022). In the second scenario, an intensive economic model, more common in developed countries with sufficient access to technology, focuses on efficient input usage to increase output (Tawiah et al., 2021). This production method increases green productivity by ensuring increased efficiency, thereby lowering emissions (Ding et al., 2021; Hussain et al., 2022). Both scenarios imply that economic growth is likely to increase CO_2 emissions in developing countries but reduce them in developed countries, reflecting differences in sustainable practices and technologies (Yan et al., 2022). Despite these distinctions, both groups face increasing pressure to adopt green technologies and sustainable practices to address environmental challenges, while developing countries face greater challenges in green transition and require external support (de Angelis et al., 2019; Li et al., 2022; United Nations, 2023). However, as Freeman et al. (2016) and Giampietro and Mayumi (2018) explained, increased efficiency may inadvertently lead to increased economic activity and therefore higher emissions, due to more efficient and lower-cost production. This paradox highlights the delicate balance between economic and environmental priorities.

This study aims to investigate the determinants of CO_2 intensity and the impact of CO_2 intensity on green productivity among the sub-groups of CPTPP member countries. It focuses on how green productivity and non-renewable energy use affect CO_2 emissions to achieve national sustainability and climate goals, particularly among the developed and developing member groups of the CPTPP. The research underscores the importance of increasing green productivity by improving efficiency and promoting innovation to reduce emissions and guide nations towards sustainable economic practices. Furthermore, this study has important implications for addressing the challenges of minimizing the environmental impact of economic activities while maintaining economic performance by improving green productivity, as mentioned in Cheng et al. (2023), Fan and Wang (2024) and Zhao and Ehigiamusoe (2024). Moreover, it explores how CO_2 intensity affects green productivity, providing insights into how the current status of country groups (technological, regulatory, economic, and market demand) can adapt to and mitigate high CO_2 intensity levels, thereby influencing the effectiveness and feasibility of sustainable practices, which potentially affect green productivity. The ultimate goal of green production is to fully decouple economic growth from emissions, but significant progress towards this goal can be achieved by reducing the emissions intensity of economic activity.

This study offers several unique contributions. First, although previous studies, such as Du et al. (2018), Hu and Liu (2017), Ma and Wu (2022) and Yu et al. (2020), used the Malmquist-Luenberger (ML) index to evaluate green productivity, they primarily focused on the proportion of technical efficiency and technological progress that affect green productivity without considering the broader implications for emissions reduction. Second, green productivity has not been extensively explored as a strategy for achieving emission reduction strategies compared to green growth, which is more commonly addressed in the literature (e.g., Fernandes et al., [2021]; Hao et al., [2021]; Wang et al., [2021]) and policy focus due to its broader implications for economic development and sustainability. Unlike green growth, which emphasizes systemic economic transformation, green productivity focuses on improving resource optimization, waste reduction, and production processes within existing frameworks. Third, while many studies have examined variables affecting CO_2 emissions, few have explored the reverse relationship—how CO_2 intensity impacts green productivity (e.g., de Nicola et al., [2025]; Kuosmanen and Maczulskij, [2024] and Napolitano et al., [2023]). This bidirectional approach provides a more nuanced understanding of the interplay between productivity and environmental sustainability. Finally, CPTPP countries remain underexplored in this context, with existing studies (e.g., Gretton, [2021], Khan et al., [2018] and Wu and Chadee, [2022]) focusing on other topics, such as trade liberalization and economic integration, rather than its environmental dimensions. This study focuses on CPTPP countries because, despite their biodiversity and environmental provisions in agreements like Chapter 20 of the CPTPP, many member states are major users and exporters of fossil fuels and have non-binding environmental commitments (Hasan et al., 2022). Overall, the study will contribute to the body of knowledge on the relationship between CO_2 emissions and green productivity, offering valuable insights for policymaking and business practices in CPTPP countries and potentially impacting other countries and regions striving to balance economic growth with environmental sustainability.

2. LITERATURE REVIEW

2.1. Jevons Paradox and Environmental Kuznets Curve (EKC)

The Jevons Paradox and the EKC together provide a comprehensive theoretical framework to understand the complex relationship between CO_2 emissions and green productivity. While green productivity aims to improve resource efficiency and reduce environmental degradation, the Jevons Paradox suggests that increased efficiency may paradoxically lead to higher resource consumption as reduced costs and increased demand offset the initial environmental gains (Lange et al., 2021; Siami and Winter, 2021). This rebound effect may be more pronounced during economic growth, where advancements in green productivity spur greater production and energy use, potentially exacerbating environmental challenges (Fich et al., 2022). This effect, thus, highlights the need for policies to ensure efficiency gains lead to actual emissions reductions.

On the contrary, the traditional EKC introduces an inverted U-shaped relationship between economic development and environmental degradation, where early industrial growth increases CO_2 emissions, but as economies mature, higher income levels foster greater awareness of environmental issues, leading to stronger regulatory frameworks, increased investment in cleaner technologies, and a shift toward sustainable practices (Grossman and Krueger, 1995; Wang et al., 2024). According to the green productivity-context EKC frameworks, initial improvements in green productivity may contribute to higher emissions at first due to increased production and resource usage, but stringent environmental policies, such as higher pollution taxes and stricter regulations, alongside continuous technological innovation, can mitigate these effects, guiding economies toward lower emissions and sustainable growth. Zoaka et al. (2022) pointed out that the EKC suggests a turning point where rising income levels begin to improve environmental quality, whereas beyond this point, income growth leads to environmental degradation. These theories emphasize the need for targeted policies to balance efficiency, consumption, and environmental impacts.

2.2. Green Productivity and CO_2 Emissions

Numerous studies have examined the intricate dynamics between productivity, energy efficiency, and CO_2 emissions. Tzeremes (2020) highlighted nonlinear causal linkages between energy use, total factor productivity (TFP), and CO_2 emissions in G20 nations, revealing variations in the Environmental Kuznets Curve (EKC) across countries using time-varying Granger causality analysis. Alhassan's (2021) study is notable for its focus on sub-Saharan African (SSA) nations and the assessment of the impact of agricultural TFP on CO_2 emissions, validating the Jevons paradox but violating the EKC. This research underscores regional nuances, illuminating that increased agricultural TFP in SSA nations contributes to higher CO_2 emissions rather than mitigating them. Similarly, Liu et al.'s (2018) study on China exposes the paradoxical rebound effect, illustrating that energy efficiency improvements may inadvertently lead to increased energy consumption and environmental harm. The confirmation of the Jevons paradox, where technological progress leads to increased energy usage and environmental harm, challenges assumptions about the straightforward benefits of energy efficiency.

Zhong and Wang's (2021) spatial econometric model revealed that CO_2 emissions negatively spill over into forestry TFP, while forestry TFP positively spills over into CO_2 emissions, highlighting the need for policies to maximize TFP's environmental benefits while mitigating its unintended contributions to emissions and offering insights into regional policy coordination. Additionally, an inverted U-shaped EKC curve was found with an inflection point of 0.9395. Yang et al. (2022) extended the understanding of this relationship by exploring the mediation effects of industrial structure upgrades in Chinese provinces, revealing that industrial advancements can increase the reverse effect of green productivity on CO_2. Although green productivity improvements suppressed emissions in some areas, they caused adverse spatial spillovers on neighboring regions, underlining the need for balanced regional and national policies. Mukhtarov (2024) utilized the ARDL method to examine the impact of TFP on consumption-based CO_2 emissions. The findings indicate that TFP has a negative effect on CO_2 emissions, suggesting that enhancements in TFP contribute to emission reductions.

Hussain et al. (2022) examined the impact of green technology and environmental factors on green productivity in high-GDP countries. Their findings reveal that higher CO_2 emissions are associated with decreased green productivity, emphasizing the need for cleaner technologies and sustainable development policies to enhance environmental and economic outcomes. Ahmed (2012) investigated the impact of CO_2 intensity on productivity growth and found that incorporating CO_2 emissions into productivity models would lead to a significant decline in TFP growth, indicating that higher CO_2 intensity adversely affects green productivity. According to research by Rusiawan et al. (2015), integrating CO_2 emissions into TFP estimates results in a negative average growth rate of −1.83% annually, indicating that higher emissions are associated with lower GTFP. Napolitano et al. (2023) found that CO_2 emissions efficiency has a productivity-enhancing effects, but its impact on productivity varies across countries, with developed countries experiencing greater gains due to advances in technology and policies, while developing countries face limitations in achieving similar benefits.

The existing body of research on the relationship between CO_2 emissions and TFP presents a multifaceted and complex picture. However, several notable gaps and areas for further investigation can be identified. Firstly, future research is needed to address gaps in how TFP impacts CO_2 emissions across regions, as prior studies often focus on narrow, country-specific scopes without comparative analysis. Secondly, the complex and nonlinear relationship between TFP and CO_2 emissions necessitates further exploration, as studies reveal various patterns like the inverted U-shaped EKC or U-shaped EKC (or Jevons paradox) in different contexts.

3. MATERIALS AND METHODS

3.1. Data Description

Table 1 displays variables, indicator name, unit measurement and source of data. This study includes a 21-year sample span, from 2001 to 2021. The gathered data is then assessed employing E-views software. A series of panel data analyses is performed on four models. Models 1a and 2a represent developed country groups of CPTPP (Australia, Canada, Japan, New Zealand, and Singapore), while Models 1b and 2b represent developing country groups of CPTPP (Brunei, Chile, Malaysia, Mexico, Peru, and, Vietnam).

3.2. Methodology

3.2.1. Panel unit root tests

The unit root test must be applied to confirm the stationarity of the panel data for the entire variable group in this research prior to performing the cointegration test. To ascertain the variables' stationary properties in this investigation, the Fisher-ADF, LLC, and IPS tests will be carried out.

3.2.2. Panel autoregressive distributed lag model (ARDL)

The panel unit root test results show that the mix of I(0) and I(1) exists, but that no variable is I(2). This supports the adoption of the panel ARDL model (including Pooled Mean Group [PMG]), which is suitable for variables with the mix of I(0) and I(1). This model, as stressed by Sogah et al. (2024), is a newly developed cointegration technique capable of estimating the short- and long-run links between CO_2 emissions and their drivers in this study. Long-run linkage models for PMG are (1) and (2), as developed by Pesaran et al. (1999).

Table 1: Variables and source

Variables	Indicator name	Unit measurement	Source
Carbon dioxide-intensity emissions	CO_2	Metric tons per GDP	Global Carbon Atlas
Green total factor productivity	GRTFP	-	Calculated using data envelopment analysis (DEA) (The inputs used in calculating the ML index are labor, capital stock, fossil fuels, and low-carbon energy use, whereas the desired output is GDP and the undesired output is CO_2 intensity.)
Non-renewable energy	NRE	% equivalent primary energy	Our World in Data
Technology use	TU	Trade value (US$)	*UN Comtrade (High-tech machinery and equipment are chosen based on* the features of industries at varying technological levels*, l*aid out by (Soltanisehat et al., 2019).) [1]

1 High-tech machinery and equipment are characterized by advanced, rapidly evolving technology, complex electronics, and high R&D investment, emphasizing product design, specialized technical skills, and collaboration between companies and research institutions.

$$CO2_{i,t} = \mu_{1i} + \sum_{j=1}^{p} \lambda_{11i,j} CO2_{i,t-j} + \sum_{j=1}^{q} \delta_{11i,j} GRTFP_{i,t-j} + \sum_{j=1}^{q} \delta_{12i,j} GRTFP^2_{i,t-j} + \sum_{j=1}^{q} \delta_{13i,j} NRE_{i,t-j} + \varepsilon_{1i,t}$$

(Model 1) (1)

$$GRTFP_{i,t} = \mu_{2i} + \sum_{j=1}^{p} \lambda_{21i,j} GRTFP_{i,t-j} + \sum_{j=1}^{q} \delta_{21i,j} lnCO2_{i,t-j} + \sum_{j=1}^{q} \delta_{22i,j} lnTU_{i,t-j} + \varepsilon_{2i,t}$$

(Model 2) (2)

The short-run relationship with ECM:

$$\Delta CO2_{i,t} = \mu_{1i} + \varphi_{1i}(CO2_{i,t-1} - \lambda_{11} GRTFP_{i,t} - \lambda_{12} GRTFP^2_{i,t} - \lambda_{13} NRE_{i,t}) + \sum_{j=1}^{p} \lambda_{11i,j} CO2_{i,t-j} + \sum_{j=1}^{q} \delta_{11i,j} GRTFP_{i,t-j} + \sum_{j=1}^{q} \delta_{12i,j} GRTFP^2_{i,t-j} + \sum_{j=1}^{q} \delta_{13i,j} NRE_{i,t-j} + \mu_{1i,t}$$

(Model 1) (3)

$$\Delta GRTFP_{i,t} = \mu_{2i} + \varphi_{2i}(GRTFP_{i,t-1} - \lambda_{21} lnCO2_{i,t} - \lambda_{22} lnTU_{i,t}) + \sum_{j=1}^{p} \lambda_{21i,j} GRTFP_{i,t-j} + \sum_{j=1}^{q} \delta_{21i,j} lnCO2_{i,t-j} + \sum_{j=1}^{q} \delta_{22i,j} lnTU_{i,t-j} + \mu_{2i,t}$$

(Model 2) (4)

Where j = the optimum time lag and μ_i = a fixed effect.

3.2.3. Panel fully modified OLS analysis (FMOLS) test

FMOLS is applied as a part of robustness check. FMOLS has high viability to access cointegration regression in panel analysis (Stock and Watson, 1993).

Since the dataset of this study includes a mix of I(0) and I(1) variables, the PMG-ARDL approach has been applied to capture both short-run dynamics and long-run relationships. However, FMOLS remains suitable for validating the long-run estimates, as it corrects for endogeneity and serial correlation in cointegrated panels (Phillips, 1995). Given that Models 1 have T = 21 and N = 5 and Models 2 have T = 21 and N = 6, FMOLS can provide unbiased long-run coefficients across small-sized samples, complementing the ARDL results. While ARDL accounts for dynamic adjustments, FMOLS strengthens the robustness of the findings by estimating the long-run equilibrium relationships under different econometric assumptions.

3.2.4. Panel threshold

Accordingly, this study hypothesizes that green productivity significantly affects CO_2 intensity, and simultaneously, CO_2 intensity significantly affects green productivity. This impact is assumed to be nonlinear and to have a threshold effect, with levels of technology use as the key variable. A threshold effect model is used to investigate the function between the two variables and the threshold effect (Liu et al., 2020). This study uses a panel threshold model developed by (Hansen, 1999). The model has the following basic structure:

$$CO2_{i,t} = \mu_{1i} + \beta_{11} GRTFP_{i,t} I(TU_{i,t} \leq \gamma) + \beta_{12} GRTFP_{i,t} I(TU_{i,t} \geq \gamma) + \varepsilon_{1i,t}$$

(Model 1) (5)

$$GRTFP_{i,t} = \mu_{2i} + \beta_{21} lnCO2_{i,t} I(lnTU_{i,t} \leq \gamma) + \beta_{22} lnCO2_{i,t} I(lnTU_{i,t} \geq \gamma) + \varepsilon_{2i,t}$$

(Model 2) (6)

Where threshold variable, TUi,t is levels of technology use; γ represents the projected threshold value; and different regression slopes, β1 and β2, can be used to distinguish the regimes.

Technology use is chosen as the threshold variable for Models 1 and 2 due to its critical role in shaping the relationship between green productivity and CO_2 intensity. In Model 1, technology determines how effectively green productivity reduces emissions, with low technology use failing to offset emissions growth and high technology use aligning productivity gains with emissions reductions. In Model 2, technology impacts the ability to overcome inefficiencies and costs associated with high CO_2 intensity, with higher levels enabling cleaner processes and boosting green productivity. Technology also captures non-linear effects, distinguishing its influence across low, moderate, and high use, making it essential for understanding the balance between economic growth and sustainability.

4. EMPIRICAL RESULTS AND DISCUSSIONS

4.1. Panel Unit Root Tests

Table 2 presents the results of the LLC, IPS, and ADF-Fisher unit root tests, both at level and first difference in two types of models, which are the intercept model and intercept and trend model of the values. For Model 1a, in the LLC test, at the level, all variables are insignificant, but at the first difference, all variables are significant. This means that at the level, all variables are non-stationary, whereas at the first difference, all variables are stationary. CO_2, GRTFP, GRTFP^2, and NRE are integrated of order 1, I(1) in the LLC test. Both the IPS and ADF-Fisher tests yield similar results. In both tests, GRTFP and GRTFP^2 are I(0), while CO_2 is I(1), and NRE is I(1) in the IPS test but I(0) in the ADF-Fisher test.

For Model 1b, in all tests, CO_2, GRTFP, and GRTFP^2 are I(0), while NRE is I(1). For Model 2a, GRTFP is I(0) in the IPS and ADF-Fisher tests and I(1) in the LLC test. In all tests performed, LTU is I(0), whilst LCO_2 is I(1). For Model 2b, In the LLC test, all variables are I(0), while in the IPS and ADF-Fisher tests, GRTFP and LCO_2 are I(0), and LTU is I(1).

The panel unit root test shows a mixture of I(0) and I(1), indicating that an ARDL test should be performed.

4.2. Panel ARDL Test and FMOLS Test

The outcomes of the PMG method is shown in Table 3 for estimating the coefficients in the short and long runs. According to the akaike information criterion (AIC) tests, the optimal lag (2,3,3,3) of the PMG estimator is selected for Model 1a, (3,3,3,3) for Model 1b, (6,2,2) for Model 2a, and (5,2,2) for Model 2b.

In PMG results, Models 1a and 1b confirm the null hypotheses' rejection for all variables in the long-run estimations, demonstrating the existence of their relationship with CO_2 in the long run. The ECT coefficient of Model 1a is −0.0439, while that of Model 1b is −0.1474. This indicates that Models 1a and 1b, which have prior year disequilibrium of about 4.39% and 14.74%, respectively, will be adjusted in subsequent years, of which approximately 22.779 and 6.7843 years are required to correct the long-run linkage between the CO_2 drivers and CO_2, respectively. Since the squared variables for Models 1a and 1b have positive coefficients, there are U-shaped productivity curves. In PMG results, in the long-run estimations, Models 2a and 2b reject the null hypotheses for CO_2 and TU. The ECT coefficients of Models 2a and 2b in PMG are −0.7656 and −0.3812, respectively.

Using Table 4 as a basis, the FMOLS equation for Model 1a and 1b can be expressed in the following way:

$$CO_2=2.574GRTFP^2-5.0994GRTFP-0.1062NRE \quad (7)$$

$$CO_2=0.5154GRTFP^2-1.004GRTFP+2.8545NRE \quad (8)$$

The FMOLS test results in Model 1a reveal significant negative coefficient for GRTFP and NRE and significant positive coefficient for GRTFP^2. In Model 1b, GRTFP^2 and NRE have a significant positive coefficient, while GRTFP has a significant negative coefficient. In this study, the developed and developing countries exhibit Jevons paradox-compliant U-shaped productivity curve because GRTFP^2 has a positive coefficient.

$$GRTFP=-0.1781lnCO_2+0.0637lnTU \quad (9)$$

$$GRTFP=-0.1491lnCO_2+0.0012lnTU \quad (10)$$

The FMOLS equation for Model 2a and 2b, which is based on Table 4, is as shown in:

Additionally, in both Models 2a and 2b, CO_2 has a significant negative impact on GRTFP, whereas TU has a significant positive effect on GRTFP.

Table 2: Results of panel unit root tests

	Level (trend and intercept)			First difference (intercept)		
	LLC	IPS	ADF-fisher	LLC	IPS	ADF-fisher
Developed countries (model 1a)						
CO_2	0.2495	−1.0725	13.4451	−1.4869*	−4.6646***	40.6397***
GRTFP	1.4529	−2.2762**	21.5932**	−2.3006**	−6.4044***	55.1963***
$GRTFP^2$	0.1500	−2.1524**	20.7921**	−2.6745***	−6.4526***	55.6311***
NRE	2.0169	0.7016	16.8153*	−1.8405**	−4.0487***	44.0992***
Developing countries (Model 1b)						
CO_2	−5.1780***	−3.1292***	31.3982***	−8.9661***	−7.7590***	73.8684***
GRTFP	−3.9387***	−4.1718***	38.4096***	−10.9095***	−11.8788***	113.3337***
$GRTFP^2$	−4.1952***	−4.1658***	38.2836***	−11.0860***	−11.8168***	112.7492***
NRE	0.0422	2.5842	6.4377	−5.4769***	−4.8962***	46.5782***
Developed countries (Model 2a)						
GRTFP	1.4529	−2.2762**	21.5932**	−2.3006**	−6.4044***	55.1963***
LCO_2	−0.1837	−1.2681	15.2557	−1.8507**	−4.5957***	40.5634***
LTU	−4.1421***	−2.2348**	20.8704**	−7.5546***	−6.7085***	57.9032***
Developed countries (Model 2b)						
GRTFP	−3.9387***	−4.1718***	38.4096***	−10.9095***	−11.8788***	113.3337***
LCO_2	−4.6620***	−2.8369***	30.3978***	−8.6644***	−7.4298***	70.1513***
LTU	−1.3925*	0.5516	8.9241	−4.0728***	−5.0551***	48.0614***

The asterisk (***) signifies the significance level of 1%, (**) the level of 5%, and (*) the level of 10%

Table 3: Results of panel ARDL test

PMG	Developed countries (model 1a)	Developing countries (model 1b)
GRTFP	26.9729***	−7.1425**
GRTFPSQ	13.2975***	3.6189**
NRE	0.0045***	0.0099***
Δ*GRTFP*	−0.2446	0.1567
Δ*GRTFPSQ*	0.0933	−0.1552
Δ*NRE*	−0.1390	1.5692
ECT(−1)	−0.0439***	−0.1474***
PMG	**Developed countries (model 2a)**	**Developing countries (model 2b)**
LCO_2	−0.0632***	−0.0866***
LTU	0.0257***	0.0254**
ΔLCO_2	0.3881	0.0831
Δ*LTU*	0.1646**	0.1181
ECT(−1)	−0.7656**	−0.3812***

The asterisk (***) signifies the significance level of 1%, (**) the level of 5%, and (*) the level of 10%

Table 4: Results of FMOLS test

FMOLS	Developed countries (model 1a)	Developing countries (model 1b)
GRTFP	−5.0994*	−1.0040**
GRTFPSQ	2.5740*	0.5154**
NRE	−0.1062**	2.8545***
FMOLS	**Developed countries (Model 2a)**	**Developing countries (Model 2b)**
LCO_2	−0.1781***	−0.1491**
LTU	0.0637*	0.0012*

The asterisk (***) signifies the significance level of 1%, (**) the level of 5%, and (*) the level of 10%

4.2.1. Discussions of major findings for panel ARDL and FMOLS

4.2.1.1. The relationship between green productivity and CO_2 emissions and evidence

In Model 1a, both panel ARDL reveals a significantly positive relationship between GRTFP and $GRTFP^2$ with CO_2. However, as shown by the panel ARDL test in Model 1b, GRTFP and $GRTFP^2$ exhibit negative and positive linkages with CO_2, respectively, while FMOLS results in Models 1a and 1b indicate similar linkages. These findings align with theoretical relationship (Jevons paradox) and prior research Amri et al. (2019), Liu et al. (2018) and Loganathan et al. (2020), implying a U-shaped curve due to the positive sign of $GRTFP^2$.

If both CPTPP developed and developing members exhibit a U-shaped productivity curve in relation to green productivity and CO_2-intensity emissions, it would indicate a shared pattern where initial improvements in green productivity lead to decreased CO_2-intensity emissions, followed by an increase in emissions as green productivity reaches higher levels, as elucidated by Kalaitzidakis et al. (2018), Mushafiq and Prusak (2023) and Nica et al. (2025). This trend aligns with the Jevons Paradox but contradicts the EKC, which suggests that green productivity gains may increase emissions as consumers will in turn increase production and resource use due to increased output per input. Stringent policies and technological innovation can, nevertheless, mitigate these effects, steering economies toward lower emissions and sustainable growth (Ahmed, 2020; Mihai et al., 2023). However, the underlying factors contributing to this U-shaped curve differ between developed and developing countries, reflecting their distinct economic structures, technological capacities, and regulatory environments (Napolitano et al., 2023; Tawiah et al., 2021). These differences were analysed individually to narrow down the scope of influencing factors and draw more accurate conclusions on the CO_2-green productivity relationship.

The stronger GRTFP and $GRTFP^2$ coefficients and a smaller NRE positive impact suggest that developed CPTPP members experience a more pronounced downward slope in the U-shaped curve due to their advanced technology, stricter regulation, and diversified economic structure. Initially, green productivity improvements lead to high CO_2 intensity due to intensified industrial activities and higher consumption driven by economic growth. As these countries reach a certain level of affluence, green productivity improvements eventually reduce CO_2 intensity as technological advancements, stricter environmental regulations, and economic diversification offset the initial high emissions. Developed CPTPP members leverage advanced technologies such as renewable energy systems, smart grids, and energy-efficient processes to enhance efficiency and minimize waste—all of which contribute to improving green productivity, which lowers CO_2 intensity (Jahanger et al., 2023). Stricter regulations, such as carbon pricing and mandatory energy standards, compel industries to adopt greener practices, thereby increasing green productivity and consequently further enforcing CO_2 emission reductions while driving green technology innovation (Ahmed, 2020). Furthermore, diversified economic structures in developed CPTPP members reduce reliance on energy-intensive industries, improving efficiency and strengthening green productivity's ability to lower CO_2 intensity (Yang et al., 2022). Additionally, ensuing higher environmental awareness promotes demand for sustainable practices, creating a positive feedback loop, where green productivity gains are both driven by and contribute to sustainability efforts (Cheng et al., 2023). These factors help decouple economic growth from CO_2-intensity emissions, leading to a decline in emissions even as green productivity continues to rise.

In contrast, smaller GRTFP and $GRTFP^2$ coefficients and a greater NRE positive impact indicate that developing CPTPP members face a slower downward shift in the U-shaped curve. In developing CPTPP countries, economic growth-driven industrialization and energy reliance tend to increase CO_2 intensity. They thus must balance the dual goals of industrialization and economic catch-up with the need to reduce CO_2 emissions (Avenyo and Tregenna, 2022). However, green productivity has a slower impact on reducing CO_2 intensity due to weaker technology adoption, regulations, and dependence on energy-intensive industries. Limited access to advanced technologies hinders these countries' ability to implement sustainable and energy-efficient practices, thereby decelerating green productivity gains and subsequent emissions reductions (Nyangchak, 2022). Weaker environmental regulations and reliance on energy-intensive industries exacerbate the issue, as they weaken incentives for green practices, attract pollution-intensive foreign businesses, and hampers the transition to greener alternatives, resulting in a slower alignment of green productivity improvements with subsequent emissions reductions (Wang et al., 2023). These factors collectively hinder efforts to align with global climate goals and reduce CO_2-intensity emissions. The decline in emissions thus occurs as these countries gradually overcome barriers to technological progress and implement more robust environmental policies.

In both country groups, despite an initial fall in emissions, the productivity curve eventually rose, highlighting the challenge of balancing economic growth with the sustainability posed by rebound effects. In developed countries, the rebound effect occurs when energy efficiency improvements lead to higher overall consumption, as cost savings in affluent societies often drive increased production and usage despite more efficient and cheaper production, thereby reducing the environmental benefits of green technologies and sustainable practices (Adua et al., 2021; Font Vivanco et al., 2016; Freeman et al., 2016). In developing countries, improved energy efficiency generally reduces energy costs, thereby increasing energy use, with the resulting rebound effect being more pronounced because of unmet energy demand, rapid economic growth (de la Rue du Can et al., 2015), and weaker environmental regulations (Wang et al., 2023), further complicating efforts to reduce emissions. To counteract this impact, reliance on efficiency policies alone is insufficient to ensure that efficiency gains translate into absolute reductions in total energy consumption and emissions. Therefore, it is essential to implement complementary measures, such as carbon pricing and regulatory interventions, to curb overconsumption and support sustainable economic development (Braungardt et al., 2021; Freebairn, 2020; Xu and Yang, 2024).

In short, both developed and developing CPTPP members share a U-shaped CO_2 intensity-green productivity relationship, but their pathways differ. Developed nations are better positioned to decouple economic growth from emissions, benefiting from advanced technologies and strong regulations, whereas developing nations require international collaboration, financial support, and capacity-building initiatives to overcome barriers and align green productivity with lower CO_2 intensity, enabling a more sustainable growth trajectory.

4.2.1.2. The relationship between CO_2 emissions and green productivity and evidence

In Models 2a and 2b, a negative link between CO_2 and GRTFP was observed in panel ARDL test, a pattern supported by various studies (Ahmed, 2012; Hussain et al., 2022; Rusiawan et al., 2015).

According to the Jevons Paradox, efficiency gains from green productivity, such as improved energy efficiency, can increase consumption and CO_2 emissions, disrupting the balance between growth and sustainability and limiting productivity improvements in turn (Lange et al., 2021; Siami and Winter, 2021). The relationship between CO_2 intensity and green productivity forms a critical feedback loop because inefficiencies associated with high CO_2 intensity, such as inefficient energy use and resource management, environmental costs from pollution control, health impacts and resource depletion, regulatory costs, reliance on outdated technologies, and low market demand for sustainable practices, will reduce the economic and environmental benefits of green productivity improvements by increasing costs and limiting efficiency gains (Ekins and Zenghelis, 2021; Ian et al., 2014; Wang and Yan, 2022). Conversely, continuance improvements in green productivity, through efficiency gains and sustainable practices, can ultimately reduce CO_2 intensity, highlighting the interdependence of economic output and environmental impact. As efficiency improvements driven by CO_2 reduction efforts become the norm and standard practice, factors like market saturation, regulations, and consumer shifts stabilize consumption, embedding sustainability into the economy and increasing green productivity through emissions reductions, energy savings, resource efficiency, job creation, and green technology development (Intergovernmental Panel on Climate Change (IPCC), 2023; Niu et al., 2024; Wang et al., 2024; Wu and Yu, 2025). In short, reducing CO_2 intensity is essential to improving green productivity by minimizing emissions-related inefficiencies and supporting sustainable economic output through advanced technologies, policies, and cleaner practices. Growth in carbon productivity is critical to economic performance, as it typically driven by lower resource and energy intensity and cleaner energy (Wu and Yao, 2023).

Both developed and developing countries share underlying mechanisms—technology, regulation, economics, and market demand—that govern the interplay between CO_2 intensity and green productivity. However, the scope and nature of these mechanisms differ based on each group's context, influencing their ability to adapt to inefficiencies associated with high CO_2 levels by mitigating the negative impact of CO_2 intensity on green productivity (Napolitano et al., 2023; Tawiah et al., 2021). This adaptability will influence the feasibility of sustainable practices in terms of barriers to CO_2 reduction in these country groups. This study indicates that developed CPTPP members experience a lesser reduction in green productivity due to high CO_2 intensity compared to developing members as reflected in the coefficients of LCO_2. For developed countries, the coefficient is −0.0632, while for developing countries, it is −0.0866, indicating a stronger negative impact of CO_2 intensity on green productivity in developing members. This suggests that developed countries are better equipped to manage and reduce CO_2 intensity, strengthening the link between green productivity gains and emissions reductions, while developing countries face greater barriers to this alignment (Deng et al., 2024; Tawiah et al., 2021).

In developed CPTPP members, CO_2 intensity has a reduced negative impact on green productivity due to advanced resources, greater access to clean technologies, stricter environmental regulations, diversified economies, and higher consumer demand for sustainability (Degirmenci et al., 2024). These factors enable these countries to offset the negative effects of CO_2 intensity-induced inefficiency on green productivity. For instance, a better technological landscape and substantial R&D investment accelerate the adoption of innovative solutions, such as low-carbon technologies and energy-efficient systems, reducing emissions while maintaining or enhancing productivity (Eid et al., 2024). Strict environmental regulations, despite incurring short-term costs, drive long-term green productivity by encouraging cleaner technologies, with developed countries better equipped to comply due to rapid technological innovation, financial resources to absorb regulatory costs, and effective environmental and public health systems to control environmental costs (De Santis et al., 2021). Diversified economies also help mitigate the impact of CO_2 intensity by reducing reliance on high-emission industries, enabling a smoother transition to greener practices without significant economic disruption (Marra et al., 2024). Additionally, strong consumer and investor demand for sustainable products incentivizes businesses to adopt eco-friendly practices, making sustainability a competitive advantage, further lessening the negative impact of CO_2 intensity on green productivity (Yang and Roh, 2019). However, challenges remain in sectors like heavy industry, where high carbon footprints and slower progress necessitate targeted policy interventions to reduce the adverse effects of CO_2 intensity.

In contrast, developing CPTPP members, reliant on energy-intensive industries and constrained by limited resources, face significant challenges in reducing CO_2 emissions, resulting in a more pronounced negative impact on green productivity due to limited technology access, weaker regulations, and low consumer demand for sustainability, which are difficult to address without external support or investment (Shen et al., 2018). Limited access to advanced technologies, lower R&D investment, and high initial costs of transitioning to greener technologies restrict the adoption of energy-efficient systems, making it harder to counteract the inefficiencies caused by high CO_2 emissions (Seetharaman et al., 2019). However, with international support, these nations can leapfrog to sustainable solutions. Weaker regulatory frameworks fail to incentivize sustainable practices, allowing CO_2 intensity to persist and impede green productivity improvements. Strengthening regulations could improve green productivity, but this often requires balancing environmental priorities with economic development needs (Liu et al., 2024). Additionally, lower consumer demand for sustainable products, driven by affordability and short-term economic gains, makes alignment challenging. However, international demand for eco-labeled exports presents opportunities for greener practices. Domestic and international demands are therefore crucial for industry efficiency improvements (Shen et al., 2018). Consequently, the pronounced negative impact of CO_2 intensity delays the downward shift in the U-shaped curve, underscoring the need for targeted support, such as technology transfer and stronger policy frameworks, to alleviate these challenges.

The effectiveness and feasibility of sustainable practices are higher in developed CPTPP members due to their ability to mitigate CO_2 intensity's impact on green productivity through advanced technologies, robust policies, and diversified economies. In contrast, developing members face greater challenges but can improve effectiveness and feasibility with targeted external support and stronger domestic policies. Addressing these disparities is essential for achieving regional sustainability goals and reducing the negative effects of CO_2 intensity across all CPTPP members.

4.2.1.3. The relationship between non-renewable energy use and CO_2 emissions and evidence

According to the panel ARDL results (cited due to low significance level), both Models 1a and 1b indicate that NRE has a significant positive impact on CO_2 intensity, which can be attributed to the carbon-rich nature of fossil fuels. The positive impact of NRE on CO_2 intensity varies between developed and developing CPTPP members, depending on their energy profiles and economic contexts. In developed countries, NRE has a smaller positive impact on CO_2 intensity, likely due to advanced technologies like carbon capture (Eldardiry and Habib, 2018), diversified energy portfolios (Gozgor and Paramati, 2022), and stricter environmental policies that mitigate emissions despite fossil fuel use. Conversely, in developing countries, NRE has a greater positive impact on CO_2 intensity, reflecting reliance on fossil fuels, outdated industrial processes, and weaker regulatory frameworks. This contrast underscores the need for technological and policy support to help developing members transition to cleaner energy systems.

4.2.1.4. The relationship between technology use and green productivity and evidence

Models 2a and 2b demonstrate that there is a positive link between TU and GRTFP in panel ARDL and FMOLS tests. Technological innovation drives green productivity by enhancing efficiency and reducing environmental impact. Developed countries outperform developing nations in green productivity due to greater R&D investments, advanced infrastructure, and stronger policies that incentivize technology adoption. Furthermore, higher education levels and environmental awareness in developed nations support sustainable practices, including energy efficiency standards, carbon pricing mechanisms, and comprehensive waste management systems, further advancing their green productivity through triggering technologies (World Bank, 2010; Zhang and Li, 2023).

4.3. Panel Threshold Model

As illustrated in Table 5, panel threshold model reveals the relationship between GRTFP and CO_2 when TU is considered a threshold variable. In Model 1a, $GRTFP^2$ has positive coefficients at all thresholds, confirming U-shaped curves in developed countries. When the value of TU is below the threshold (TU < US\$28b), indicating low technology use, GRTFP has a moderate positive impact on CO_2 (β_{12} = 1.4655), with a 1-unit rise in GRTFP resulting in a 1.4655-unit rise in CO_2. This is because low efficiency gains fail to counteract rebound effects, in which a lower input per output leads to a higher usage of resources and the consumption of lower-cost products, limiting the impact of sustainability and mitigation measures on CO_2 emissions (Berner et al., 2022). When the value of TU is between the thresholds (US\$28b ≤ TU < US\$94b), with moderate technology use, the positive impact increases (β_{22} = 2.1632) due to stronger rebound effects brought about by technological progress and efficiency-enhancing measures (Wang et al., 2018). When the value of TU exceeds or equals the threshold (TU ≥ US\$94b), demonstrating high technology use, the impact decreases (β_{32} = 1.5622) as sustainability and mitigation measures attenuate the rebound effect, thereby increasing efficiency and reducing emissions (Amjadi et al., 2022; Du et al., 2023)

Table 5: Results of panel threshold model

Developed countries (Model 1a)		**Developing countries (Model 1b)**	
GRTFP (*TU*<US\$28b) (Low *TU*)	1.4655***	*GRTFP* (*TU*<US\$31b) (Low *TU*)	0.2588**
GRTFP (US\$28b≤*TU*<US\$94b) (Moderate *TU*)	2.1632***	*GRTFP* (US\$31b≤*TU*<US\$110b) (Moderate *TU*)	0.4497**
GRTFP (*TU*≥*U*S\$94b) (High *TU*)	1.5622***	*GRTFP* (*TU*≥*U*S\$110b) (High *TU*)	0.4945*
$GRTFP^2$ (*TU*<US\$28b)(Low *TU*)	0.7394**	$GRTFP^2$ (*TU*<US\$31b) (Low *TU*)	0.1691**
$GRTFP^2$ (US\$28b≤*TU*<US\$94b) (Moderate *TU*)	1.0680***	$GRTFP^2$ (US\$31b≤*TU*<US\$110b) (Moderate *TU*)	0.2553
$GRTFP^2$ (*TU*≥*U*S\$94b)(High *TU*)	0.6663***	$GRTFP^2$ (*TU*≥*U*S\$110b) (High *TU*)	0.3720
NRE	−0.0075***	*NRE*	0.0017***
Developed countries (model 2a)		**Developing countries (model 2b)**	
LCO_2(*LTU*<US\$24.864) (Low *TU*)	−0.0838***	LCO_2(*LTU*<US\$22.297) (Low *TU*)	−0.1091***
LCO_2(*LTU*≥*U*S\$24.864) (High *TU*)	−0.0170	LCO_2(US\$22.297≤*LTU*<US\$24.731) (Moderate *TU*)	−0.0309
		LCO_2(*LTU*≥*U*S\$24.731) (High *TU*)	0.0392
LTU	0.0387***	*LTU*	0.0410***

The asterisk (***) signifies the significance level of 1%, (**) the level of 5%, and (*) the level of 10%

In Model 1b, $GRTFP^2$ is positive at low thresholds (TU < US\$31b), confirming U-shaped curves in developing countries. When the value of TU is below the threshold (TU < US\$31b), representing low technology use, GRTFP has a smaller positive impact on CO_2 (β_{12} = 0.2588), with a 1-unit rise in GRTFP translating to a 0.2588-unit rise in CO_2. This is driven by transitions away from long-standing, heavily relied-upon inefficient processes, allowing these countries to leapfrog directly to cleaner technologies and skip carbon-intensive development stages that many developed countries experienced (Iizuka, 2015). However, positive GRTFP impact increases (β_{22} = 0.4497) at moderate technology use, when the value of TU is between the thresholds (US\$31b ≤ TU < US\$110b) and increases again (β_{32} = 0.4945) at high technology use, when the value of TU exceeds or equals the threshold (TU ≥ US\$110b), reflecting stronger rebound effects. Although efficiency gains will initially result in only a small increase in emissions, shifts in consumption and economic growth offset beneficial effects of efficiency gains, necessitating continuous technological adoption to manage rebound effects (Amjadi et al., 2022; Berner et al., 2022).

In Models 2a and 2b, when the value of LTU is below the threshold (LTU < US\$24.864 and US\$22.297, respectively), low technology use results in a negative impact of LCO_2 on GRTFP (β1 = −0.0838 and −0.1091, respectively) in both country groups, with a 1-unit rise in LCO_2 leading to respective −0.0838 and 0.1091 decreases in GRTFP, due to poor resource management, outdated production processes, and limited access to cleaner technologies (Albrizio et al., 2017; Prigozhin et al., 2023). This implies the barriers to reducing CO_2 emissions are higher, and green productivity is compromised since these country groups have less adaptability to inefficiencies brought on by high CO_2 levels when technology use is limited, suggesting sustainable practices are less effective and feasible. At medium and high thresholds, CO_2 intensity and green productivity exhibit a linear relationship. In developed countries, higher technology use reduces the negative impact of CO_2 intensity on green productivity, while in developing nations, advanced technologies turn this negative impact positive, allowing emissions reductions to enhance productivity. However, in developed countries, entrenched energy-intensive industries and economic growth can resist positive technology-led changes, limiting green productivity gains (Nabernegg et al., 2017). Since the negative impact of CO_2 intensity on green productivity is decremental, this means that sustainable practices and technologies are effective and feasible in both country members, but their effectiveness and feasibility differ between the two country groups.

5. CONCLUSION AND RECOMMENDATION

CO_2 emissions and green productivity vary across developed and developing CPTPP countries due to differences in historical emissions, economic development stages, and policy approaches. This study has achieved its objectives by identifying long-run relationships between variables through panel ARDL and FMOLS analysis, and by revealing the non-linear impacts of specific factors (variables) on outcomes through panel threshold analysis. Both developed and developing CPTPP members exhibit a Jevons Paradox-compliant U-shaped productivity curve or U-shaped EKC curve, and experience CO_2-induced negative impacts on green productivity, emphasizing the need for robust emission reduction policies. These findings underscore the urgency of addressing climate change and advancing sustainable development in line with SDG 13.

One of the strategies is shifting towards deep decarbonisation, which involves adopting cleaner energy sources, improving energy efficiency, and transforming production processes to minimize CO_2 emissions. Developed nations should focus on large-scale renewable energy projects, advanced energy storage, and efficiency upgrades in infrastructure and industries, while developing nations should adopt decentralized renewable systems and energy management, supported by international aid to improve energy access and affordability and grid reliability. Moreover, leveraging promising technologies such as hydrogen fuel cells for clean energy storage and transportation, electric vehicles to reduce reliance on fossil fuels in the automotive sector, and carbon capture, utilization, and storage (CCUS) to mitigate industrial CO_2 emissions, alongside substantial investments in related R&D, is essential for achieving significant emission reductions. These technologies require significant investment, making it more feasible for developed nations, while developing countries can leapfrog these technologies with international support in investment, technology transfer, and capacity building. Apart from these measures, exploring the potential of natural and artificial carbon sinks and intensifying them has become crucial to combating increasing CO_2 emissions. Developed countries can lead in deploying artificial sinks, while developing nations can focus on preserving and expanding natural carbon sinks.

To combat the Jevons Paradox and CO_2-induced negative green productivity, policies must ensure that efficiency gains do not lead to increased resource consumption. This can be accomplished using environmental policy tools, such as economic instruments like carbon taxes and subsidies, regulatory instruments like emission standards, and voluntary measures like eco-labeling and public-private partnerships. Additionally, promoting climate awareness and education can encourage responsible consumption and sustainable behavior changes. To bridge the green productivity gap between developed and developing CPTPP members, it is critical that the CPTPP's environmental provisions, particularly Chapter 20, offer a framework for climate action through cooperative strategies. These provisions can drive technology transfer, set regional emissions benchmarks, and enable joint sustainable investments, with developed members supporting developing nations through shared best practices, R&D funding, and standardized green productivity goals. Moreover, establishing peer review and monitoring mechanisms under CPTPP is essential to enhance accountability and ensure compliance with environmental goals. Member nations can strengthen the relationship between green productivity and emissions reductions by adopting these targeted strategies and leveraging the CPTPP's environmental provisions. This ensures that economic growth aligns with global sustainability goals, promoting balanced development across the region.

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REFERENCES

Adua, L., Clark, B., York, R. (2021), The ineffectiveness of efficiency: The paradoxical effects of state policy on energy consumption in the United States. Energy Research and Social Science, 71, 101806.

Ahmed, E.M. (2012), Green TFP intensity impact on sustainable East Asian productivity growth. Economic Analysis and Policy, 42(1), 67-78.

Ahmed, K. (2020), Environmental policy stringency, related technological change and emissions inventory in 20 OECD countries. Journal of Environmental Management, 274, 111209.

Albrizio, S., Kozluk, T., Zipperer, V. (2017), Environmental policies and productivity growth: Evidence across industries and firms. Journal of Environmental Economics and Management, 81, 209-226.

Alhassan, H. (2021), The effect of agricultural total factor productivity on environmental degradation in sub-Saharan Africa. Scientific African, 12, e00740.

Amjadi, G., Lundgren, T., Zhou, W. (2022), A dynamic analysis of industrial energy efficiency and the rebound effect: implications for carbon emissions and sustainability. Energy Efficiency, 15(7), 54.

Amri, F., Zaied, Y.B., Lahouel, B.B. (2019), ICT, total factor productivity, and carbon dioxide emissions in Tunisia. Technological Forecasting and Social Change, 146, 212-217.

Avenyo, E.K., Tregenna, F. (2022), Greening manufacturing: Technology intensity and carbon dioxide emissions in developing countries. Applied Energy, 324, 119726.

Berner, A., Bruns, S., Moneta, A., Stern, D.I. (2022), Do energy efficiency improvements reduce energy use? Empirical evidence on the economy-wide rebound effect in Europe and the United States. Energy Economics, 110, 105939.

Braungardt, S., Bürger, V., Köhler, B. (2021), Carbon pricing and complementary policies-consistency of the policy mix for decarbonizing buildings in Germany. Energies, 14(21), 7143.

Cheng, C., Ahmad, S.F., Irshad, M., Alsanie, G., Khan, Y., Ahmad (Ayassrah), A.Y.A.B., Aleemi, A.R. (2023), Impact of green process innovation and productivity on sustainability: The moderating role of environmental awareness. Sustainability, 15(17), 12945.

de Angelis, E.M., Di Giacomo, M., Vannoni, D. (2019), Climate change and economic growth: The role of environmental policy stringency. Sustainability, 11(8), 2273.

de la Rue du Can, S., McNeil, M. A., & Leventis, G. (2015). Rebound Effects in the Context of Developing Country Efficiency. Available from https://www.osti.gov/servlets/purl/1377400

de Nicola, F., Mattoo, A., Tran, T.T. (2025), Green Technologies: Decarbonizing Development in East Asia and Pacific. World Bank. Available from: https://hdl.handle.net/10986/43008

De Santis, R., Esposito, P., Lasinio, C.J. (2021), Environmental regulation and productivity growth: Main policy challenges. International Economics, 165, 264-277.

Degirmenci, T., Sofuoglu, E., Aydin, M., Adebayo, T.S. (2024), The role of energy intensity, green energy transition, and environmental policy stringency on environmental sustainability in G7 countries. Clean Technologies and Environmental Policy, 27, 2981-2993.

Deng, W., Meng, T., Kharuddin, S., Ashhari, Z.M., Zhou, J. (2024), The impact of renewable energy consumption, green technology innovation, and FDI on carbon emission intensity: Evidence from developed and developing countries. Journal of Cleaner Production, 483, 144310.

Ding, Q., Khattak, S., & Ahmad, M. (2021). Towards sustainable production and consumption: Assessing the impact of energy productivity and eco-innovation on consumption-based carbon dioxide emissions (CCO2) in G-7 nations. Sustainable Production and Consumption, 27, 254-268.

Du, J., Chen, Y., Huang, Y. (2018), A modified Malmquist-Luenberger productivity index: Assessing environmental productivity performance in China. European Journal of Operational Research, 269(1), 171-187.

Du, K., Liu, X., Zhao, C. (2023), Environmental regulation mitigates energy rebound effect. Energy Economics, 125, 106851.

Eid, A. G., Mrabet, Z., & Alsamara, M. (2024). Assessing the impact of energy R&D on green growth in OECD countries: a CS-ARDL analysis. Environmental Economics and Policy Studies, 1-40.

Ekins, P., Zenghelis, D. (2021), The costs and benefits of environmental sustainability. Sustainability Science, 16(3), 949-965.

Eldardiry, H., Habib, E. (2018), Carbon capture and sequestration in power generation: Review of impacts and opportunities for water sustainability. Energy, Sustainability and Society, 8(1), 6.

Fan, L., Wang, D. (2024), Natural resource efficiency and green economy: Key takeaways on clean energy, globalization, and innovations in BRICS countries. Resources Policy, 88, 104382.

Fernandes, C.I., Veiga, P.M., Ferreira, J.J.M., Hughes, M. (2021), Green growth versus economic growth: Do sustainable technology transfer and innovations lead to an imperfect choice? Business Strategy and the Environment, 30(4), 2021-2037.

Fich, L.E., Viola, S., Bentsen, N.S. (2022), Jevons paradox: Sustainable development goals and energy rebound in complex economic systems. Energies, 15(16), 5821.

Font Vivanco, D., Kemp, R., van der Voet, E. (2016), How to deal with the rebound effect? A policy-oriented approach. Energy Policy, 94, 114-125.

Freebairn, J. (2020), A portfolio policy package to reduce greenhouse gas emissions. Atmosphere, 11(4), 337.

Freeman, R., Yearworth, M., & Preist, C. (2016). Revisiting Jevons' Paradox with System Dynamics: Systemic Causes and Potential Cures. Journal of Industrial Ecology, 20(2), 341–353.

Giampietro, M., Mayumi, K. (2018), Unraveling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Frontiers in Energy Research, 6, 26.

Gozgor, G., Paramati, S.R. (2022), Does energy diversification cause an economic slowdown? Evidence from a newly constructed energy diversification index. Energy Economics, 109, 105970.

Gretton, P. (2021), The comprehensive and progressive agreement for trans-pacific partnership: Implications for Southeast Asia, Cassey Lee and Pritish Bhattacharya (eds) ISEAS Publishing, Yusof Ishak Institute, Singapore, 2021, Pp. 318+xv. Asian-Pacific Economic Literature, 35(2), 177-178.

Grossman, G.M., Krueger, A.B. (1995), Economic growth and the environment. The Quarterly Journal of Economics, 110(2), 353-377.

Hansen, B.E. (1999), Threshold effects in non-dynamic panels: Estimation, testing, and inference. Journal of Econometrics, 93(2), 345-368.

Hao, L.N., Umar, M., Khan, Z., Ali, W. (2021), Green growth and low carbon emission in G7 countries: How critical the network of environmental taxes, renewable energy and human capital is? Science of The Total Environment, 752, 141853.

Hasan, S.T., Wood, M.O., Singh, S. (2022), Revealing embedded carbon emissions within the comprehensive and progressive agreement for trans-pacific partnership. Economic Systems Research, 34(3), 294-319.

Hu, X., Liu, C. (2017), Total factor productivity measurement with carbon reduction. Engineering, Construction and Architectural Management, 24(4), 575-592.

Hussain, Z., Mehmood, B., Khan, M.K., Tsimisaraka, R.S.M. (2022), Green growth, green technology, and environmental health: Evidence from high-GDP Countries. Frontiers in Public Health, 9, 816697.

Ian, P., Dirk, H., Eliza, L., Shanjun, L. (2014), Getting Energy Prices Right. United States: International Monetary Fund.

Iizuka, M. (2015), Diverse and uneven pathways towards transition to low carbon development: The case of solar PV technology in China. Innovation and Development, 5(2), 241-261.

Intergovernmental Panel on Climate Change (IPCC) (Ed.) (2023), Climate Change 2022 - Mitigation of Climate Change. Cambridge: Cambridge University Press.

Jahanger, A., Ozturk, I., Chukwuma Onwe, J., Joseph, T.E., Razib Hossain, M. (2023), Do technology and renewable energy contribute to energy efficiency and carbon neutrality? Evidence from top ten manufacturing countries. Sustainable Energy Technologies and Assessments, 56, 103084.

Kalaitzidakis, P., Mamuneas, T., Stengos, T. (2018), Greenhouse emissions and productivity growth. Journal of Risk and Financial Management, 11(3), 38.

Khan, M.A., Zada, N., Mukhopadhyay, K. (2018), Economic implications of the comprehensive and progressive agreement for trans-pacific partnership (CPTPP) on Pakistan: A CGE approach. Journal of Economic Structures, 7(1), 2.

Kuosmanen, N., Maczulskij, T. (2024), Going green while getting lean: Decomposing carbon and green total factor productivity. Journal of Environmental Management, 352, 120046.

Lange, S., Kern, F., Peuckert, J., Santarius, T. (2021), The Jevons paradox unravelled: A multi-level typology of rebound effects and mechanisms. Energy Research and Social Science, 74, 101982.

Li, F., Zhang, J., Li, X. (2022), Research on supporting developing countries to achieve green development transition: Based on the perspective of renewable energy and foreign direct investment. Journal of Cleaner Production, 372, 133726.

Liu, M., Zhu, Y., Zhang, J. (2024), Can environmental regulation enhance green total factor productivity?-Evidence from 107 Cities in the Yangtze River Economic Belt. Sustainability, 16(12), 5243.

Liu, W., Liu, Y., Lin, B. (2018), Empirical analysis on energy rebound effect from the perspective of technological progress-a case study of China's transport sector. Journal of Cleaner Production, 205, 1082-1093.

Liu, Y., Li, Z., Xu, M. (2020), The influential factors of financial cycle spillover: Evidence from China. Emerging Markets Finance and Trade, 56(6), 1336-1350.

Loganathan, N., Mursitama, T.N., Pillai, L.L.K., Khan, A., Taha, R. (2020), The effects of total factor of productivity, natural resources and green taxation on CO_2 emissions in Malaysia. Environmental Science and Pollution Research, 27(36), 45121-45132.

Ma, A., Wu, Y. (2022), Total factor productivity of land urbanization under carbon emission constraints: A case study of Chengyu urban agglomeration in China. Economic Research-Ekonomska Istraživanja, 35(1), 4481-4499.

Marra, A., Colantonio, E., Cucculelli, M., Nissi, E. (2024), The 'complex' transition: Energy intensity and CO_2 emissions amidst technological and structural shifts. Evidence from OECD countries. Energy Economics, 136, 107702.

Mihai, D.M., Doran, M.D., Puiu, S., Doran, N.M., Jianu, E., Cojocaru, T.M. (2023), Managing environmental policy stringency to ensure sustainable development in OECD Countries. Sustainability, 15(21), 15427.

Mukhtarov, S. (2024), Do renewable energy and total factor productivity eliminate CO_2 emissions in Turkey? Environmental Economics and Policy Studies, 26(2), 307-324.

Mushafiq, M., Prusak, B. (2023), Resource productivity and environmental degradation in EU-27 countries: Context of material footprint. Environmental Science and Pollution Research, 30(20), 58536-58552.

Nabernegg, S., Bednar-Friedl, B., Wagner, F., Schinko, T., Cofala, J., Clement, Y.M. (2017), The deployment of low carbon technologies in energy intensive industries: A macroeconomic analysis for Europe, China and India. Energies, 10(3), 360.

Napolitano, O., Foresti, P., Kounetas, K., Spagnolo, N. (2023), The impact of energy, renewable and CO_2 emissions efficiency on countries' productivity. Energy Economics, 125, 106795.

Nica, I., Georgescu, I., Kinnunen, J. (2025), Economic growth, innovation, and CO_2 emissions: Analyzing the environmental Kuznets curve and the innovation Claudia curve in BRICS countries. Sustainability, 17(8), 3507.

Niu, B., Zhang, N., Xie, F., Zhang, H. (2024), Optimisation of carbon emission reduction in a competitive market with varying saturation and eco-conscious consumers. International Journal of Production Research, 62(18), 6518-6541.

Nyangchak, N. (2022), Emerging green industry toward net-zero economy: A systematic review. Journal of Cleaner Production, 378, 134622.

Peng, K., Feng, K., Chen, B., Shan, Y., Zhang, N., Wang, P., Fang, K., Bai, Y., Zou, X., Wei, W., Geng, X., Zhang, Y., Li, J. (2023), The global power sector's low-carbon transition may enhance sustainable development goal achievement. Nature Communications, 14(1), 3144.

Pesaran, M.H., Shin, Y., Smith, R.P. (1999), Pooled mean group estimation of dynamic heterogeneous panels. Journal of the American Statistical Association, 94(446), 621.

Phillips, P.C.B. (1995), Fully modified least squares and vector

autoregression. Econometrica, 63(5), 1023.
Prigozhin, V., Zheng, W., Lee, F. (2023), Implementing cleaner production technologies: General aspects. E3S Web of Conferences, 392, 01006.
Rusiawan, W., Tjiptoherijanto, P., Suganda, E., Darmajanti, L. (2015), Assessment of green total factor productivity impact on sustainable Indonesia productivity growth. Procedia Environmental Sciences, 28, 493-501.
Seetharaman, Moorthy, K., Patwa, N., Saravanan, Gupta, Y. (2019), Breaking barriers in deployment of renewable energy. Heliyon, 5(1), e01166.
Shen, W., Tang, W., Siripanan, A., Lei, Z., Duffield, C.F., Hui, F.K.P. (2018), Understanding the green technical capabilities and barriers to green buildings in developing countries: A case study of Thailand. Sustainability, 10(10), 3585.
Siami, N., Winter, R.A. (2021), Jevons' paradox revisited: Implications for climate change. Economics Letters, 206, 109955.
Sogah, E., Tuffour, J.K., Mawutor, J.K.M., Gborse, F.C. (2024), The relationship between external debt and agriculture GDP growth in Ghana: An ARDL cointegrating bound testing, approach. Cogent Economics and Finance, 12(1), 2330426.
Sohail, T., Irving, D.B., Zika, J.D., Gregory, J.M. (2023), Anthropogenic aerosols offsetting ocean warming less efficiently since the 1980s. Geophysical Research Letters, 50(23), 105374.
Soltanisehat, L., Alizadeh, R., Mehregan, N. (2019), Research and development investment and productivity growth in firms with different levels of technology. Iranian Economic Review, 23(4), 795-818.
Stock, J.H., Watson, M.W. (1993), A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica, 61(4), 783.
Tawiah, V., Zakari, A., Adedoyin, F.F. (2021), Determinants of green growth in developed and developing countries. Environmental Science and Pollution Research, 28(29), 39227-39242.
Tzeremes, P. (2020), The impact of total factor productivity on energy consumption and CO_2 emissions in G20 countries. Economics Bulletin, 40(3), 2179-2192.
United Nations. (2023), Recent Developments, Challenges and Opportunities in Sustainable Economic Diversification. United Nations Conference on Trade and Development. p. 1-15. Available from: https://unctad.org/system/files/official-document/ciimem4d28_en.pdf?
von Schuckmann, K., Cheng, L., Palmer, M.D., Hansen, J., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F.J., Desbruyères, D., Domingues, C., García-García, A., Gentine, P., Gilson, J., Gorfer, M., Haimberger, L., Ishii, M., Johnson, G.C.,…& Wijffels, S.E. (2020), Heat stored in the Earth system: Where does the energy go? Earth System Science Data, 12(3), 2013-2041.
Wang, D., Yu, Z., Liu, H., Cai, X., Zhang, Z. (2024), Green consumption, environmental regulation and carbon emissions-an empirical study based on a PVAR Model. Sustainability, 16(3), 1024.
Wang, L., Yan, Y. (2022), Environmental regulation intensity, carbon footprint and green total factor productivity of manufacturing industries. International Journal of Environmental Research and Public Health, 19(1), 553.
Wang, Q., Li, Y., Li, R. (2024), Rethinking the environmental Kuznets curve hypothesis across 214 countries: The impacts of 12 economic, institutional, technological, resource, and social factors. Humanities and Social Sciences Communications, 11(1), 292.
Wang, Q., Yang, T., Li, R., Wang, X. (2023), Reexamining the impact of foreign direct investment on carbon emissions: Does per capita GDP matter? Humanities and Social Sciences Communications, 10(1), 406.
Wang, X., Wen, X., Xie, C. (2018), An evaluation of technical progress and energy rebound effects in China's iron steel industry. Energy Policy, 123, 259-265.
Wang, Y., Li, Y., Zhu, Z., Dong, J. (2021), Evaluation of green growth efficiency of oil and gas resource-based cities in China. Clean Technologies and Environmental Policy, 23(6), 1785-1795.
World Bank. (2010), World Development Report 2010. Washington, DC: World Bank.
Wu, J., Yu, Z. (2025), The impact of market-based environmental regulation on carbon emission intensity: An analysis based on policy texts. Sustainability, 17(2), 465.
Wu, T., Chadee, D. (2022), Comprehensive and Progressive Agreement for trans-Pacific Partnership (CPTPP): Implications for the Asia-Pacific Region. Berlin: Springer. p. 53-74.
Wu, Y., Yao, L. (2023), Carbon productivity and economic growth patterns in China. Economic Research-Ekonomska Istraživanja, 36(1), 1247-1260.
Xu, L., Yang, J. (2024), Carbon pricing policies and renewable energy development: Analysis based on cross-country panel data. Journal of Environmental Management, 366, 121784.
Yan, K., Gupta, R., Wong, V. (2022), CO_2 Emissions in G20 nations through the three-sector model. Journal of Risk and Financial Management, 15(9), 394.
Yang, J.Y., Roh, T. (2019), Open for green innovation: From the perspective of green process and green consumer innovation. Sustainability, 11(12), 3234.
Yang, Y., Wei, X., Wei, J., Gao, X. (2022), Industrial structure upgrading, green total factor productivity and carbon emissions. Sustainability, 14(2), 1009.
Yu, J.L., Lee, H.S., Kim, J.D. (2020), Analysis of Korean firms' green productivity using the MML model. Carbon Management, 11(1), 1-9.
Zhang, J., Li, S. (2023), The impact of human capital on green technology innovation-moderating role of environmental regulations. International Journal of Environmental Research and Public Health, 20(6), 4803.
Zhao, X., & Ehigiamusoe, K. U. (2024). A Study on the Evaluation and Determinants of Green Economic Efficiency: Empirical Evidence from Provincial Panel Data in China. Sage Open, 14(3), 21582440241280750.
Zhong, S., Wang, H. (2021), The effect of total factor productivity of forestry industry on CO_2 emissions: A spatial econometric analysis of China. Scientific Reports, 11(1), 14200.
Zoaka, J.D., Ekwueme, D.C., Güngör, H., Alola, A.A. (2022), Will financial development and clean energy utilization rejuvenate the environment in BRICS economies? Business Strategy and the Environment, 31(5), 2156-2170.