Anita Pelle – Sarolta Somosi (eds) 2025: From Policy to Practice: Studies on the Green and Digital Transition in Europe, Szeged, DOI: https://doi.org/10.14232/gtk.ppsgdte.2025.2

Effects of Technological Progress on EU's Green Transition: An Empirical Study Based on the Environmental Kuznets Curve Hypothesis

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The World Economic Forum identifies climate-induced extreme weather events as the leading global risk of the coming decade. Despite growing awareness and formal pledges, global greenhouse gas emissions reached a record 53 billion metric tons of CO_2-equivalent in 2023, which is over 60% higher than in 1990. In response, the European Union has placed green and digital transitions at the core of its long-term strategy for climate neutrality. This study examines whether technological development contributes to reducing emissions in the EU, drawing on the Environmental Kuznets Curve (EKC) hypothesis. Using panel data from 2014 to 2023 and applying panel quantile regression, the analysis considers the role of ICT capacity, R&D investment, and renewable energy use. The results support the EKC at the median quantile. R&D spending is positively associated with emissions in lower-emitting countries, suggesting that its environmental benefits may be delayed. ICT capacity shows no statistically significant effect, while renewable energy use demonstrates a consistent negative relationship with emissions, particularly at the lower end of the distribution. These findings suggest that technological progress has heterogeneous effects across EU member states and therefore policy makes should consider context-specific approaches to sustainable transition in the European Union.

Keywords: technological progress, green transition, greenhouse gas emissions, Environmental Kuznets Curve Hypothesis, European Union

1. Introduction

In recent years, reducing carbon emissions has become a central priority for policymakers globally. This urgency is reflected in major governance frameworks such as the Paris Agreement, the Sustainable Development Goals (SDGs) (UN 2017), and the European Green Deal. For example, as part of the European Grean Deal, the European Union (EU) has promised to achieve net-zero greenhouse gas (GHG) emissions and to become climate-neutral by 2050 (EC 2019) and has made it mandatory for member states to contribute to these objectives (EU 2021a, EEA 2025). These objectives stem from growing recognition that rising GHG emissions, particularly carbon dioxide, pose critical risks to environmental and human well-being most notably through the intensification of global warming due to the greenhouse effect (Shahbaz et al. 2023, Ustaoglu et al. 2021).

Shahbaz et al. (2023) have noted that global warming and its resulting climate disruptions raise serious uncertainties about the planet's long-term habitability. Similarly, climate-related risks have consistently ranked among the most severe threats in the Global Risks Reports of the World Economic Forum (WEF). In its most recent 2025 report, the WEF identifies extreme weather events directly driven by climate change, which has occupied the top position since 2017, as the top global risk for the next decade (WEF 2025).

Despite growing awareness and formal climate pledges at global, regional, and national levels, global GHG emissions continue to rise (IEA 2025, Statista 2025a). Carbon dioxide emissions from high-impact sectors such as energy and transportation remain high, while more potent gases like methane and nitrous oxide are also increasing (IEA 2025, Statista 2025a). For instance, in 2023, global GHG emissions reached a record high of 53 billion metric tons of carbon dioxide equivalent ($GtCO_2e$), which represented a 2% year-over-year increase and more than 60% higher than 1990 levels (Statista 2025a).

According to the WEF (2025) climate change and its related greenhouse gas emissions are vital, interconnected risks that require immediate and sustained global efforts in order to mitigate the adverse impacts on both planetary health and human well-being. For instance, it has been found that GHG-driven climate change is linked to falling agricultural productivity, limited access to water resources, and widespread health issues, including respiratory and cardiovascular diseases (Shahbaz et al. 2023). While industrialization, fossil fuel use, urbanization, and population growth have been identified as drivers of emissions, technological development has emerged as both a contributor to and a potential mitigator of climate impacts (Shahbaz et al. 2023). According to Todaro and Smith (2020) technological progress is among the many strategies have been proposed for mitigation of emissions. Similarly, scholars such as Mutambara (2025), Harr (2024), and Hanna (2024) have noted that technology can be marshalled to address environmental sustainability and mitigate climate challenges.

While technological progress has been identified as essential for achieving climate neutral objectives, the empirical literature on the relationship between technology and emissions has produced mixed results (Shahbaz et al. 2023, Saetra 2023). For instance, some researchers have found that technological innovation especially in areas such as information and communication technologies (ICTs), smart grids, and renewable energy can improve energy efficiency and lower emissions while some technologies have been associated with increased energy demand and e-waste, which has the potential to offset environmental gains (Sinha−Schneider 2023). The Environmental Kuznets Curve (EKC) have been used by several scholars to explain how technological progress can have different effects on greenhouse emissions in countries depending of the development status and economic structure (Sinha−Schneider 2023).

Although the empirical literature remains inconclusive on the environmental impacts of technological progress, the European Commission has consistently emphasized the critical role of new technologies and disruptive innovation in achieving its net-zero emissions objectives (EC 2019, EU 2024). Despite this growing policy focus, few empirical studies have specifically examined how different dimensions of technological progress contribute to emissions reductions across EU member states, or whether the emissions levels of countries influence this relationship. Understanding this dynamic is particularly relevant in the context of the Union's green and digital transitions, which form central pillars of both the European Green Deal and the EU Climate Law. In view of this, the present study draws on the Environmental Kuznets Curve (EKC) framework to empirically assess the relationship between technological progress and net CO_2 emissions in the European Union. Specifically, the study seeks to answer the following questions:

- RQ1. How does technological progress impact GHG emissions across EU member states?
- RQ2. How does a country's emissions level influence the effectiveness of technological progress in reducing greenhouse gas emissions in the EU?
- RQ3. Is the relationship between technological progress and greenhouse gas emissions consistent with the Environmental Kuznets Curve across the EU emissions distribution?

In next section, the theoretical underpinnings and empirical literature relating to the nexus between technological and greenhouse gas emissions will be discussed. This will be followed by an overview of the empirical strategy used to investigate the central research question before concluding with the findings and recommendations.

2. Literature Review

2.1. Defining Technological Progress

Technological progress defined as the increased application of new scientific knowledge in the form of inventions and innovations with regard to both physical and human capital is considered by many economists as the most important source of economic growth (Todaro–Smith 2020). In the modern era of Industry 4.0, technology is expected to play a massive role in transforming the global production and consumption processes as wells ensure environmental sustainability while stimulating the growth (UNCTAD 2023). Similarly, Todaro and Smith (2020) have observed that improved access to new technologies can prevent environmental degradation while (Harr 2024) posits that innovative powers and the ability to create technological progress will accelerate the changes needed to make human activities on the planet sustainable.

While technological progress generally and the fourth industrial revolution together with its accompanying digital technologies promise significant opportunities for humanity (UN 2023); several scholars have warned that these technological advancements could widen national and global gaps in access to social services and perpetuate inequity (Mutambara 2025, Ramsetty–Adams 2020, Todaro–Smith 2020). Thus, Walker et al. (2019) notes that leveraging technology for the public good requires global cooperation and partnerships to amplify its benefits, as well as the need to identify the risks associated with technological development and mitigate them.

Over the years, several scholars have sought to explain the potential and drawbacks of how technology impacts sustainable development generally and greenhouse gas emissions in particular. The next section will discuss some of the key theoretical perspectives in this regard with a focus on early economic theories and the Environmental Kuznets Hypothesis. After this, a summary of empirical studies on the nexus between technological progress and greenhouse gas emissions will be presented before the chapter ends by discussing emissions trends in the European Union.

2.2. Theoretical Foundations: Role of Technology in Economic Growth and Sustainable Development

The theoretical underpinnings of the role of technology in sustainable development can be traced to foundational economic theories such as the Harrod-Domar growth model, which identified investment and capital accumulation as the main drivers of economic growth. Although, technology was not included in the original model, Todaro and Smith (2020) have noted that technological progress in the Harrod-Domar framework can be viewed as a decline in the national capital-output ratio over time, not as a separate variable, but as a factor that enhances the efficiency of investment, which indirectly positively impacts economic growth.

This reinterpretation of the Harrod-Domar provides an important conceptual bridge to models like Solow's growth model in which technological change is formalized, and to modern endogenous growth theories that directly link innovation, sustainability, and long-run development. Todaro and Smith (2020, p. 136) have explained that the Solow neoclassical growth model "differed from the Harrod-Domar formulation by adding a second factor, labour, and introducing a third independent variable, technology, to the growth equation. Unlike the fixed-coefficient, constant-returns-to-scale assumption of the Harrod-Domar model, Solow's neoclassical growth model exhibited diminishing returns to labour and capital separately and constant returns to both factors jointly. Technological progress became the residual factor explaining long-term growth, and its level was assumed by Solow and other neoclassical growth theorists to be determined exogenously, that is, independently of all other factors in the model." Although Solow's model was a landmark advancement, the model's assumption of exogenous technology limits its utility in explaining how innovation can be endogenously driven by investment, institutions, and policy, all of which are crucial for sustainable development and are also relevant in the context of green technologies, which have been identified as critical for achieving the climate neutral targets.

The criticisms of the Solow Model and Neoclassical economic theory led to Endogenous growth theory (new growth theory) which argued that economic growth is generated by factors within the production process (e.g., increasing returns or induced technological change) that are studied as part of a growth model. Unlike the Solow model, new growth theory models explain technological change as an endogenous outcome of public and private investments in human capital and knowledge-intensive industries (Todaro–Smith 2020). An example is the Romer Endogenous Growth Model which addresses technological spillovers (in which one firm or industry's productivity gains lead to productivity gains in other firms or industries) that may be present in the process of industrialisation.

According to Romer's theory, during industrialization, technological spillovers become particularly potent, as interconnected industries diffuse innovations that can accelerate overall economic transformation (Huichao 2025, Barbosa 2024). From a sustainability perspective, such spillovers are particularly important because they facilitate the broader adoption of cleaner and more efficient technologies. When public policy can supports research and development, education, and innovation ecosystems, it can amplify these spillover effects can cause green technologies to disseminate more rapidly across the economy. Based in this premise, Romer's model not only provides a framework for understanding long-term economic growth but also offers theoretical grounding for how technological progress and industrial development can jointly contribute to sustainability and climate change mitigation.

While endogenous growth models such as Romer's place technological innovation at the center of long-term economic expansion, they primarily focus on productivity and output. However, as concerns about climate change and environmental degradation have grown, scholars have increasingly sought to understand how economic growth interacts with environmental quality more explicitly. This shift in focus leads to the Environmental Kuznets Curve (EKC) hypothesis, which attempts to capture the dynamic relationship between income growth and environmental degradation (Shahbaz et al. 2023).

2.3. The Environmental Kuznets Curve Hypothesis and Technology

According to Sinha and Schneider (2023) emergence of the EKC concept can be traced back to an old debate on how to elaborate a development framework deemed suitable to balance the costs and benefits associated with anthropogenic activities. The EKC hypothesis was originally a theory about the relationship between environmental degradation and per capita income. The theory, which can be traced back to Grossman and Krueger (1991), posits there is the existence of an inverted U-shaped relationship between aggregate income and environmental degradation (Sinha–Schneider 2023). The main tenets of the EKC are that, in the early stages of economic growth, pollution tends to rise, but after reaching a certain income threshold, economic growth leads to improved environmental conditions in high income countries. This shift is commonly attributed to technological advancement, heightened environmental awareness, and stronger regulatory frameworks that emerge at higher levels of development (Adebayo 2021, Leal–Marques 2020, Shahbaz et al. 2023, Tenaw–Beyene 2021).

According to Shahbaz et al. (2023), the EKC is based on the several key assumptions. Firstly, environmental quality is treated like any other economic good and people are willing to pay more for it as their income increase; therefore, individuals and societies are more likely to invest more in environmental protection as their welfare improves. Secondly, rising income tends to elevate environmental issues on the political agenda; Thirdly, as the income of countries rise, their structures shift from resource-intensive industries toward services and light manufacturing. This assumption is consistent with other structural change theories such as the Lewis Dual-Sector Model, which posits that technology is a fundamental enabler of the transition from low-productivity to high-productivity sectors (Todaro–Smith 2020).

The final assumption of the EKC hypothesis is that, higher income levels are often associated with improved technological eco-efficiency that is caused by more or less voluntary changes in consumption patterns that pollute the environment less (Shahbaz et al. 2023). Based on these assumptions, the EKC framework can be adapted to explain the relationship between technological progress and greenhouse gas emissions. It is reasonable to conclude based on the EKC framework and its assumptions that countries with lower levels of technological development are more likely to have higher levels of emissions, especially during the early stages of economic growth. As noted by Sinha and Schneider (2023) technology and innovations stand as the key mechanism driving this dynamic shift in the carbon structure of any development process. To further examine these theoretical arguments, the next section synthesizes recent empirical studies that highlight the impact of various dimensions of technological progress such as ICT, R&D, and green technologies on greenhouse gas emissions.

2.4. Empirical Studies on Technological Progress and Greenhouse Gas Emissions Nexus

Whiles technological progress has been identified as being essential to the achievement carbon neutral goals, empirical studies on the effects of various components of technological progress on greenhouse gas emissions have produced mixed results as summarized in Table 1. For instance, some scholars applied the EKC hypothesis and found that technological innovation in high-income, high-technology, and high-CO2 emission countries can significantly reduce CO2 emissions in neighbouring countries; however the EKC turning point may not occur without policy and capacity (Chen–Lee 2020, Shahbaz et al. 2023, Zhao et al. 2023).

Table 1. Summary of empirical results on technology and emissions nexus

Focus	**Result**	**Authors**
Information & Communication Technology (ICT), Automation, and Digitalisation	Mixed	Amin–Rahman (2019), Magazzino et al. (2021), Sinha–Schneider (2023)
Technological Innovation (R&D)	Mixed	Chen–Lee (2020), Sinha–Schneider (2023), Rissman (2024)
Green Technologies	Negative	Patel et al. (2023), Zhang et al. (2019), Zhao et al. (2023), Rissman (2024), IEA (2025)
General Technological Development	Mixed	Shahbaz et al. (2023), Zhang et al. (2019), Rissman (2024)
EKC & Technology	Mixed	Chen–Lee (2020), Shahbaz et al. (2023), Zhao et al. (2023)

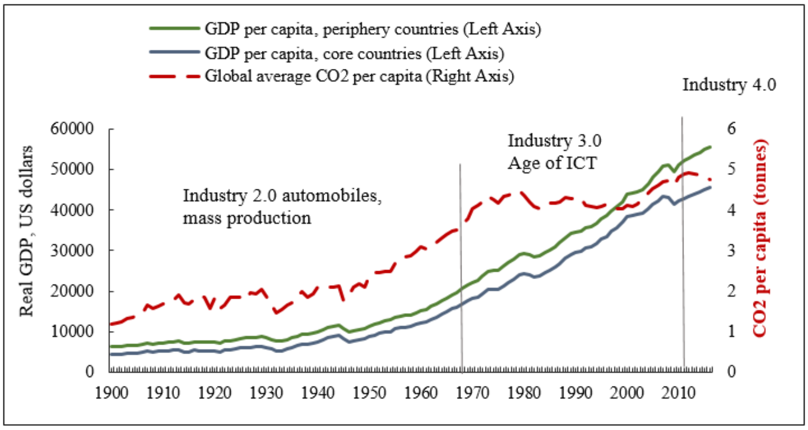
Source: author's construct

With respect to ICT, empirical studies have found that ICT enhances energy efficiency and grid reliability, but data centers and e-waste may raise emissions (Sinha–Schneider 2023) while ICT power consumption may exceed its energy efficiency gains, leading to increased carbon emissions, especially in regions with non-decarbonized electricity (Amin–Rahman 2019, Magazzino et al. 2021).

R&D has also been linked to lower emissions and SDG compliance other scholars have noted that clear R&D pathways exist to eliminate emissions (Chen–Lee 2020, Sinha–Schneider 2023, Rissman 2024). There has also been Strong evidence that renewable energy technologies reduce emissions. Furthermore, Hydrogen-based DRI furnace have been found to reduce emissions while rapid adoption of clean energy technologies have also been found to be limiting emissions growth (Patel et al. 2023, Zhang et al. 2019, Zhao et al. 2023, Rissman 2024, IEA 2025).

The mixed results regarding the effect of technology on emissions are consistent with critiques of the various theoretical perspectives discussed earlier. For example, while endogenous growth models highlight the potential for technological spillovers and innovation-led growth, Todaro and Smith (2020) emphasize that the realization of these gains in some countries are often hindered by coordination failures and institutional constraints. In many developing countries even when modern technologies are available, firms may remain trapped in low-productivity, high-emissions equilibria due to the absence of joint investment incentives and weak absorptive capacities (Mutambara 2025, Todaro–Smith 2020).

Figure 1. The rise in CO2 per capita, and waves of technological progress



Source: author's construct based on data from UNCTAD (2023)

Several scholars have argued that technological progress alone may not deliver sustainability outcomes without complementary policy and institutional frameworks especially in developing countries. Even in the developed countries, UNCTAD (2023) has noted that rises in per capita incomes have historically been accompanied by higher CO2 emissions (Figure 1) and wow, governments need to raise the incomes of the poor while also limiting carbon emissions. In order to achieve these objectives, there is complex trade-offs between competing policy priorities between promoting inclusive economic growth and protecting the planet (UNCTAD 2023).

The theoretical and empirical insights discussed above suggest that while technological progress holds promise for mitigating greenhouse gas emissions and promoting sustainable development, its impacts remain inconclusive and can be influence by several factors income levels, institutional contexts, and patterns of adoption in various countries. This also reinforces critiques of the Environmental Kuznets Curve and some of the empirical results which suggest that the transition to cleaner production is not automatic especially if not accompanied by policy, capacity, and coordination (Rissman 2024, Shahbaz et al. 2023). As such, the role of technology in the sustainability-development nexus remains both vital and contingent. These insights provide the basis for investigating the role of technological progress in reducing greenhouse gas emissions by using the European Union as a case.

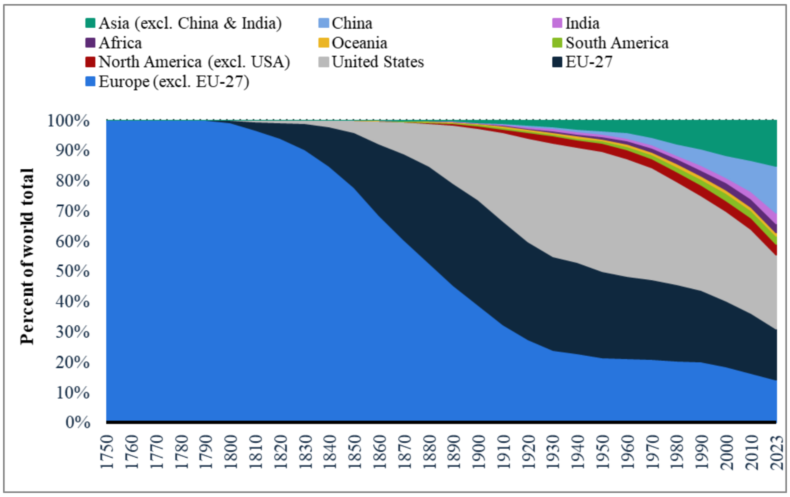
3. Global Trends and Greenhouse Gas Emissions in the European Union

As part of the United Nations Framework Convention on Climate Change (UNFCCC) modalities, procedures and guidelines (MPGs) under the Enhanced Transparency Framework (ETF) of the Paris Agreement (Decisions 18/CMA.1 and 5/CMA.3), the EU, as a party to the Paris Agreement and to the UNFCCC is required to report annually on greenhouse gas(GHG) inventories of anthropogenic emissions and removals within the area covered by its member states including all emissions taking place within the EU territory (EEA 2025). This section presents and discusses some of the key findings in the EU's 2025 inventory submission. However, before discussing EU emissions trends and sectoral emissions distribution, there is a need to provide a global historical context.

3.1. Global Historical and Contemporary Emissions Context

Since 1750, the distribution of regional cumulative carbon dioxide emissions has changed dramatically. For many decades the vast majority of emissions were produced in countries in Europe, specifically Great Britain, where the Industrial Revolution originated; however, as the United States began to emerge as a global power. By the start of the twentieth century, the United States accounted for almost a quarter of cumulative emissions (Statista 2025a).

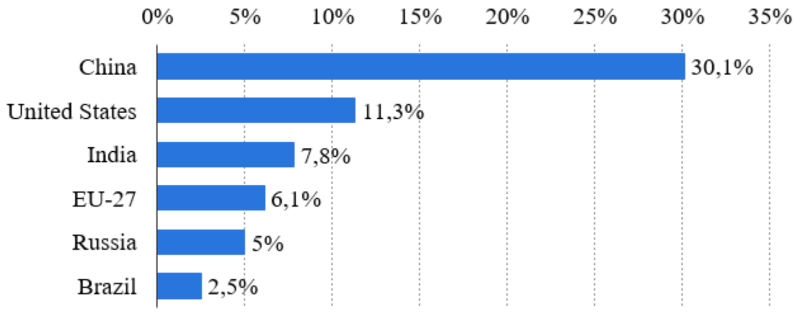
Figure 2. Cumulative carbon emissions globally 1970–2023



Source: Statista (2025a)

Currently, the EU ranks second in terms of cumulative carbon dioxide emissions globally and is responsible for around 17 percent of the historical global carbon dioxide emissions behind the US (24.4%). China ranks third with 15.4% of the cumulative carbon dioxide emissions globally followed by the rest of Asia excluding China and India with 15.1% and the rest of Europe excluding the EU with 14.1% if the cumulative carbon emissions as at 2023 (Figure 2). The European Union is also estimated to have caused 10 percent of global warming since 1850 (Statista 2025a).

Figure 3. Top greenhouse gas emitters share of global emissions (2023)



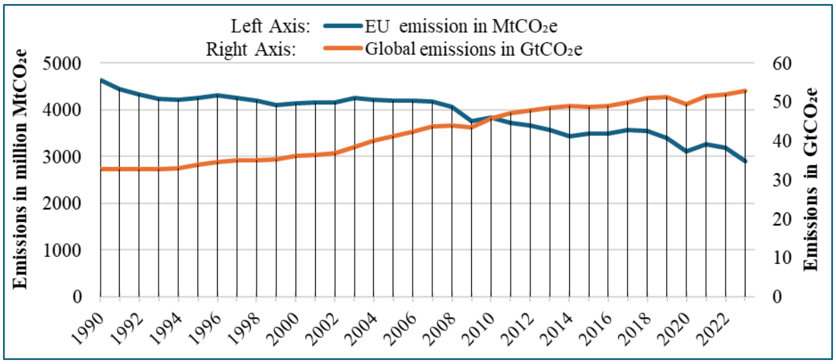
Source: Statista (2025b)

In 2023 global greenhouse gas emissions reached a record high (Statista 2025a). According to IEA (2025) the warmest year in history was recorded in 2023, setting a very high baseline, but 2024 proved to be even warmer, becoming the first year that was more than 1.5 °C above pre-industrial levels. This contributed to an increase in global emissions in 2024 (IEA 2025). Currently the European Union is the world's fourth-largest greenhouse gas emitter behind China, the US, and India (IEA 2025; Statista 2025a). As indicated in Figure 3, in 2023 the EU accounted for 6.1% of the global greenhouse gas emissions worldwide. Data from IEA (2025) indicates that in 2024, the EU's global greenhouse gas emissions share increased slightly to 6.4%.

3.2. EU Emissions Profile and Sectoral Breakdown

While the global emissions continue to grow annually globally, the emissions levels in the EU have been trending downward since 1990 (Figure 4). In 2024, the European Union recorded a 2.2% decline in energy-related CO_2 emissions, amounting to a reduction of 55 million tonnes.

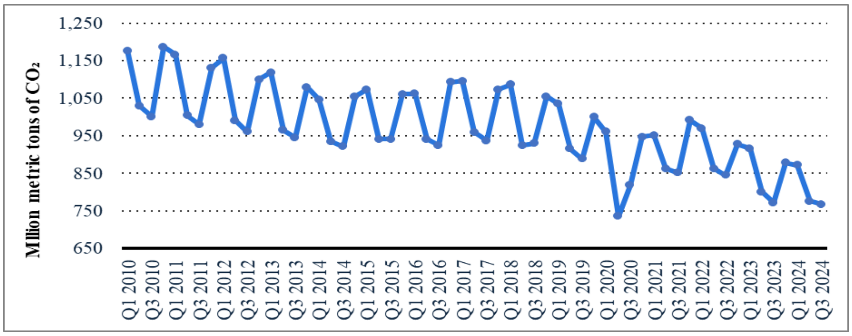
Figure 4. European Union and global emissions trends 1990–2023



Source: author's construct based on data from Statista (2025a)

A trend analysis of the quarterly GHG emissions trends in the EU indicates a cyclical pattern where emissions levels trend downward in the first 2 quarters of the year with Q3 typically recording the lowest emissions each year (Figure 5). As indicated in Figure 5, a similar pattern can be observed from the period 2010 to 2024. The notable exception to this trend was in 2020, when COVID-19-related restrictions caused emissions in Q2 of that year to plummet almost 20 percent compared to Q2 2019 levels. However, the pre-pandemic trend was restored after the pandemic.

Figure 5. Greenhouse gas emissions in the European Union (EU–27) from Q1 2010 to Q3 2024



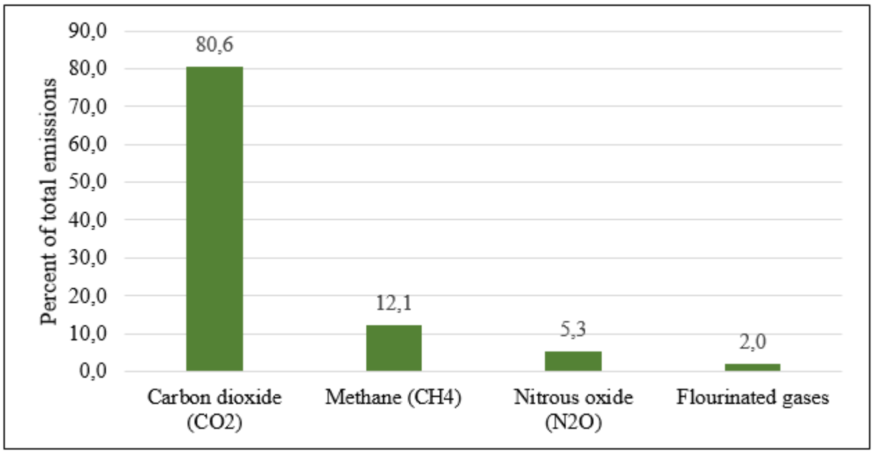
Source: Statista (2025b)

3.2.1. Greenhouse Gas Emissions in EU by Pollutants

The distribution of greenhouse gas emissions by type in the EU follows a similar composition as the global trend. As indicated in Figure 6, carbon dioxide consititutes the most emitted greenhouse. It is commonly produced by human activities. The European Parliament (2024) have noted that other greenhouse gases such as methane and nitrous oxide are emitted in smaller quantities, but they trap heat far more effectively than CO_2. For example, methane is more than 80 times more potent than

CO_2 over a 20-year period (European Parliament 2024). Nitrous oxide also has a global warming potential 300 times greater than carbon dioxide (Statista 2025a).

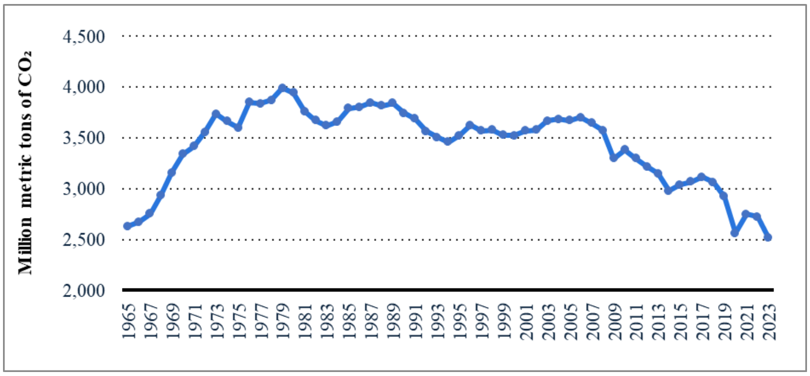
Figure 6. Greenhouse gas emissions in EU by pollutants (share of emissions in CO_2 equivalents, 2022)



Source: author's construct based on data from European Parliament (2024 p. 2)

According to Statista (2025b) methane emissions in the EU amounted to around 460 million metric tons of carbon dioxide ($MtCO_2e$) in 2023 although the EU-27 has slashed its annual CH4 emissions by more than 40 percent. At the same time the emissions of nitrous oxide in the EU also decreased by almost 30 percent between 1990 and 2023, to 241 million metric tons of carbon dioxide equivalent (Statista 2025b). Meanwhile, an observation of CO_2 emissions trend in the EU from 1965 to 2023 resembles an EKC curve (Figure 7).

Figure 7. Carbon dioxide emissions in the European Union (1965–2023)



Source: Statista (2025b)

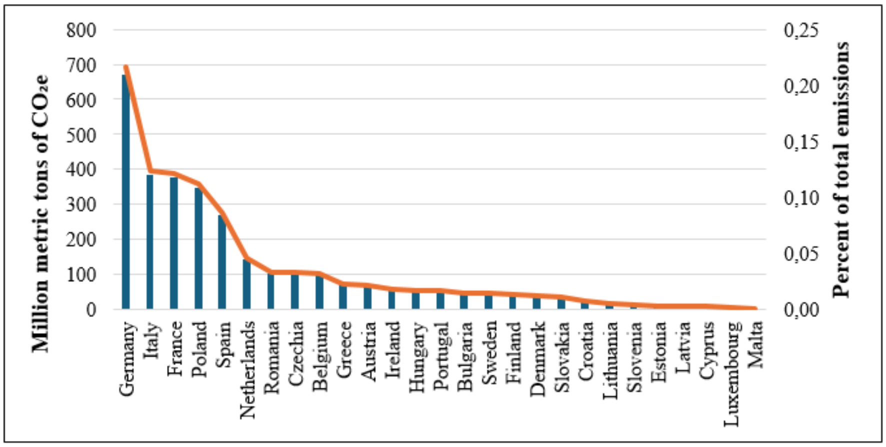
As indicated in Figure 7, in the earlier periods from the 1960s CO_2 emissions of the EU countries increased and peaked around1979. In the later years from the early

2000s the emissions levels began to decline. This is consistent with the EKC hypothesis which posits that emissions increases in the early stages of economic development and declines at high income levels. As indicated by EEA (2025) there has been a progressive decoupling between gross domestic product (GDP) and emissions, with GDP increasing by 70% and greenhouse gas emissions falling by 37% between 1990 and 2023. The CO_2 emissions of the EU reached their lowest level in more than 58 years in 2023 at 2.5 billion metric tons ($GtCO_2$). Consistent with the EKC hypothesis, EEA (2025) has noted that reduction of emissions in industrial sectors can be attributed to a combination of factors such as improved efficiency and lower carbon intensity as well as structural changes in the economy, with a higher share of services and a lower share of more-energy-intensive industry in total GDP. This is also consistent with the expectations of the EKC hypothesis.

3.2.2. Greenhouse Gas Emissions in EU by Member States

With regards to greenhouse gas emission in the EU by member countries, Germany was the biggest contributor to EU-27 greenhouse gas (GHG) emissions in 2023, having released the equivalent of 672 million metric tons of carbon dioxide ($MtCO_2e$) into the atmosphere. This was almost double the GHG emissions produced by Italy, which was the second-largest emitter. The top 5 emitters namely Germany, Italy, France, Poland, and Spain account for close to 70 (i.e. 66) percent of the total greenhouse gas emissions in EU (EEA 2025, Statista 2025b). Figure 8 shows the greenhouse gas emissions distribution by EU member states.

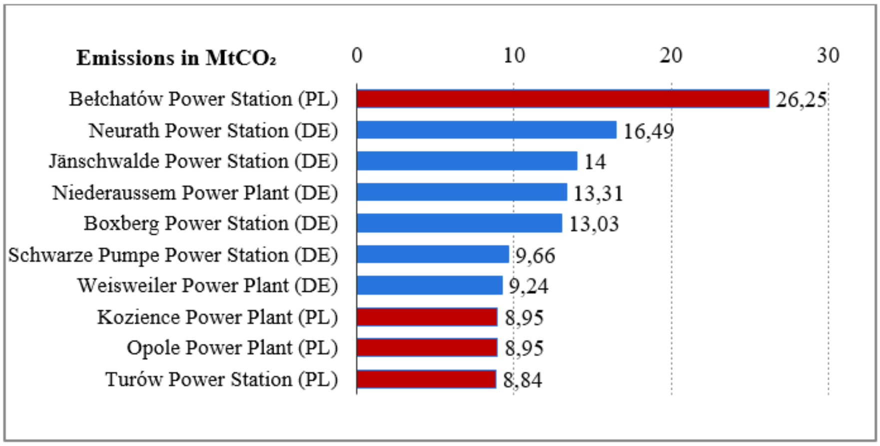
Figure 8. Distribution of greenhouse gas emissions in the EU by member states (2023)



Source: author's construct based on data from Statista (2025b)

In terms of the source of the emissions, the Bełchatów lignite-fired power plant in Poland was the biggest carbon polluter in the EU in 2023 According to Statista (2025b) the Bełchatów lignite-fired power plant has remained the biggest emitter in the EU for more than a decade. Out of the EU's top 10 polluters, 6 are based in Germany while the other 4 are based in Poland (Figure 9).

Figure 9. Top 10 biggest carbon polluters in the European Union (2023)

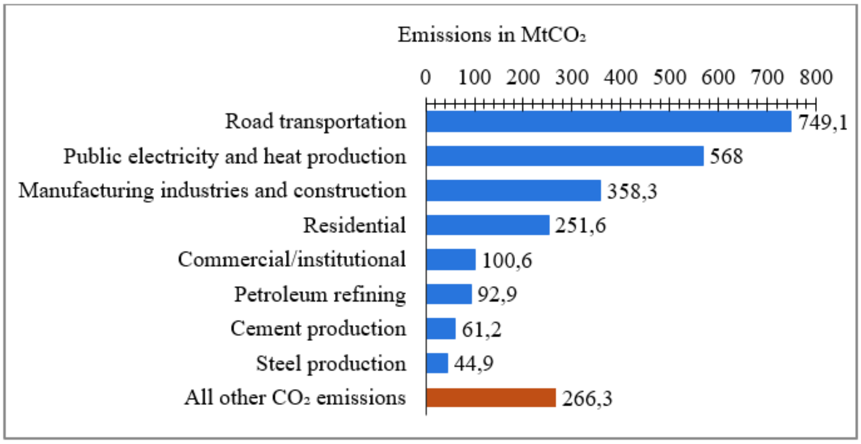


Source: Statista (2025b)

3.2.3. Greenhouse Gas Emissions in EU by Sectors

In 2023, the road transportation was the largest source of carbon dioxide emissions in the European Union in 2023 followed by public electricity and heat production (Figure 10). These two sectors combined were responsible for approximately 50 percent of total EU CO_2 emissions in 2023. According to EEA (2025) although GHG emissions decreased in the majority of sectors between 1990 and 2023, emissions increased in the transport, refrigeration and air conditioning sectors.

Figure 10. Carbon dioxide emission in the European Union (2023, by key source)



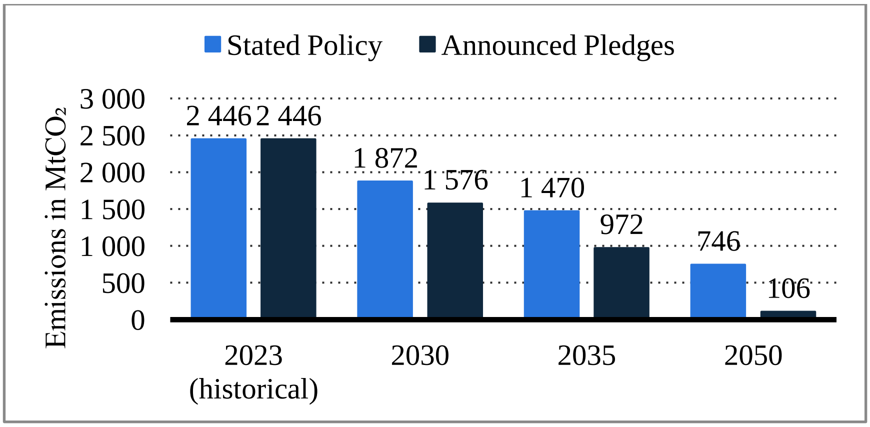
Source: Statista (2025b)

3.3. European Union Climate Targets and Greenhouse Gas Emissions Policy Responses

Although the EU has made considerable progress in reducing greenhouse gas emissions in the past decades, it is still behind its climate targets. The European Green Deal is the EU's major climate policy adopted in 2019 with the aim to achieve net-zero greenhouse gas (GHG) emissions and become climate-neutral by 2050 (EC 2019). Subsequent to that, the European Climate Law entered into force on 29 July 2021 to make the goals set out in the Green Deal binding on EU member states (EU 2021a). The law also sets the intermediate target of reducing net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels. This target forms the basis of the EU's Fit for 55 package.

Prior to the Green Deal and Fit for 55 package, in 2008, the European Union set the target of cutting 20 percent of net greenhouse gas emissions by 2020, relative to 1990 levels as part of its Effort Sharing Regulation. The EU overshot this target by cutting GHG emissions 34 percent below 1990 levels by 2020 (Statista 2025c). Consequently, in 2023, the Effort Sharing Regulation was amended with new national targets for EU member states to collectively contribute to EU-level emission reductions of 40 percent by 2030, relative to 2005 levels (EC 2023).

Figure 11. Projected CO emission in the EU under different policy scenarios



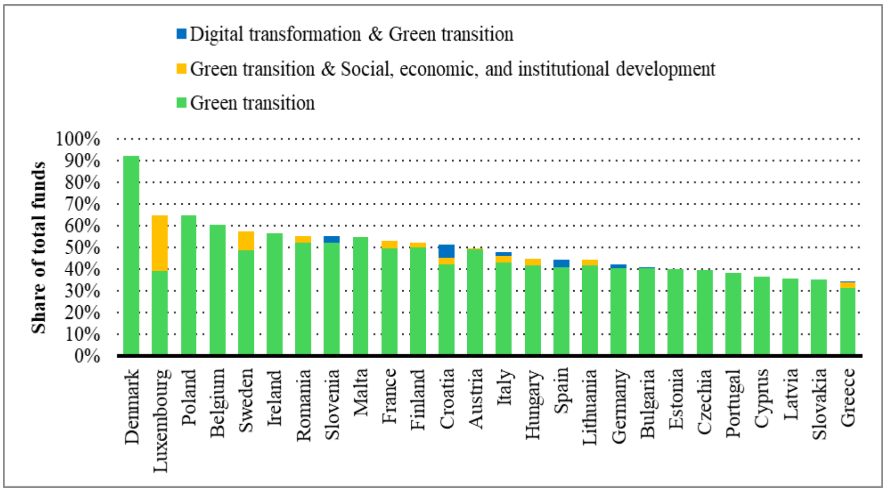
Source: Statista (2025c)

Future carbon dioxide (CO_2) emissions in the European Union will depend on the extent to which climate policies are implemented. Under the Stated Policies scenario, which includes only currently enacted or officially adopted policies, emissions are expected to decline steadily based on existing measures alone (Figure 11). In this pathway, EU emissions would drop by approximately 23% by 2030 and fall to around 750 million metric tons ($MtCO_2$) by mid-century (Statista 2025c). By contrast, the Announced Pledges scenario assumes that all publicly declared targets such as long-term net-zero commitments are fully implemented, even if they have not yet been backed by formal policy. Under this more ambitious scenario, EU CO_2 emissions could decline significantly, reaching just over 100 $MtCO_2$ by 2050.

Meanwhile Statista (2025c) has noted that in 2023, greenhouse gas emissions in the EU fell by 8% to just under three billion metric tons of carbon dioxide equivalent ($GtCO_2e$). This means that EU GHG emissions have fallen by 31 percent since 2005, and 37 percent when compared to 1990 levels. Despite this progress, current projections show that the EU will not reach its 2030 emissions target. Nevertheless, the EU continues to pursue its ambitious climate targets through policies as well as budgetary support.

A key financial mechanism supporting the EU's climate objectives is the Recovery and Resilience Facility (RRF), introduced post-COVID. The RRF allocated €723.8 billion in grants and loans to EU member states, with 37% earmarked for climate-related investments. As of 2023, the European Commission had disbursed approximately €225 billion in pre-financing and first instalments under the facility. As indicated in Figure 12, the majority of the RRF have been used by member countries to fund the EU's green transition. This includes funding for green technologies such as renewable energy expansion, energy efficiency upgrades, electric mobility, and R&D in low-carbon innovations.

Figure 12. Share of Recovery & Resilience Facility funds allocated to green transition projects in the European Union in 2020, by member state



Source: European Commission cited in Statista (2025c)

The RRF is an instrument created by the European Union as part of their economic stimulus plan launched in the wake of the COVID-19 pandemic, known as the NextGenerationEU plan, which seeks to boost the European economy through strategic investments in the green transition, digital infrastructure, and social, economic, and institutional development (EU 2021b). The expenditure patterns of the RRF shows a trend where EU member states with stronger economic growth tending to invest more in the green transition, while the struggling states have tended to prioritize investments in digital infrastructure or institutional development, which may be more urgent for their short-term economic needs (Macchi 2025). Nevertheless, the RRF has been found to play a key role in the EU's digital and green transitions.

3.4. Conceptual Framework for Investigating the Role of Technological Progress in Reducing Emissions in the European Union

The EU is the second biggest polluter in the world after the US with regards to the cumulative level of CO_2 emissions globally. Despite significant progress in reducing emissions backed by various regulations and funding mechanisms such as the RRF, the reductions have not been heterogeneous across member states and sectors. According to EEA (2025) common drivers to lower GHG emissions in most EU countries over the past 33 years have been the use of less carbon intensive fuels, with a switch from coal to gas and a strong increase in the use of renewable energy sources, as well as significant improvements in energy efficiency, both in transformation and end use. The IEA (2025) also points out that in 2024, emissions from the power sector alone fell by nearly 10% compared to the previous year and this was largely due to fossil fuels accounting for only 28% of electricity generation, which is a historic low. At the same time, renewables contributed to almost half of the EU's electricity mix in 2024, with wind and solar reaching a record combined share of 28%, surpassing the total contribution from coal and gas for the first time (IEA 2025).

Although the net emissions in the EU has been declining, in some sectors such as transportation and refrigeration emissions have been increasing. Furthermore, based on the 2023 level of emissions, the European Union remains off track to meet its 2030 and 2050 climate targets. In a recent review of empirical studies, Shahbaz et al. (2023) has noted that the main determinants of carbon emissions include industrialization, population growth, urbanization, hazardous wastes, fossil, fuel consumption, economic growth, and technological developments.

The results of empirical studies have been mixed regarding effects of technological progress on greenhouse gas emissions. That notwithstanding, EC (2019) have identified new technologies and innovations as critical for achieving the European Green Deal objectives of net-zero emissions, climate neutrality and resource efficiency. Considering that the EU is currently undergoing its twin digital and green transitions, it is essential to empirically examine the nexus between technological progress and emissions. Building on the EU's emissions context outlined above as well the theoretical and empirical literature regarding the nexus between technological progress and greenhouse gas emissions, this study fills the empirical gap by answering the research question: *How does the level of technological progress impact GHGs emissions across EU member states*? The next section will discuss the empirical methodology used to investigate this research question.

4. Methodology

4.1. Data and Sample

This study uses panel dataset comprising all 27 EU member states over the period 2014 to 2023. Since the objective of the study was to investigate the effects of technological of technological progress on greenhouse gas (GHG) emissions, the dependent variable was net greenhouse gas emissions per capita. The selection of explanatory variables were based on the literature review. Table 1 summarizes all the variables used in this study. Three different measures were used to capture technological progress grounded in both economic theory and empirical literature on sustainable development, climate policy, and innovation.

The three measures of technological progress used in this study included the ICT Productive Capacity Index, R&D expenditure, and renewable energy share of the gross final energy consumption. The rationale for including these variables are as follows:

4.1.1. ICT Productive Capacity Index (ICT)

This composite index, developed by UNCTAD, captures a country's ability to deploy and integrate digital technologies across sectors. It reflects technological readiness, digital infrastructure, skills, and innovation potential. ICT development is a key enabler of the digital transition and is assumed to reduce emissions through improved energy efficiency, smart grid systems, dematerialization, and optimization of production processes (Hanna 2024, European Commission 2023). However, its empirical impact on environmental outcomes remains contested, justifying its inclusion.

4.1.2. R&D Expenditure as a Share of GDP (R&D)

Research and development spending is a widely accepted proxy for innovation intensity and technological advancement. As emphasized in endogenous growth theory and in recent EU policy frameworks such as STEP and Horizon Europe, R&D investment is a principal mechanism through which clean technologies are expected to be developed and diffused (EC 2019, EU 2021a, EU 2021b, EU 2024). For instance, the EU Green Deal states that at least 35% of the budget of Horizon Europe (the EU's R&D fund) will fund new solutions for climate, which are relevant for implementing the Green Deal (EC 2019). Several empirical studies have found R&D to have a significant role in reducing emissions, particularly in early-stage or low-emitting economies (Sinha et al. 2022, Shahbaz et al. 2023).

4.1.3. Share of Renewable Energy Consumption (RE)

Renewable energy share serves as a proxy for technology adoption in the energy sector, which is one of the most emissions-intensive sectors. Its inclusion in this study is intended to capture the tangible deployment of green technologies and reflects both supply-side investments and demand-side policy incentives. It aligns with EKC theory, where the turning point is often associated with structural shifts in energy systems toward cleaner sources.

Together, these variables intend to capture how different stages of technological progress from capability (ICT), to innovation generation (R&D), to application and diffusion of green technologies (renewables) impact greenhouse gas emissions in the EU. In addition, GDP per capita and its square were included to test the Environmental Kuznets Curve (EKC), along with urban population and environmental protection investments to reflect demographic and policy influences.

Table 2. Variables and data sources used for the study

Category	Variable	Description
Dependent Variable	Net National Greenhouse gas emissions per capita in metric tons CO_2 eq. per person (GHG)	Measures total national GHG emissions normalized by population.
Key Explanatory Variables for Technological Progress (Lagged by 1 year)	UNCTAD ICT Productive Capacity Index	Proxy for digital infrastructure and technology absorption.
	R&D expenditure (% of GDP)	Expenditures within various sectors of performance (business, government, higher education, private non-profit), regardless of the source of funds
	Renewable energy share as a % of gross final energy consumption (RE	Indicates green energy/technology adoption and diffusion
Economic Development Variables (EKC Specification)	GDP per capita in purchasing power parity GDPpc	Captures level of economic development.
	$(GDPpc)^2$	Tests for Environmental Kuznets Curve (EKC).
Control Variables	Urban population as a % of total population (Urban	Accounts for urbanization-related environmental pressures.
	Environmental protection investments as a % of GDP (EnvInv)	Investments of total economy (governments and corporations) to provide environmental protection services

Source: author's construct
Note: ICT index data was from UNCTADstat. All other data from Eurostat

4.2. Quantile Regression Model Specification

In order to address the issues of possible heteroskedasticity, autocorrelation, non-normality, and outliers in the data set, panel quantile regression was used. This method allows for the analysis of the conditional distribution of emissions, rather than focusing solely on the conditional mean as in OLS or fixed effects regression. Panel quantile regression is particularly useful for this study given the potential heterogeneity in the effects of the explanatory variables and the expectation from the EKC hypothesis that technological progress may vary across countries at different economic development and emissions levels.

The quantile regression model used in this study is as follows:

$$Q \quad (\tau) = \alpha_\tau + \beta_{1\tau} ICT_{it} + \beta_{2\tau} R \wedge D_{it} + \beta_{3\tau} GDPpc_{it} + \beta_{4\tau} GDPpc_{it}^2 + \beta_{5\tau} RE_{it} + \beta_{6\tau} Urban_{it} + \beta_{7\tau} EnvInv_{it} + \varepsilon_{it} \quad (1)$$

Where $Q \quad (\tau)$ is the conditional quantile τ of greenhouse gas emissions per capita for country *i* at time t, α_τ is the quantile-specific intercept term, which captures the baseline level of emissions at quantile τ, $\beta_{1\tau}$ to $\beta_{7\tau}$ represent the quantile-specific slope coefficients for the explanatory variables included in the model, and ε_{it} is the quantile-specific error term. The technological progress variables (ICT, R&D, and RE) were lagged by one period to account for implementation delays and the time it takes for technological advancements to translate into measurable environmental outcomes. In contrast, GDP per capita, urbanization, and environmental protection investments were modelled contemporaneously, as their influence on emissions is expected to manifest more immediately. Panel quantile regressions were estimated at the 10^{th} to 90^{th} percentiles to evaluate the impact across the emissions distribution. The next section presents and discusses the key findings of the study.

5. Results and Discussion

This section presents and interprets the key results from the panel quantile regression analysis, which was conducted to assess the impact of technological progress on per capita greenhouse gas (GHG) emissions across EU member states between 2014 and 2023. The results are presented across selected quantiles ($\tau = 0.1$ to 0.9), with special emphasis on the median ($\tau = 0.5$), where the conditional distribution centers.

The pseudo R-squared of 0.2836 and Quasi-LR statistic of 124.10 ($p < 0.001$) suggest a reasonable model fit at the median. In order to provide a holistic picture of how technological progress impacts emissions in the EU, quantile process estimates and slope equality tests are also presented and discussed before the section concludes by discussing the implications of the results.

5.1. Impact of Technological Progress on Greenhouse Gas Emissions in the European Union

The study first examines the conditional median to capture the central tendency of the technology–emissions nexus across EU member states. The subsequent sections then contrast these results with distributional patterns at lower and higher quantiles.

5.1.1. Median Quantile Regression Results

Based on the findings R&D expenditure is positively and significantly associated with emissions at the 50th percentile. In the median emitting countries, a 1 percentage point increase in R&D spending (as a share of GDP) is associated with 1.92 additional tons of CO_2 per capita (Table 2). This result is counterintuitive but consistent with the possibility that R&D investment may initially fuel economic activity, leading to higher emissions before cleaner technologies are adopted at scale. It also suggests that in middle-emitting EU countries, R&D investments are not yet translating into immediate decarbonization potentially due to a lag in deployment or lock-in effects.

The study also finds that renewable energy consumption shows a significant negative relationship with emissions, with a coefficient of –0.125 ($p < 0.001$). This finding supports the hypothesis that the deployment of renewable energy technologies contributes to emissions reductions, in line with the literature (e.g. Shahbaz et al. 2023). However, ICT development, proxied by the ICT Productive Capacity Index is statistically insignificant in all quantiles including the median, indicating that digital infrastructure alone does not meaningfully reduce emissions in middle-emitting countries. This is consistent with Todaro and Smith’s (2020) caution that technological access must be paired with institutional and regulatory change to be environmentally beneficial as well as prior empirical ambiguity in the literature (Hanna 2024).

Table 3. Quantile regression results on impact of technological progress on greenhouse gas emissions in the European Union

Dependent Variable: GHGCAPITA				
Method: Quantile Regression (Median)				
Sample (adjusted): 1 269				
Included observations: 215 after adjustments				
Huber Sandwich Standard Errors & Covariance				
Sparsity method: Kernel (Epanechnikov) using residuals				
Estimation successfully identifies unique optimal solution				
Variable	**Coefficient (β)**	**Std. Error**	**t-Statistic**	**Prob.**
α	12.97353	3.551225	3.653253	0.0003
ICT_1	–0.017005	0.052161	–0.326009	0.7447
R&D_1	1.924740	0.468539	4.107965	0.0001*
RE_1	–0.125360	0.034779	–3.604487	0.0004*
GDPC	–0.109065	0.067309	–1.620362	0.1067
EKC	0.000598	0.000274	2.181093	0.0303*
Urban	–0.008284	0.019213	–0.431150	0.6668
EnvInv	0.071524	0.751738	0.095144	0.9243
Pseudo R-squared	0.283559			
Adjusted R-squared	0.259331			
S.E. of regression	2.733573			
Quantile dependent var	7.000000			
Prob (Quasi-LR stat)	0.000000	Quasi-LR statistic		124.0997

Source: author's calculations

Additionally, GDP per capita was found to be negatively associated with emissions, while its squared term is positive and significant (p = 0.03), providing support for the Environmental Kuznets Curve (EKC) hypothesis at the median quantile. Meanwhile, control variables such as urbanization and environmental protection investment were not statistically significant at this quantile.

5.1.2. The Impact of Technological Progress on Countries in Different Emissions Quantiles

The Quantile Slope Equality Test yields a Wald chi-square statistic of 56.70 ($p < 0.001$), indicating that the slope coefficients differ significantly across quantiles. The Symmetric Quantiles Test also rejects the null hypothesis of symmetry at the 5% level, with a chi-square value of 32.55 (p = 0.0001). This suggests that the effects of variables are not symmetric around the median and justifies evaluating impacts separately across the distribution.

Effects of R&D expenditure on greenhouse gas emissions in the EU.

As indicated in figure 11, R&D expenditure is strongly and positively significant at lower quantiles ($\tau = 0.1$ to 0.4), with coefficients between 1.83 and 2.16. This result suggests that in lower-emitting countries, R&D is associated with higher emissions. The effect weakens and becomes insignificant above $\tau = 0.6$ and turns negative but non-significant at $\tau = 0.8$ and 0.9, potentially indicating a long-run shift toward cleaner innovation in high-emitting countries.

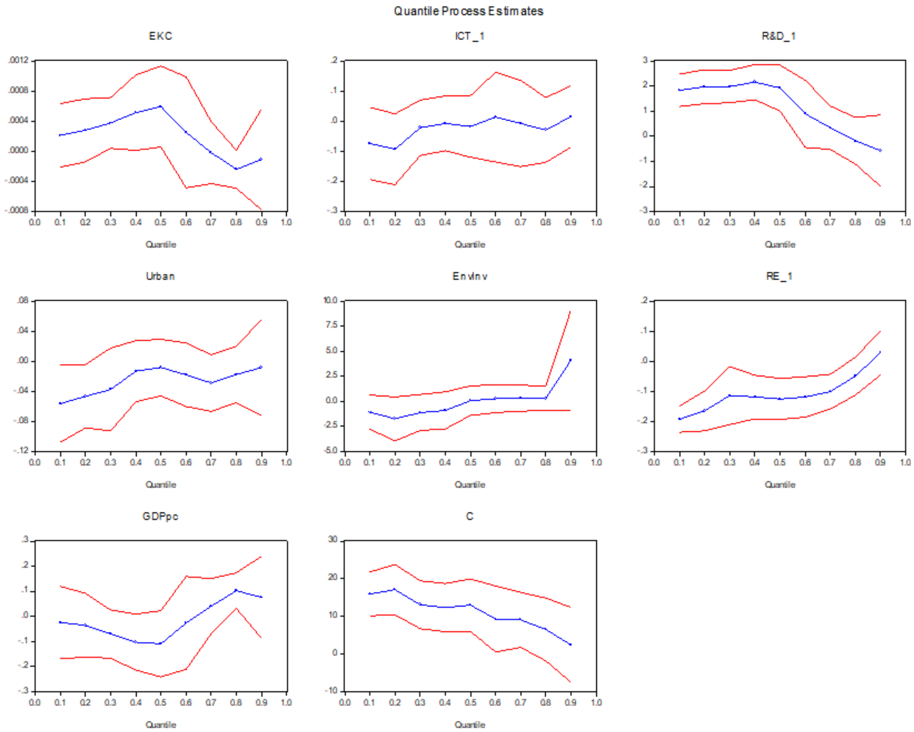
Effects of renewable energy on greenhouse gas emissions in the EU.

With regards to renewable energy share the quantile process estimates shows that the strongest negative effect is observed at $\tau = 0.1$, with a coefficient of -0.193 ($p < 0.001$). The implications is that at the 10th quantile, a 1 percentage point increase in R&D is associated with a reduction of approximately 2 tons of CO_2 per capita. The results indicated that renewable energy adoption is most impactful in lower-emitting states. The effect remains negative and significant up to $\tau = 0.7$ but becomes statistically insignificant at the 80th and 90th percentiles, suggesting that structural constraints may limit renewables effectiveness in high-emitting EU member states.

Effects of ICT development on greenhouse gas emissions in the EU.

Across all quantiles, ICT is statistically insignificant, reaffirming the result at the median. This suggests that while digital infrastructure may contribute to growth and efficiency, digital readiness alone is insufficient for decarbonization without supporting environmental policies, consistent with prior empirical ambiguity in the literature (Hanna 2024).

Figure 13. Quantile process estimates



Source: author's calculation

5.1.3. Environmental Kuznets Curve (EKC)

The study finds that the EKC pattern is most clearly supported at the median quantiles between τ = 0.3 and 0.5, where both GDP and its squared term follow the expected inverted-U shape. At higher quantiles, no evidence of EKC is observed, implying that high-emitting countries may not yet have reached the EKC turning point. For instance, while German, France and Italy have the highest GDP in the EU, they also have the highest greenhouse gas emissions respectively.

In all the quantiles GDP per capita did not have a significant impact on emissions. These results suggest that income growth alone does not guarantee emissions reductions, particularly for high-emitting EU states.

Table 4. Summary of significance of explanatory variables across quantiles

Variable	**τ = 0.1**	**τ = 0.2**	**τ = 0.3**	**τ = 0.4**	**τ = 0.5**	**τ = 0.6**	**τ = 0.7**	**τ = 0.8**	**τ = 0.9**
ICT	x	x	x	x	x	x	x	x	x
R&D	✔	✔	✔	✔	✔	x	x	x	x
GDPpc	x	x	✔	✔	✔	x	x	x	x
EKC	x	x	✔	✔	✔	x	x	x	x
RE	✔	✔	✔	✔	✔	✔	✔	x	x
Urban	x	x	x	x	x	x	x	x	x
EnvInv	x	x	x	x	x	x	x	x	x
X = not significant, ✔=significant									

Source: author's construct

6. Conclusions and Recommendations

This study examined the relationship between technological development and greenhouse gas emissions in the European Union within the framework of the Environmental Kuznets Curve. Specifically, the study sough to answer the following 3 research questions: (1) How does technological progress impact greenhouse gas emissions across EU member states? (2) How does a country's emissions level shape the effectiveness of technological progress in reducing emissions? (3) Is the relationship between technological progress and emissions consistent with the Environmental Kuznets Curve across the EU emissions distribution? Based on panel quantile regression analysis of from 2014 to 2023, the following conclusions can be made with respect to each research question:

RQ1: How does technological progress affect greenhouse gas emissions across EU member states?

The results show that technological progress has a heterogeneous impact on greenhouse gas emissions across EU member states. While renewable energy adoption consistently contributes to emissions reductions in most parts of the distribution, R&D expenditure shows a positive association with emissions at lower and median quantiles. This suggests that the environmental benefits of R&D may not be immediate and may depend on how such investments are aligned with green priorities. ICT development does not significantly influence emissions in any quantile. This is an indication that digital infrastructure alone is insufficient to achieve climate objectives without complementary environmental policies.

RQ2: How does a country's emissions level shape the effectiveness of technological progress in reducing emissions?

The quantile regression results confirm that the effectiveness of technological progress varies significantly by a country's emissions level. In lower-emitting EU member states, renewable energy is more strongly associated with reductions in emissions, while these effects diminish and become statistically insignificant at higher quantiles. This suggests that high-emitting countries may face structural, institutional, or other barriers that limit the short-term effectiveness of innovation and clean energy adoption. The slope equality and symmetry tests reinforce the need for policy makers to account for these differences when designing regionally differentiated climate policies.

RQ3: Is the relationship between technological progress and emissions consistent with the Environmental Kuznets Curve across the EU emissions distribution?

The findings offer partial support for the Environmental Kuznets Curve (EKC) hypothesis. The GDP and GDP^2 terms follow the expected inverted-U pattern primarily at the 0.3 to 0.5 quantiles, suggesting that middle-income, middle-emitting EU countries may be at or near the EKC turning point. However, the absence of EKC evidence at the higher quantiles indicates that advanced economies with high emissions have not yet decoupled economic growth from environmental degradation. This highlights the importance of aligning technological progress with targeted emission reduction strategies, particularly in high-emitting industrialized member states.

This study contributes to the empirical literature by highlighting how the environmental effects of technological progress vary not only by the type of innovation but also by the emissions level of each country. The use of quantile regression reveals important distributional dynamics that are often obscured in average-effect models. By demonstrating that green technologies have stronger emissions-reducing effects in lower-emitting EU member states, this paper provides a new lens for understanding how technology and policy interact in the transition to net-zero. These insights have broader implications for climate policy design in other regional blocs undergoing similar green and digital transitions.

While the study provides important insights, it only focused on 3 measures of technological progress namely ICT index, R&D expenditure, and renewable energy adoption, meanwhile there are other measures of technological development and green technologies. Future research could extend this analysis by exploring how other measures of technological progress impact emissions. This study also focused on the macro level. Further studies can disaggregate the analysis by sectors and also distinguishing between public and private R&D expenditures. Furthermore, qualitative case studies could complement the quantile findings to explore how national institutions mediate the impact of technology on emissions outcomes.

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