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The Non-Linear Impact of Medium and High-Technology Manufacturing on Environmental Quality: Evidence from Leading Technological Economies Using a PSTR Approach

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ABSTRACT

High-tech manufacturing presents a dual challenge: while it offers opportunities to enhance environmental quality through innovation and efficiency, it can also exacerbate environmental risks if not properly managed. This study explores the non-linear relationship between medium and high-technology manufacturing (MHTM) and CO_2 emissions, utilizing data from 12 leading MHTM countries over the period 1990-2021. Employing the Panel Smooth Transition Regression (PSTR) model of Gonzàlez et al. (2005), the analysis uncovers a threshold effect in the MHTM-CO_2 emissions nexus. Specifically, an MHTM threshold of 56.68% is identified: below this level, MHTM significantly increases CO_2 emissions, whereas, above it, MHTM significantly reduces emissions, thereby enhancing environmental quality. The findings also reveal a threshold-dependent effect of renewable energy (RE); below the threshold, RE increases CO_2 emissions, while above it, RE significantly improves environmental quality. Conversely, non-renewable energy (NRE) and trade consistently contribute to environmental degradation, regardless of the threshold. Sensitivity analyses, based on European and non-European sub-samples, show that for European countries, MHTM reduces emissions both below and above a threshold of 58.49%. For non-European countries, however, significant reductions in CO_2 emissions occur only when MHTM exceeds a threshold of 66.7%. These results provide critical insights into the nuanced role of technology, energy, and trade in shaping environmental outcomes.

Keywords: Environmental Quality, Technology Manufacturing, Renewable Energy, Non-renewable Energy, PSTR
JEL Classifications: C23; O33; O44

1. INTRODUCTION

Improving environmental quality requires targeted policy measures that address both the drivers of carbon emissions and their health and climate consequences. Given the significant role of industrialization and fossil fuel dependence in driving up carbon dioxide (CO_2) emissions (Intergovernmental Panel on Climate Change, IPCC, 2021), policies should prioritize a shift toward cleaner energy sources, such as renewable energy incentives, subsidies for green technology, and carbon taxes that disincentivize fossil fuel use (Stern, 2007; Nordhaus, 2019).

Policies targeting industrial innovation could drive meaningful reductions in CO_2 emissions. This could include funding for research in carbon capture and storage technologies, as well as regulations requiring industries to implement sustainable practices (International Energy Agency, IEA, 2020). Governments might also consider implementing stricter emissions standards, encouraging firms to adopt environmentally friendly practices that not only reduce emissions but can also improve public health outcomes by limiting pollution exposure (World Health Organization, 2018).

A highly effective method for mitigating emissions is the integration of renewable energy sources through the adoption of advanced technologies that utilize renewables in both production processes and electricity generation (IEA, 2021). This transition has the potential to significantly decrease the carbon footprint of industrial operations, thereby supporting long-term sustainability. Renewable energy technologies—such as solar, wind, and hydroelectric power—are increasingly feasible for incorporation into industrial activities, and policies that promote this transition can yield enduring reductions in emissions. Incorporating renewable energy technologies into various economic sectors can not only lower the carbon footprint but also lessen the overall environmental impact, generating positive externalities for both the economy and public health.

Medium and higher technologies manufacturing (MHTM) is one of the most important keys that could contribute to the evolution of environmental quality (CO_2 emissions). Research in both theory and practice demonstrates that MHTM affects CO_2 emissions through mechanisms related to energy consumption, innovation, and regulatory frameworks. MHTH sectors, such as electronics and automotive manufacturing, often use advanced technologies that improve energy efficiency, which can lower emissions per unit of production (Popp, 2019). For example, studies in OECD nations reveal that MHTM manufacturing adopting cleaner processes has led to significant CO_2 emission reductions (Liu et al., 2020). In contrast, emerging economies, where industrial expansion sometimes outpaces the adoption of clean technology, may see increased emissions in MHT sectors due to energy-intensive practices and less stringent environmental policies (Zhang and Cheng, 2019). The Environmental Kuznets Curve (EKC) hypothesis further suggests that as economies grow, emissions may initially increase but later decrease as MHTH manufacturing incorporates more sustainable technologies and renewable energy sources (Grossman and Krueger, 1995). This transition is often driven by policy; regulations and incentives for renewable energy use encourage MHTM sectors to reduce their environmental impact, underscoring the essential role of policy in harmonizing industrial activities with environmental objectives (Jaffe and Palmer, 1997).

Recent data demonstrate varied impacts of MHTM on CO_2 emissions, influenced by each country's energy sources, technology efficiencies, and regulatory frameworks. For instance, Denmark uses renewable energy in approximately 50% of its MHT manufacturing, resulting in one of the lowest CO_2 emissions rates in European industry (OECD, 2023). Similarly, Sweden achieves low emissions, with over 40% of industrial energy supplied by hydro and nuclear sources (IEA, 2022). On the other hand, South Korea's MHT industries, including electronics and shipbuilding, rely heavily on fossil fuels, with more than 60% of industrial energy demand dependent on non-renewable sources, leading to higher emissions (World Bank, 2023). Germany, the EU's largest MHT producer, has reduced CO_2 emissions by around 8% over the past decade through energy efficiency improvements, particularly in automotive production (Eurostat, 2022). These statistics highlight that while MHT sector growth often increases emissions, countries with a focus on renewable energy and advanced technology are better equipped to balance industrial growth with environmental sustainability.

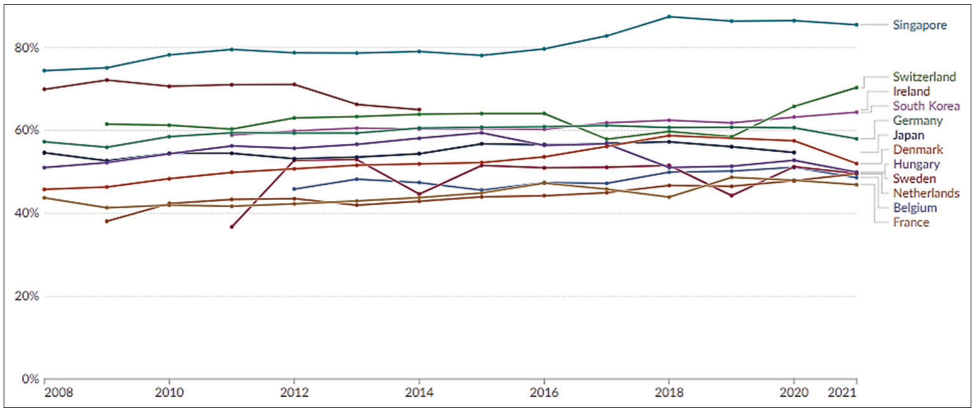
The present study tries to examine the influence of MHTM on environmental quality for the leading technological manufacturing economies. The selection of these countries is crucial as they represent some of the world's most prominent technological manufacturing economies, where the integration of advanced technologies plays a pivotal role in both economic growth and environmental sustainability. These countries provide a spectrum of approaches, ranging from leaders in green technology integration to those still dependent on conventional manufacturing methods (Tarraço et al., 2023). This variety enables a thorough exploration of how different MHTM strategies impact environmental outcomes, offering insights for other nations aiming to balance industrial development with environmental sustainability (Pylaeva et al., 2022). Moreover, these economies are often at the forefront of shaping global standards for sustainable manufacturing, making them ideal subjects for understanding the broader effects of MHTM on environmental quality (Lee et al., 2022).

Figure 1 presents the share of MHTM in GDP from 2008 to 2021, with Singapore maintaining a dominant position, nearing 80%, while Switzerland, Ireland, and South Korea also show significant contributions. To enhance MHTM's impact, countries with lower shares should strengthen policies that foster innovation by increasing R&D investment and support for high-tech industries. Additionally, developing a skilled workforce through STEM education, promoting sustainable technologies, enabling international collaborations, and supporting small and medium enterprises (SMEs) can collectively enhance MHTM's role in economic growth and global competitiveness.

Figure 2 shows a significant increase in CO_2 emissions from fossil fuels and industry, with China and the United States as the primary contributors. China's emissions have sharply risen in recent decades, now surpassing 10 billion tons annually, while the United States has stabilized below 6 billion tons. India's emissions are also increasing, approaching 3 billion tons. To address these levels, major emitters should enhance carbon reduction efforts, invest in renewable energy, collaborate internationally for sustainable industrial practices, and regularly monitor emissions to ensure policy effectiveness in curbing future growth.

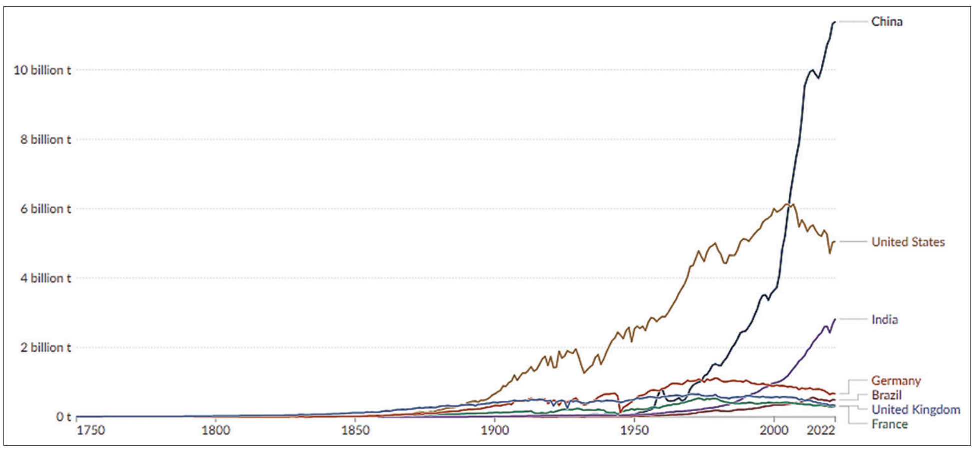
Based on the analysis presented in Figures 1 and 2, it is recommended that countries with substantial industrial activity prioritize the integration of cleaner technologies to reduce emissions while sustaining economic growth. Countries with lower shares of MHTM should direct investments toward the expansion of high-tech industries to promote development with a diminished environmental footprint. Furthermore, countries with high emissions are encouraged to enhance international partnerships with technologically advanced economies to facilitate the transfer of sustainable technologies and practices. It is also imperative for

Figure 1: Share of MHTM in GDP (2008-2021)



Global Carbon Budget (2023)

Figure 2: CO_2 emissions from fossil fuels and industry



Global Carbon Budget (2023)

governments to implement and rigorously enforce strict emission regulations, particularly within traditional manufacturing sectors, to mitigate environmental harm. Finally, ongoing monitoring of emission patterns, coupled with adaptive policy measures, is crucial to ensuring that industrial growth aligns with long-term sustainability goals.

This study aims to assess the effect of MHTM on environmental quality, focusing on CO_2 emissions, across leading technological manufacturing nations. Utilizing the Panel Smooth Transition Regression (PSTR) model developed by González et al. (2005), this research employs a non-linear econometric approach to capture the dynamic relationship between MHTM and environmental outcomes. Moreover, the PSTR model can capture gradual changes and smooth transitions between regimes, making it ideal for analyzing economies with diverse policy frameworks and environmental strategies, as it accounts for heterogeneity across countries. Several factors justify the selection of this sample: (i) These countries are acknowledged as global frontrunners in technological manufacturing, with highly developed Medium- and High-Technology Manufacturing (MHTM) sectors that foster economic growth and drive innovation; (ii) They have robust industrial infrastructures that facilitate extensive, high-tech production, establishing these nations as key players in both regional and international markets; (iii) These countries implement diverse policy frameworks for environmental regulation and technological advancement, offering a broad foundation for analyzing how various MHTM approaches influence environmental outcomes, particularly CO_2 emissions.

The structure of the paper is as follows: Section 2 provides a review of relevant literature; Section 3 outlines the methodology; Section 4 presents the empirical results; Section 5 discusses the sensitivity analysis; and Section 6 concludes with policy recommendations.

2. LITERATURE REVIEW

The academic literature has extensively highlighted the significant atmospheric challenges caused by global CO_2 emissions. Economic growth is frequently identified as a primary contributor to the increase in emissions, driven by factors such as industrialization, energy consumption, and urban expansion. This relationship is often analyzed within the framework of the Environmental Kuznets Curve (EKC), which suggests an inverted U-shaped connection between economic development and environmental degradation. According to this theory, CO_2 emissions rise during the early stages of economic growth but eventually decline as nations reach higher income levels, adopt cleaner technologies, and implement stricter environmental regulations (Grossman and

Krueger, 1995; Stern, 2004). While the EKC framework provides valuable insights, it has also been critiqued for oversimplifying the multifaceted relationship between economic growth and environmental impact. Some scholars argue that variables like trade policies, institutional quality, and global energy markets significantly shape emission trends (Copeland and Taylor, 2004). Nevertheless, the EKC remains a foundational concept for exploring the interactions between economic development and CO_2 emissions, emphasizing the importance of sustainable growth strategies that integrate environmental objectives.

The literature has shown that factors beyond economic growth significantly influence CO_2 emissions. Key among these is the types of energy consumed, with renewable energy sources such as wind and solar typically contributing to reduced emissions (Shahbaz et al., 2013; Ben Jebli and Boussaidi, 2024), whereas non-renewable sources like coal and oil are linked to heightened environmental degradation (Sadorsky, 2014). Furthermore, economic and financial development also play crucial roles in determining emission levels. For instance, access to financial resources can enable investments in clean technologies and sustainable infrastructure (Meng et al., 2024), while rapid industrialization without sustainability measures often leads to increased emissions (Stern, 2004). These findings underscore the complexity of CO_2 emissions and the necessity for policies that integrate energy consumption dynamics with broader economic and financial considerations.

The section reviews the existing research evidence with particular attention to the effect of MHTM on CO_2 emissions. Different studies focused on the effect of the high-tech industry on CO_2 emissions using several methodologies. Xu and Lin (2017) used the non-parametric model to identify the nonlinear association between the high-tech industry and CO_2 emissions in China spanning the period 1998-2014. They found that the high–tech industry produces an inverted U–shaped nonlinear impact on CO_2 emissions in the eastern region, but a positive U–shaped nonlinear effect in the central and western regions. Huang et al., (2010) reported that industrial restructuring is an important driver of CO_2 emission reduction and that high-tech industries' role in optimizing industrial structure is becoming increasingly significant. Many studies have investigated the impact of industrial structure on CO_2 emissions such as Zhou et al., 2013; Tian et al., 2014; Mi et al., 2015; Chang, 2015; Li et al., 2017; Zhang et al., 2018). According to Li and Lin (2015); Balogh and Jámbor (2017); Liu and Bae (2018) and Appiah et al., (2019) research. The results showed the impact of industrialization on CO_2 emissions primarily occurs at lower stages of industrialization and diminishes at more advanced stages, where production and consumption are typically much cleaner and more energy-efficient. Moreover, Xu and Lin (2015) used the non-parametric additive regression technique in China. They found a U-shaped association between CO_2 and industrialization. It implies that lower levels of industrialization are linked to lower CO_2 emissions, whereas higher levels of industrialization are linked to higher CO_2 emissions. Then, Liu and Bae (2018) found that industrialization is positively related to CO_2 emissions in China. They used the autoregressive distributed lag (ARDL) method.

The medium- and high-tech manufacturing sectors are frequently at the forefront of technological advancement and serve as a source of connection effects. Therefore, the medium- and high-tech manufacturing industries can propel low-carbon industrialization in developing nations. Generally, the medium- and high-tech industries may be greener and linked to lower CO_2 emissions than low-tech manufacturing. Additionally, manufacturing industries with high levels of technology are anticipated to produce less pollution than those with medium levels of technology (Avenyo and Tregenna, 2021).

3. RESEARCH DESIGN

3.1. The Sample

To assess the non-linear relationship between Medium and high technology manufacturing and CO_2 emissions, we used a sample of 12 top countries in MHTM from 1990-2021. As displayed in Table 1, the first remark is that all countries recorded on average a ratio of MHTM in % manufacturing value added >40%. Hence, the choice of this sample is based on countries that register the higher contribution of MHM in the manufacturing value-added. The second remark is that all countries except Singapore belong to the OECD countries. To check whether the asymmetric effect of MHTM on CO_2 emissions differs across regions, the whole sample was divided into two sub-samples. The first one covers European countries (9 countries) and the second is relative to non-European countries (3 countries). Data related to the MHTM are collected from Our World in Data (2024) while data relative to, RE, and NRE were sourced from the U.S. Energy Information Administration (EIA, 2023), CO_2 emissions and economic indicators are derived from the World Development Indicators database (WDI, 2024).

Table 1 presents the selected sample of 12 countries. It also gives information about the average evolution (1990-2021) of the two main indicators MHTM and CO_2 emissions. From Table 1 we note that the highest level of MHTM is registered by Singapore with a value of 73.23%. However, the weakest level is recorded by Belgium with a ratio of around 40%. We also conclude that five countries among 12 recorded a level of MHTM which is

Table 1: List of countries and average evolution of high-technology manufacturing and CO_2 emissions

Countries	Average MHTM (%) (1990-2021)	Average CO_2 emissions (1990-2021)
1) Belgium	40.01	9.95
2) Denmark	44.23	9.04
3) France	47.67	5.51
4) Germany	55.57	9.77
5) Hungary	47.63	5.21
6) Ireland	56.51	9.21
7) Japan	52.93	9.15
8) Korea, Rep,	53.67	9.97
9) Netherlands	42.51	9.82
10) Singapore	73.23	9.03
11) Sweden	48.63	5.27
12) Switzerland	54.91	5.64

Source: The authors from Our World in Data (2024) and WDI (2024). WDI: World Development Indicators database, MHTM: Medium and high-technology manufacturing higher than 50%[1]. Concerning the level of CO_2 emissions, it varies between 5 and 9 metric tons per capita. Statistics presented in Table 1 show that only five countries[2] among twelve recorded weak levels of CO_2 emission that did not exceed 5 metric tons per capita. However, the rest of the countries registered levels of CO_2 emissions around 9 metric tons per capita.

Figures 3 and 4 represent the average evolution of MHTM and CO_2 emissions respectively, during the period 1990-2021.

3.2. Empirical Approach, Model Specification and Variable Definition

Prior studies have tested the relationship using high-tech industry and environmental quality using both FMOLS and DOLS techniques (Du et al. 2022), Dynamic Seemingly Unrelated Regression and Augmented Mean Group (Yadav et al., 2024) or SIRAPT model (Gu et al. 2023). Unlike previous works, in the current study, we performed a non-linear approach based on the PSTR model developed by González et al. (2005). The PSTR model is an econometric model that considers the nonlinear relationship in panel data. It can also be viewed as a powerful tool in the capture of dynamics in relationships. It allows smooth transitions between regimes or states, which is particularly useful when thresholds are affecting the relationship between dependent and independent variables. The PSTR model is the extension of Hansen's (1999) panel threshold model-PTR. Theoretically, the PSTR can be computed as shown in equation (1):

$$y_{i,t} = \mu_i + \beta_0^{'} x_{i,t} + \beta_1^{'} x_{i,t} g\left(q_{i,t}, \gamma, c\right) + \varepsilon_{i,t} \quad (1)$$

Where *i*= *1., N*, and *t*= *1., T*. *N* and *T* refer to the temporal and the individual dimensions. $y_{i,t}$ is the dependent variable and $g(q_{i,t}, \gamma, c)$ is the transition function that depends on a transition variable denoted (q_{it}). (C) is the optimal threshold and (γ) is the smooth transition parameter, respectively. $x_{i,t} = (x_{i,t}^1, ..., x_{i,t}^k)$ is a matrix of k explanatory variables, and where $\varepsilon_{i,t}$ is a random disturbance. β_0 and β_1 indicate the parameter vector of the linear model and the non-linear model, respectively.

Similarly to Jansen and Teräsvirta (1996), Teräsvirta (1994), Granger and Teräsvirta (1993), González et al. (2005) proposed the logistic form of *m* orders indicated in equation (2) to express the following transition function.

$$g\left(q_{i,t}, \gamma, c\right) = \left[1 + \exp(-\gamma \prod_{j=1}^{m} \left(q_{i,t} - C_j\right)\right]^{-1} \quad (2)$$

Where; $\gamma > 0$, $c_1 < \ldots < c_m$ and $c = (c_1 \ldots \ldots c_m)$ is a vector of the level parameter. γ represents the supposed positive smooth parameter. To investigate the non-linear relationship between high-tech industry and CO_2 emissions, we estimate the following econometric models, and the transition function is given in equations (3). The econometric model comprises various variables, including carbon dioxide (CO_2) emissions (in million metric tonnes of CO_2) which is the dependent variable, and the contribution of medium and high technology to manufacturing MHTM (expressed as a percentage of value added in manufacturing) which is the transition variable, renewable (RE) and non-renewable (NRE) energy consumption (measured in quadrillion British thermal units or quad Btu, trade openness in % of GDP (TRADE) and growth rate of GDP (in%).

$$\begin{aligned} CO2_{i,t} &= \mu_i + \alpha CO2_{i,t-1} + \beta_0^1 MHTM_{i,t} + \beta_0^2 RE_{i,t} \\ &+ \beta_0^3 NRE + \beta_0^4 FDI_{i,t} + \beta_0^5 TRADE_{i,t} + \beta_0^6 GPDG_{i,t} \\ &\begin{bmatrix} \beta_1^1 MHTM_{i,t} + \beta_1^2 RE_{i,t} \\ + \beta_1^3 NRE + \beta_1^4 FDI_{i,t} \\ + \beta_1^5 TRADE_{i,t} + \beta_1^6 GDPG_{i,t} \end{bmatrix} g\left(MHTM_{i,t}, \gamma, c\right) \end{aligned} \quad (3)$$

Where; CO_2 is the dependent variable that represents environmental quality. MHTM is the medium and high-technology industry and is considered the transition variable.

4. EMPIRICAL DISCUSSION

In this section, we present summary statistics and check for multicollinearity problem, first. Second, it tests the panel unit root

1. Germany, Ireland, Japan, Korea, Rep and Switzerland.
2. France, Hungary, Sweden and Switzerland.

Figure 3: Average evolution of MHTM (1990-2021)

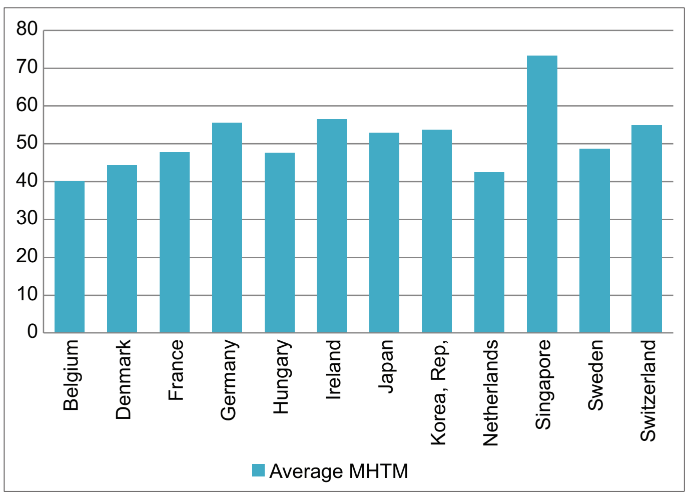
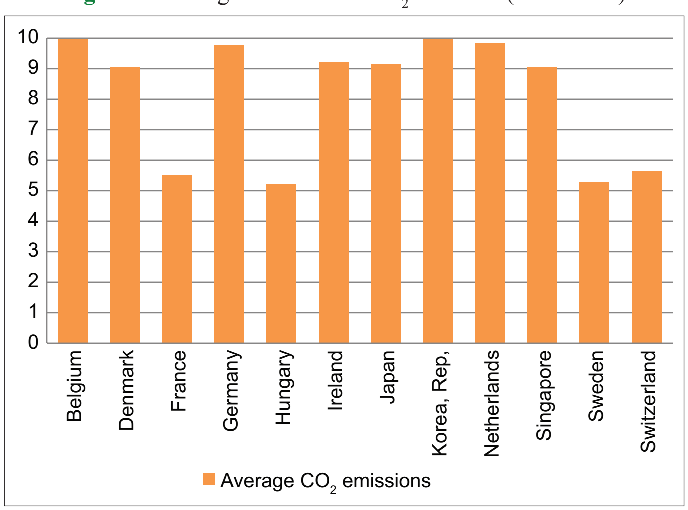


Figure 4: Average evolution of CO_2 emission (1990-2021)



test for all variables included in the econometric model. Third, some initial conditions should be confirmed before testing the PSTR model. Finally, it presents and discusses the results of the PSTR model.

4.1. Summary Statistics and Correlation Matrix

Statistics in Table 2 show that the mean value of CO_2 emissions is 8.13 with a maximum of 13.94 and a minimum of 3.24. On average, Medium and high technology manufacturing registers a value of 51.46% with a maximum value of 83.72% and a minimum of 13.36%. Descriptive statistics also indicate that renewable energy registers a mean value of 0.16 quadrillion British thermal units (*quad Btu)* with a maximum of 1.13. In addition, the average value of non-renewable energy is 5.41 *quad Btu* with a maximum of 21.55. From these statistics, we note that countries in the sample used more NRE rather than RE. From Table 2, we also note that on average FDI is about 7.01% with a maximum value of 106.57%. We can conclude that among the sample, there are countries that attract more FDI rather than others. Additionally, the mean value of trade openness is 117.79% and the maximum value is 437.32%. Concerning the macroeconomic conditions, leading technological manufacturing Countries record 24.47% as the highest level of growth rate and −7.54% as the weakest level during 1990-2021. Table 2 presents the variables' definitions and summarizes descriptive statistics.

After giving some descriptive information about the data used in this study, it is very useful to check whether there is a problem with multicollinearity. We used Pearson's correlation (PC), which is the measure of correlation between two data sets, as a method to check for multicollinearity between independent variables. The PC is the most common measure of a linear correlation. Therefore, correlation coefficients between independent variables are very weak, which serves as the indicator of a moderate level of collinearity between variables. In this way, there is no problem of multicollinearity. To reconfirm that there is no problem of multicollinearity, variance inflation factors (VIFs) were conducted. The results are presented in Table 3. A value of 1 will indicate that there is no correlation between the variables in the model. A value between 1 and 5 shows a moderate correlation, while a value greater than 5 will indicate a potentially severe correlation between the variables in the model. From Table 3, we show that the mean value of the VIFs is 1.86 indicating a moderate level of correlation.

4.2. Panel Unit Root Test (PURT)

The PSTR specification processes are predicated on the hypothesis that all variables in Model (1) are an *I(0)* process. We employed the Levin, et al., (LLC, 2002), Im, et al., (IPS, 2003), Augmented Dickey and Fuller (ADF, 1981), and Phillips and Perron (PP, 1988) tests to check for stationarity. The findings shown in Table 4 demonstrate that, for every variable utilized in this study, the LLC, IPS, ADF, and PP tests reject the null hypothesis at a significance level of 1%. We can infer from these findings that every data set is an *I(0)* process.

4.3. Results of the Pre-tests

As a prerequisite to the test of the PSTR model, three conditions have to be checked. The first condition is related to the question of non-linearity between the transition variable and the dependent variable. The second one is the test of the number of regimes. The threshold values represent the third condition.

In the linearity test, the null hypothesis considers that H_0: $\beta_1 = 0$ while the alternative is H_1: $\beta_1 \neq 0$. Table 5 summarizes the results of the linearity test between MHTM and CO_2 emission. Lagrange Multiplier (*Wald test*), Lagrange Multiplier (*F-test*) and

Table 2: Variable definition and descriptive statistics

Variable	Definition	Measurements	Mean	SD	Minimum	Maximum
CO_2	Environmental Quality	CO_2 emission (metric tons per capita)	8.13	2.33	3.24	13.94
MHTM	Medium and high−technologymanufacturing	MHTM (% manufacturing value added)	51.46	11.03	13.36	83.72
RE	Renewable energy	In quadrillion British thermal units or quad Btu	0.16	0.21	0.001	1.13
NRE	Non−renewable energy	In quadrillion British thermal units or quad Btu	5.41	5.98	0.35	21.55
FDI	Foreign direct investment	Foreign direct investment in % GDP	7.01	13.83	−40.08	106.57
TRADE	Trade openness	(Export+import) in % of GDP	117.79	84.15	15.72	437.32
GDPG	Economic growth	Annual growth rate of GDP	2.65	3.39	−7.54	24.47

SD: Standard deviation, MHTM: Medium and high-technology manufacturing, RE: Renewable energy, NRE: Non-RE

Table 3: Correlation matrix and variance inflation factor

	MHTM	RE	NRE	FDI	TRADE	GDPG	Variable	VIF	1/VIF
MHTM	1.0000						TRADE	2.96	0.337691
RE	0.1259*	1.0000					MHTM	2.09	0.479425
	0.0135						NRE	1.94	0.515554
NRE	0.0730	0.5303*	1.0000				RE	1.77	0.566007
	0.1533	0.0000					FDI	1.20	0.830556
FDI	0.1196*	−0.2030*	−0.2380*	1.0000			GDPG	1.17	0.852842
	0.0190	0.0001	0.0000						
TRADE	0.5593*	−0.3896*	−0.4837*	0.3892*	1.0000				
	0.0000	0.0000	0.0000	0.0000					
GDPG	0.2128*	−0.2624*	−0.1743*	0.1829*	0.3293*	1.0000			
	0.0000	0.0000	0.0006	0.0000	0.0000		Mean VIF	1.86	

VIF: Variance inflation factor, MHTM: Medium and high-technology manufacturing, RE: Renewable energy, NRE: Non-RE

Table 4: Panel unit root tests*

Test	CO_2	MHTEM	RE	NRE	FDI	TRADE	GDPG
Levin, Lin and Chu	−18.4064	−16.3877	−13.1946	−15.6268	−12.3955	−24.2387	−8.66652
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Im, Pesaran and Shin W-stat	−17.9264	−16.0559	−15.6692	−16.0992	−14.5710	−20.2327	−18.7910
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ADF - Fisher Chi-square	257.596	231.119	227.421	232.951	210.646	233.034	279.537
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PP - Fisher Chi-square	266.237	261.408	256.460	267.756	356.539	300.194	329.118
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

*Automatic selection (Schwarz info criterion), individual and intercept

Table 5: The linearity test

Tests	Statistics	P
Lagrange multiplier wald test	51.096	0.0000***
Lagrange multiplier F-test	9.362	0.0000***
Likelihood-ratio test	54.831	0.0000***

***The level of significance at 1%

Likelihood-ratio test (*LR*) are computed to test the non-linearity between the two indicators. From Table 5, we note that the p-values of the three tests are smaller than 5%, this implies rejecting the null hypothesis in favor of the alternative hypothesis. Thus, the relationship between MHTM and CO_2 emissions is non-linear.

After testing the non-linearity between the dependent variable and the transition variable, we should check the number of regimes. Before testing the PSTR model, we test whether $m = 1$, regarded as the null hypothesis of having only one function of transition, against the alternative hypothesis of having at least two functions of transition, $m = 2$. Decisions about this test are based on the LMW and LMF statistics. From Table 6, both the hypotheses with no threshold, $r = 0$ and the hypothesis of at least two thresholds, $r = 2$ are rejected for the two tests at the 1% significance level. We therefore reject the null hypothesis from this outcome and agree that there are at least two threshold functions of transition. Otherwise, we fail to reject the null hypothesis; hence we conclude that the model has at least one threshold and two regimes.

Table 7 and Figure 5 show that the defined threshold of MHTM is 56.68%. This threshold means that the relationship between medium and high-technology manufacturing and CO_2 emissions changes from this level. Compared to the mean value of MHTM (51.46%) indicated in Table 2, the value of the optimal threshold is nearly to the average. This means that, on average all countries used in this study recorded a level of MHTM that satisfies the defined threshold. Nevertheless, some countries registered a weak level of MHTM with a minimum value of 13.36% and others with a maximum value of 83.72%. Concerning the positive smooth parameter γ it is about 0.9. According to Ibarra and Trupkin (2011) when γ is very weak, the PSTR model is more appropriate rather the PTR model.

4.4. Discussion of the Empirical Findings

In this sub-section, we discuss the non-linear relationship between MHTM and environmental quality measured by CO_2 emissions. Findings displayed in Table 8 indicate that the effect of MHTM on CO_2 emission differs across the defined threshold of 56.68%. More specifically, we found that below the threshold of 56.68%, MHTM significantly deteriorates the environmental quality through more CO_2 emission. However, surpassing this threshold, MHTM improves the quality of the environment since it significantly reduces CO_2 emissions. This result implies that an increase of MHTM above the threshold of 56.68% contributes to an improvement of the environmental quality.

Most advanced manufacturing processes entail the introduction of energy-efficient technologies that can bring about significant

Table 6: The test of the number of regimes

Hypotheses	Tests	Statistics	P
(1) H_0: r=0; H_1: r=1	LR	197.348	0.0000***
	F	33.834	0.0000***
(2) H_0: r=1; H_1: r=2	LR	253.419	0.0000***
	F	31.051	0.0000***

***The level of significance at 1%

Table 7: Threshold value (C) and smooth parameter (γ)

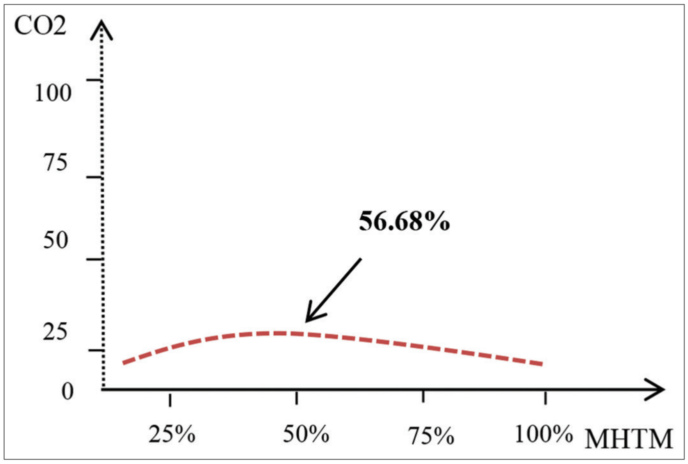
Tests	Values
γ	0.9000
C	56.68%
AIC	−0.193
BIC	−0.049

Table 8: Results of the panel smooth transition regression model

Variable	Coefficient	SE	t-statictis	Significant
MHTM <56.68% (first regime)	0.045	0.011	4.120	0.000***
RE	6.258	1.121	5.581	0.000***
NRE	0.346	0.071	4.865	0.000***
FDI	0.012	0.004	2.587	0.010***
TRADE	0.020	0.003	5.823	0.000***
GDP	−0.028	0.022	−1.284	0.200
MHTM >56.68% (second regime)	−0.032	0.013	−2.396	0.017**
RE	−2.778	1.122	−2.475	0.014**
NRE	0.236	0.045	5.209	0.000
FDI	−0.017	0.012	−1.437	0.151
TRADE	0.016	0.005	3.031	0.003
GDP	0.143	0.037	3.879	0.000
AIC		−0.193		
BIC		−0.049		
C		56.68%		
γ		0.900		
Obs		384		

*** and ** indicate the level of significance at 1% and 5%. medium and high-technology manufacturing. SE: Standard error, MHTM: Medium and high-technology manufacturing, RE: Renewable energy, NRE: Non-RE

Figure 5: The transition function



savings in energy. Such a transition is expected to result in a reduction in greenhouse gas emissions compared to traditional manufacturing methods. Moreover, with the requirement for cleaner production techniques, which minimize waste and reduce the use of hazardous materials, the high-tech industry seems to step further along that path. This practice would therefore lead to less pollution and a decreased ecological footprint. High-tech manufacturing uses advanced pollution control technologies that intercept these gases before they are released into the atmosphere, thereby improving air quality. Besides, in sustainable supply chains, several high-tech companies encourage eco-friendly practices among suppliers to lessen the overall effect of production.

Findings also indicate that, either below or above the threshold of 56.68% of MHTM, non-renewable energy significantly increases CO_2 emissions. Coal, oil, and natural gas-the major sources of non-renewable energy seriously degrade environmental quality due to air pollution. Combustion of fossil fuels emits a multitude of different types of pollutants and particulate matter, causing smog, respiratory problems, and other related health concerns. Emission from the combustion of these also contributes to acid rain, which threatens ecosystems and infrastructure. Besides, a non-renewable energy source is one of the major emitters of CO_2, a greenhouse gas that greatly brings about global warming and climatic change. Such changes manifest through increased temperatures, altered weather conditions or patterns, and extreme weather events on the rise. The extraction and refinement processes of fossil fuels may further pollute bodies of water. Events such as spills, leaks from fracking fluids, and runoff from coal mines can be extremely harmful to aquatic ecosystems and human drinking supplies.

From Table 8 we also note that below a certain threshold of MHTM, renewable energy significantly increases CO_2 emissions, however above this threshold it positively contributes to an improvement of the environmental quality. This result implies that renewable energy within a certain level of Medium and high-technology manufacturing leads to a decrease in CO_2 emissions. Renewable energy sources include wind, solar, and hydroelectric power, which emit negligible or zero GHGs during operation. This characteristic makes renewable energy important in the fight against climate change and in the assurance of cleaner air. A shift towards renewable energy will reduce harmful emissions such as sulfur dioxide and particulate matter into the atmosphere, thereby improving air quality. In this regard, such a shift could mean that the population would potentially have fewer cases of respiratory and other health problems. Besides, solar, wind, and biomass could be utilized in a manner that would result in sustainable production without depletion of the natural resources or damage to the ecosystems. This result is similar to Bilgili et al. (2024) and Raghutla and Kolati (2023).

Concerning economic indicators, we found that below the threshold of MHTM of 56.68%, FDI significantly increases CO_2 emissions, meaning that more foreign investment deteriorates the quality of the environment. With lighter regulations, multinational corporations are more apt to transfer their most harmful technologies to developing countries. This can lead to increased air, water, and soil pollution. Secondly, FDI tends to apply to natural resources, which may further cause the over-mining of minerals, oil, and gas. The result of such activities is habitat destruction, soil degradation, and the diminishment of resources at a local level. Most of the projects, particularly investments in agriculture and wood processing, contribute to forest depletion. Besides threatening biodiversity, these activities disrupt carbon storage and affect the regulation of local climates. This finding is convergent with Wang et al. (2023) and Xie et al. (2019).

Empirical results also show that either below or above the defined threshold, trade openness significantly increases CO_2 emissions. Countries with relatively lower trade barriers may face a competitive need to lower the level of environmental standards in their country to be more attractive for foreign investments. This would result in higher industrial emissions from companies that would have otherwise been subject to much more strict controls. Increased international transportation, often a corollary of free trade, also means more ships and planes burning fossil fuels and generating CO_2. The farther apart countries are trading with one another, the more CO_2 is emitted to transport those goods. This result corroborates the findings of Boussaidi and Hakimi (2024), and Afesorgbor and Demena (2022).

5. SENSITIVITY ANALYSIS: EUROPEAN VS NON-EUROPEAN COUNTRIES

To check whether the asymmetric effect of the MHTM on CO_2 emissions differs across regions, we conduct a sensitivity analysis by splitting the whole sample into *European* and *non-European* countries. The non-linearity between the dependent and the transition variable is confirmed for the two sub-samples. Results of the test of the number of regimes show that there is at least one threshold and two regimes. Statistics of the LMW and LMF tests are significant at the level of 1%. We also found the threshold of MHTM for European countries is 58.49% while for non-European countries is 66.7%. We conclude that the environmental quality is more sensitive to an increase in MHTM in the whole sample rather than European and non-European countries. We also note that non-European countries require more MHTM rather than non-European countries to benefit from a decrease in CO_2 emissions.

Table 9: Results of the panel smooth transition regression model: European versus non-European Countries

Variables	European countries threshold=58.49%		Non-European countriesThreshold=66.7%	
	Coeff	t-statistic	Coefficient	t-statistic
MHTM <thresholds	−0.046	−4.417***	0.013	0.363
RE	−7.113	−5.701***	−0.131	−0.182
NRE	0.361	1.737*	0.370	6.220***
FDI	0.009	2.256***	−0.071	−1.338
TRADE	−0.017	−5.416***	−0.009	−1.526
GDP	−0.001	−0.046	0.004	0.178
MHTM >thresholds	−0.042	−1.777*	−0.143	−4.979***
RE	2.122	1.203	−3.212	−0.954
NRE	0.417	3.524***	1.740	7.350***
FDI	0.009	0.608	0.045	0.802
TRADE	0.021	2.112**	0.000	−0.048
GDP	0.140	2.368**	0.036	1.122
AIC	−0.237		−1.623	
BIC	−0.059		−1.249	
C (thresholds)	58.49%		66.7%	
ϒ	0.5000		0.9000	
Obs	288		96	

*** and ** indicate the level of significance at 1% and 5%. medium and high-technology manufacturing. SE: Standard error, MHTM: Medium and high-technology manufacturing, RE: Renewable energy, NRE: Non-RE, MHTM: Medium and high-technology manufacturing

Table 10: Summary of the empirical findings

Samples	Thresholds *C*	Smooth parameter *ϒ*	Impact below the threshold	Impact above the threshold
Whole sample	56.68%	0.900	+ and significative	− and significative
European countries	58.49%	0.500	− and significative	− and significative
Non-European countries	66.7%	0.900	+ and N significative	− and significative

Results of the PSTR model for the two sub-samples are given in Table 9.

From Table 9 we can note that the threshold of MHTM for non-European countries is higher than that of European countries. This result implies that to benefit from a decrease in CO_2 emission, non-European countries should reach a level of MHTM which is higher than in European countries. Within a threshold of 58.49% of MHTM, it results in a decrease in the CO_2 emission for European countries. However, non-European countries should maintain a threshold of 66.7%.

A second remark that can be drawn from the results in Table 9 is that below or above the threshold of 58.49%, MHTM significantly decreases the level of CO_2 emission in European countries. However, only above the threshold of 66.7%, MHTM significantly reduces CO_2 emissions in non-European countries. Below this threshold, the effect is not significant. Medium- and high-tech manufacturing in Europe forms a very diverse family of sectors, with an emphasis on innovation and sustainability. Advanced manufacturing is driving the EU's world-leading industry. In April 2024, the European Commission organized a high-level conference on the advanced manufacturing industry to discuss these challenges and further collect ideas on how to improve the sector's competitiveness, resilience, and global position. Among the recommendations are amplifying communications of the environmental benefits of clean technology solutions made in Europe and adopting an ambitious "net-zero industry" plan for renewables and industrial efficiency technologies[3].

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Table 10 summarizes the empirical findings of this study. It presents the threshold value, the smooth parameter and the impact below and above the defined threshold. These results are relative to the whole sample, European countries and non-European countries.

6. CONCLUDING REMARKS AND POLICY RECOMMENDATIONS

Motivated by the mitigated role of high-tech manufacturing in environmental quality, this paper aimed to investigate the non-linear relationship between MHTM and CO_2 emissions. To achieve this goal, we used a sample of 12 top countries in MHTM over the period 1990-2021. The Panel Smooth Transition Regression (PSTR) model of Gonzàlez et al. (2005) is performed as a non-linear econometric approach.

Empirical results of the PSTR model reveal that there is a threshold effect in the MHTM- CO_2 emissions relationship. Below a certain threshold, MHTM significantly increases CO_2 emissions. However; above this threshold, MHTM significantly improves the environmental quality through reducing CO_2 emissions. Additionally, the results of the sensitivity analysis splitting the whole sample into two sub-samples: European versus non-European countries show that either below or above the defined threshold, MHTM significantly decreases CO_2 emission for European countries. However, only surpassing the defined threshold MHTM significantly decreases CO_2 emissions for non-European countries.

A study on such inter-linking of high-tech manufacturing with environmental quality has important policy implications:

First, there are ways that governments may use various regulatory, fiscal, and collaborative measures so that high-tech industries contribute to technological progress in addition to environmental sustainability. There is a need for policymakers to seek international cooperation through agreements and institutions on the standardization of environmental laws and the promotion of environmental sustainability in global value chains. Thirdly, governments must offer incentives to high-tech manufacturers to apply clean technology that keeps pollution and resource use at a minimum. They can also develop specific industry environmental standards on what is permissible according to the peculiar production process and requirements of resources in high-technology manufacturing. Finally, policymakers can support circular economy practices in which products are designed for reuse, remanufactured, or recycled. Besides that, there can be policies that ensure supply chains are produced at environmental standards can also be promoted by the government, wherein transparency, traceability, and environmental certification are promoted. Another thing investors in clean energy infrastructure are like policymakers, they need to be encouraged to invest in renewable sources of energy.

Such a study of the link between high-tech manufacturing and environmental quality has important policy implications: First, there are ways in which governments may use various regulatory, fiscal, and collaborative measures so that high-tech industries contribute to technological progress as well as environmental sustainability. Second, international cooperation by policymakers through agreements and institutions can be sought for the standardization of environmental laws and the promotion of environmental sustainability within global value chains. Thirdly, governments need to incentivize high-tech manufacturers to use clean technology that minimizes pollution and resource use. They can also develop specific industry environmental standards regarding what is permissible according to peculiar production processes and requirements for resources in high-technology manufacturing. Finally, policymakers can encourage circular economy practices wherein the product design will be reused, remanufactured, or recycled. In addition, policies that promote transparency, traceability, and environmental certification can add weight to the fact that supply chains are produced at environmental standards. Also, investors in clean energy infrastructure, like policymakers, need to be encouraged to invest in renewable sources of energy.

While the results of this paper could be interesting for policymakers and readers, this study has some limitations. First, the sample was only limited to 12 leading technological manufacturing countries. Second, most of the countries are OECD countries dominated by European countries, 9 European countries against 3 Asian countries. This may affect the comparative analysis. Finally, data used to perform the PSTR model are annual data. This specificity does not capture the possible monthly, quarterly, or biannual smoothness (thresholds). Hence, including other countries allow us to make a good comparative analysis. In addition, using monthly or quarterly data could improve the results of this study.

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