# EKC hypothesis: A comparative analysis on Production-based and Consumption-based Emissions Across Income Group

By

Nguyen Hoai An Vo

Student ID number: 201839574

This dissertation is submitted in part fulfilment of

**(MSc Data Science for Economics)**

**September 2025**

**I certify that this dissertation/project is entirely my own work.**

**Supervisor: Professor Taamouti Abderrahim**

**ACKNOWLEDGEMENTS**

I would like to express my sincere thanks to everyone who has accompanied me throughout this research and the completion of my master's degree.

Firstly, I am sincerely thankful to the University of Liverpool - Management School, where I have spent one full year pursuing my Master of Data Science for Economics. The university not only provided me with a solid academic foundation but also created an environment that supported my personal and professional development.

Secondly, I am grateful to my supervisor, Professor Taamouti Abderrahim, for his guidance and encouragement. Our discussions and meetings were instrumental in shaping the direction and scope of this study. His supportive comments have encouraged me to refine my work and persevere through difficulties of this research.

On a more personal note, I am immensely grateful to my family and friends for their constant motivation, patience, and belief in me. Their mental support and companionship sustained me throughout this journey, making the process both meaningful and rewarding.

Finally, I would like to express my profound gratitude to everyone else who has helped with this research. This accomplishment reflects a collective effort, and would not have been possible without the encouragement, generosity, and support from everyone.

## ABSTRACT

The Environmental Kuznets Curve (EKC) hypothesis provides a framework to investigate how emissions evolve with income. Traditional EKC studies often overlook emissions embedded in international trade and assume a homogeneous income–emissions relationship, which potentially creates a misleading picture of environmental progress. To address these gaps, this study compares EKC using both production-based (PCO2) and consumption-based (CCO2) emissions across income groups for 95 countries, from 1990 to 2021. A Panel Autoregressive Distributed Lag (ARDL) model is applied to estimate long–run income–emissions relationship, while controlling for urbanization and energy consumption. The results show that EKC models are highly dependent on emissions measures and development stage. For high-income countries, EKC patterns are confirmed for both PCO2 and CCO2 models. However, the turning point for the latter is much higher and economically unattainable, which provides evidence of a "decoupling illusion" driven by the offshoring of carbon-intensive production. For upper-middle-income countries, the EKC holds for PCO2, while CCO2 rises monotonically with income. Finally, for lower-middle-income countries, the EKC is rejected for both emissions, with PCO2 increasing linearly with growth. Across all groups, fossil fuel consumption raises emissions, and renewable energy consumption reduces emissions. The effect of urbanization depends on development stage. The findings imply that high-income economies must incorporate consumption footprints in their climate goals, while upper-middle-income countries should focus on green industrialization. Lower-middle-income countries should prioritize investments in sustainable urbanization and renewable energy.
**Keywords:** Environmental Kuznets Curve, Production-based emissions, Consumption-based emissions, Carbon leakage, Decoupling illusion, Panel ARDL, Income groups, Climate policy.

## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

## LIST OF ABBREVIATIONS

| Abbreviation | Meaning | Description |
|---|---|---|
| ARDL | Autoregressive Distributed Lag | Dynamic model that accommodates I(0), I(1) variables and estimates short- and long-run relations |
| BP–LM | Breusch–Pagan Lagrange Multiplier test | A test for cross-sectional dependence. |
| CCO2 | Consumption-based $CO_2$ emissions | Emissions embodied in goods consumed domestically, including imports. Also called consumption emissions. |
| CD | Pesaran CD | A test for cross-sectional dependence. |
| CIPS | Cross-sectionally Augmented Im, Pesaran, and Shin | A second-generation panel unit root test |
| DK | Driscoll–Kraay | A method for computing robust standard errors in panel regressions |
| EKC | Environmental Kuznets Curve | A hypothesized inverted-U relationship between economic growth and environmental degradation |
| FEC | Fossil fuel energy consumption | Share of total energy use from fossil fuels |
| GDP | Gross Domestic Product | A proxy for economic growth |
| PCO2 | Production-based $CO_2$ emissions | Emissions generated within the geographical border of a country. Also called production emissions. |
| PMG | Pooled mean group | A panel estimator that constrains long-run coefficients to be homogeneous across countries while allowing short-run dynamics to differ |
| REC | Renewable energy consumption | Share of total energy use from renewable sources |
| URB | Urbanization | Share of population living in urban areas |

## SECTION 1: INTRODUCTION

Since the Industrial Revolution, rising emissions have been attributed to economic growth. Global $CO_2$ emissions per capita increased from around 3.9 to 4.8 tons per year between 1995 and 2019 (Our World in Data, 2024). Rising emissions continue to drive global warming, such that the global surface temperature has already increased by 1.10 ± 0.12 °C during the 2011-2020 period (World Meteorological Organization, 2023). Without mitigation measures, these trends will intensify the frequency and severity of climate-related events such as extreme weather, biodiversity loss, and socio-economic instability. From the 1992 Earth Summit and the 1997 Kyoto Protocol to COP26, international efforts have attempted to reconcile economic development with environmental sustainability.

Central to this discussion is the Environmental Kuznets Curve (EKC) hypothesis, which posits that there is a nonlinear, inverted U-shaped relationship between economic development and environmental degradation. In the early stages of development, economic growth is driven primarily by industrial expansion, fossil fuel consumption, and resource extraction. Those are factors that increase emissions. As the economy continues to grow, the structural transformation in the economy shifts away from heavy industry toward more efficient manufacturing and service-based sectors, thereby reducing emissions intensity. Finally, at higher income levels, technological advancements, stricter environmental legislation, and increased public awareness of environmental issues lead to enhanced efficiency and decarbonization (Stern, 2004).

The EKC theory has made significant contributions to both academic discourse and policy debates. Theoretically, it offers a core framework for environmental economics to investigate a trade-off between economic growth and environmental quality. The inverted U-shaped pattern implies that at a certain level of income, economic progress may alleviate some of the environmental damage it originally causes. For policymakers, it reinforced a "grow first, clean up later" mindset that favored industrial expansion in the belief that as incomes rose, environmental quality would improve (Beckerman, 1992). This optimistic narrative has influenced development strategies, shaped climate negotiations, and guided international financial priorities for decades. Therefore, testing the empirical validity of the EKC is a matter of both theoretical importance and real-world policy relevance.

However, in an era of complex global supply chains, this traditional view is increasingly challenged by two gaps in literature. First, many EKC studies rely on production-based emissions (PCO2), which measure pollutants released only within a country's geographical borders. This approach overlooks emissions embodied in international trade, which are estimated to account for about a quarter of total global emissions (Davis, Peters and Caldeira, 2011). High-income countries often impose stricter environmental regulations which incentivize the relocation of pollution-intensive sectors to less developed countries. Several studies have observed that while production emissions in advanced economies showed signs of decoupling, their consumption emissions (CCO2) either continued to increase or re-coupled with growth (Knight and Schor, 2014; Mir and Storm, 2016; Leal and Marques, 2022). This phenomenon is referred to as "decoupling illusion." This divergence raises questions about whether the EKC, when tested on PCO2 alone, can capture the full environmental footprint of economic development. Second, much of the EKC literature assumes homogeneity in the income–emissions relationship, pooling countries together in cross-sectional or panel analyses. Such aggregation may obscure profound differences in economic structures, energy systems, and technological capacities across nations. A "one-size-fits-all" approach risks generating misleading conclusions that do not reflect the unique challenges countries face at different stages of development.

This paper fills the gaps in current research by conducting a comparative analysis of the Environmental Kuznets Curve (EKC) hypothesis. The study provides a comprehensive view of global carbon footprints by testing EKC using both production-based and consumption-based emissions. In addition, the analysis is divided into three income groups (high, upper-middle, and lower-middle) to clarify how the relationship between income and emissions varies by stage of economic development. From there, this study aims to answer the following two research questions:

RQ1: To what extent does the Environmental Kuznets Curve (EKC) hypothesis hold for production-based versus consumption-based $CO_2$ emissions?

RQ2: How does this relationship vary across income groups?

To address these questions, the study analyzes a panel of 95 countries from 1990 to 2021, using a second-generation panel ARDL model. This approach captures long-run dynamics and handles cross-sectional dependence, heterogeneity, and mixed integration orders. Countries are divided into three groups based on World Bank's 2021 income classifications, with the low-income group being removed due to severe data limitations. The core EKC relationship is modeled with PCO2 and CCO2 emissions as dependent variables, and per capita Gross Domestic Product (GDP) and its squared term as key explanatory variables. The model is extended to control for urbanization (URB), fossil fuel (FEC), and renewable energy consumption (REC).

The empirical results reveal different EKC patterns across emission types and income groups. For high-income countries, EKC is confirmed under both emissions measures, though the turning point for CCO2 lies at an economically unattainable level ($470,946 per capita GDP, constant at 2015 USD). For upper-middle-income countries, the EKC hypothesis holds for PCO2 model only, with turning point of $18,546. For lower-middle-income countries, EKC is rejected for both emission types, with PCO2 showing a linear increasing relationship with growth. The study also provides insights into control variables. Urbanization is conditional on developmental stage. It mitigates emissions in high-income countries, while having no significant effect in upper-middle income group. In lower-middle-income countries, urbanization mitigates production emissions while increasing consumption emissions. The role of energy variables is consistent across all models and income groups. Fossil fuel consumption consistently is the most powerful driver of emissions, while renewable energy provides a significant mitigating effect on emissions.

The study makes two important contributions. First, by rigorously testing the EKC for both production and consumption-based emissions, it provides a more thorough evaluation of global carbon footprints and empirical evidence for the "decoupling illusion." The findings demonstrate that environmental progress in developed nations often involves a geographic outsourcing of pollution. Second, by disaggregating the analysis across three distinct income levels, the study refines the EKC hypothesis, showing that the income-emissions relationship is conditional on stage of development. Collectively, these contributions enrich the EKC debate and highlight the importance of tailored climate policies. For high-income countries, incorporating consumption-based emissions into climate targets is crucial. Upper-middle-income countries should prioritize green industrialization, whereas lower-middle-income countries would benefit most from focused investments in sustainable urban planning and renewable energy.

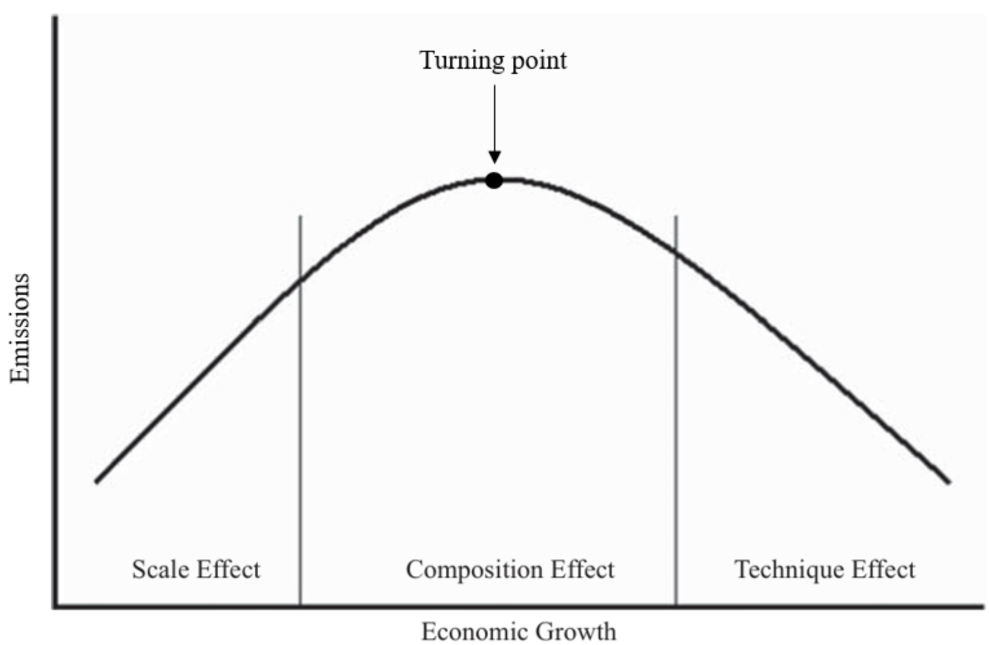
The study will be structured as follows. Section 2 provides an extensive theoretical and empirical overview of the EKC hypothesis and model variables. Section 3 describes the data sources, model specifications, and econometric methods employed. Section 4 includes empirical results, which includes descriptive statistics, pre-estimation tests, and the main Panel ARDL estimation outcomes for each income group. Section 5 discusses the findings in depth, connecting them back to the research questions and literature, as well as outlines their theoretical and practical implications. Finally, Section 6 concludes the study, summarizing important contributions and identifying areas for future research.

## SECTION 2: LITERATURE REVIEW

This section reviews the key theoretical and empirical literature that underpins our investigation into the income-emissions relationship. It begins by synthesizing the evolution of the Environmental Kuznets Curve (EKC) hypothesis, from its foundational theory to its major criticisms. The review then delves into the distinction between production-based and consumption-based emissions, a topic central to understanding the true environmental impact of economic activities in a globalized economy. To build a comprehensive model, the analysis then reviews the literature on important control variables, including urbanization, fossil fuel, and renewable energy consumption. This literature review, therefore, provides the foundation for our research questions, which examines the validity of the EKC for both PCO2 and CCO2, and how these relationships vary across high, upper-middle, and lower-middle income country groups.

### 2.1 The Environmental Kuznets Curve: Economic growth and emissions

**Figure 1.** Environmental Kuznets Curve




Source: Adapted from Shahbaz & Sinha (2019). Author's own illustration.

The Environmental Kuznets Curve (EKC) hypothesis has been a cornerstone of the environmental economics literature. The theory is an adaptation of the original work by Simon Kuznets (1955) who discovered an inverted U-shape relationship between income per capita and income inequality.

In the early 1990s, seminal studies by Grossman and Krueger (1991) and Panayotou (1995) adapted this framework to environmental outcomes. They proposed that environmental damage initially increases with economic development, reaches a peak at a specific income level (the turning point), and then declines as a country becomes wealthier. This process of breaking the link between economic growth and environmental damage is known as “decoupling.” It is theoretically explained by three effects that unfold as an economy develops (Figure 1). In the early stages, economic growth is driven by industrial expansion and resource extraction. At the same time, weak regulatory frameworks and limited investments in environmental protection exacerbate emissions and ecological degradation (Dasgupta, Laplante and Wheeler, 2002). This is called the scale effect. As countries advance to the composition stage, there is a structural transition from pollution-intensive industries toward more efficient manufacturing and service sectors. Finally, in the later stages, the technique effect becomes dominant. This is when higher income fosters public environmental awareness, stricter regulations, and diffusion of cleaner technologies, which jointly reduce emissions (Cole, Rayner and Bates, 1997; Stern, 2004). The EKC turning point represents the threshold where the composition and technique effects begin to outweigh the scale effect, leading to a peak in pollution levels followed by declines in emissions.

To empirically test the EKC hypothesis, it requires the use of proxies for environmental degradation and economic development. In previous studies, many environmental indicators have been used, including local air pollutants (e.g., $SO_2$, $NO_2$), water pollution, and deforestation. Among them, $CO_2$ emissions have become the most popular indicator of environmental degradation, due to its central role in climate change and the availability of consistent global data. On the economic side, Gross Domestic Product (GDP) per capita is typically employed as a proxy for a country’s level of development. Alternative measures such as Gross Regional Product (GRP), Gross Value Added (GVA), Foreign Direct Investment (FDI), and Gross State Product have also been employed to capture economic activity at different scales. More recently, EKC studies increasingly extend this basic model with control variables that account for structural and contextual factors. Widely used variables include energy factors (renewable, non-renewable energy consumption, oil consumption, coal consumption, biomass energy consumption), economic factors (trade openness, FDI, imports, exports), and sociodemographic drivers (urbanization, population density, globalization) (Leal and Marques, 2022).

The econometric approaches used to test the EKC are broadly divided between time-series approaches for single countries and panel approaches for groups of countries. Single-country studies often relied on cointegration analysis, with the Autoregressive Distributed Lag (ARDL) model becoming especially popular because of its flexibility with variables of different integration orders (e.g., Balaguer and Cantavella, 2016; Shah, Naqvi and Anwar, 2020; Sun *et al.*, 2021). Cross-country studies applied more robust cointegration techniques, such as Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS), to address issues of non-stationarity and endogeneity (e.g., Ben Jebli, Ben Youssef and Ozturk, 2016; Dogan and Seker, 2016; Vo, Vo and Le, 2019). More recently, researchers have concentrated on panel methods that explicitly address heterogeneity and cross-sectional dependence. These include Mean Group (MG) estimators, Augmented Mean Group (AMG), Pooled Mean Group (PMG), and Common Correlated Effects Mean Group (CCEMG), which are used with an ARDL framework. (e.g., Churchill *et al.*, 2018; Mensah *et al.*, 2021; Aydin, Koc and Sahpaz, 2023). System GMM is also employed to address endogeneity in dynamic panels (e.g., Jaunky, 2011; Makarov and Alataş, 2024).

The EKC hypothesis has been empirically supported by a substantial body of literature. Evidence is most consistent among OECD economies. For instance, Ben Jebli, Ben Youssef and Ozturk (2016) found compelling evidence of the EKC for a panel of 25 OECD countries using FMOLS and DOLS methods. Similar results were confirmed by Churchill et al. (2018) for 20 OECD countries over a very long period 1870–2014, by Lorente and Álvarez-Herranz (2016) for 17 OECD economies, and by Maranzano, Cerdeira Bento and Manera (2022), who showed that both education and income inequality condition EKC dynamics in 17 OECD countries. Kasman and Duman (2015) reached a similar conclusion for 15 EU member states. The EKC hypothesis has also been validated in transitional and emerging economies. Bah, Abdulwakil and Azam (2020) identified an inverted U-shape for 10 middle-income Sub-Saharan African countries, while Murshed, Ali and Banerjee (2021) confirmed the EKC for 6 South Asian economies. Similarly, Sinha and Sen (2016) supported EKC for the BRICS countries, underscoring that the phenomenon is not confined to advanced economies. Azam and Khan (2016) even reported evidence for low- and lower-middle-income countries, suggesting that the turning point may emerge earlier in some contexts depending on industrial structure and energy composition. Single-country studies, often based on long time series data, further support the existence of the EKC model. For example, Lindmark (2002) shows that the EKC pattern emerged in Sweden in the early period from 1870 to

1997. Balaguer and Cantavella (2016) confirmed the existence of an EKC curve in Spain based on data from 1874 to 2011, while Sephton and Mann (2016) also confirmed the hypothesis for the United Kingdom. More recent country-specific studies also provide further supporting evidence, such as in Bangladesh and India (Murshed and Dao, 2022) and in China (Sun *et al.*, 2021).

Although many studies find evidence supporting the EKC pattern, some reject it or report alternative shapes. For example, Charfeddine and Kahia (2019) reported no EKC for 24 MENA countries, while Frodyma, Papież and Śmiech (2022) found no support for production emissions in EU countries. Country-specific studies have also produced null results, including He and Richard (2010) for Canada and Shahbaz, Bhattacharya and Ahmed (2017) for Australia. Other studies suggest different forms. For example, Sinha and Sen (2016) observed a monotonically increasing relationship for the BRICS countries, while Jaunky (2011) reached a similar conclusion for high-income countries. Ben Jebli and Ben Youssef (2015) found a U-shaped pattern for Tunisia, while Shah, Naqvi and Anwar (2020) identified U-shaped relationships in Pakistan. Alam *et al.* (2016) also offered mixed evidence, with the EKC supported in Brazil and Indonesia but not in China and India. Overall, Table 1 summarizes this wide range of empirical literature, revealing a significant lack of consensus on the validity and form of the EKC hypothesis. Findings vary across countries, time periods, and methodological choices, which suggests that the EKC relationship is not a universal law but is highly sensitive to model specification and context.

**Table 1.** Summary of EKC findings

| EKC findings | Author(s) | Time Period | Countries | Methodology |
|---|---|---|---|---|
| **EKC supported (Inverted U-shape)** | Aydin, Koc and Sahpaz (2023) | 1990–2018 | G7 countries | Panel (AMG, DCCE, CCEMG) |
| | Azam and Khan (2016) | 1975–2012 | Tanzania, Guatemala, China and the USA | Time series (OLS) |
| | Bah, Abdulwakil and Azam (2020) | 1971–2012 | 10 Sub-Saharan African countries | Panel (Cointegration, DOLS) |
| | Balaguer and Cantavella (2016) | 1874–2011 | Spain | Time series (ARDL, ECM) |
| | Ben Jebli, Ben Youssef and Ozturk (2016) | 1980–2010 | 25 OECD countries | Panel (FMOLS, DOLS) |
| | Chen et al. (2019) | 1980–2014 | China | Time series (ARDL, VECM) |
| | Churchill et al. (2018) | 1870–2014 | 20 OECD countries | Panel (FE, RE, MG, CCEMG, AMG and PMG) |
| | Destek and Sarkodie (2019) | 1980–2013 | 11 newly industrialized countries | Panel (AMG) |
| | Dogan and Seker (2016) | 1985–2011 | 23 countries | Panel (DOLS, FMOLS) |
| | Kasman and Duman (2015) | 1992–2010 | 15 EU member states | Panel (FMOLS) |
| | Leal and Marques (2022) | 1990–2016 | Top 20 OECD emitters | Panel (ARDL, Driscoll-Kraay ) |
| | Lindmark (2002) | 1870–1997 | Sweden | Time series (Structural model Kalman filter) |
| | Lorente and Álvarez-Herran (2016) | 1990–2012 | 17 OECD countries | Panel (PLS, Two-stage least squares) |
| | Makarov and Alataş (2024) | 1990–2020 | 85 countries | Panel (System GMM) |
| | Maranzano, Cerdeira Bento and Manera (2022) | 1950–2015 | 17 European OECD countries | Panel (FE, RE) |
| | Matei (2022) | 1997–2015 | OECD countries | Panel (PSTR) |
| | Murshed and Dao (2022) | 1972–2014 | Bangladesh, India, Pakistan, Sri Lanka, and Nepal | Panel (MG, CCEMG, AMG - ARDL) Time series (FMOLS) |

| EKC findings | Author(s) | Time Period | Countries | Methodology |
|---|---|---|---|---|
| | Murshed, Ali and Banerjee (2021) | 1980–2016 | Bangladesh, India, Pakistan, Sri Lanka, Nepal, and Bhutan | Panel (MG, CCEMG, AMG - ARDL) |
| | Qiao et al. (2019) | 1990–2014 | 19 G20 countries | Panel (FMOLS) |
| | Rahman, Alam and Velayutham (2022) | 1990–2018 | 22 developed countries | Panel (NARDL, PMG) |
| | Saqib et al. (2022) | 1995–2019 | E-7 economies | Panel (CS-ARDL, AMG) |
| | Sephton and Mann (2016) | 1860–2009 | United Kingdom | Time series (MARS, IV) |
| | Sun et al. (2021) | 1985–2018 | China | Time series (ARDL) |
| | Vo, Vo and Le (2019) | 1971–2014 | Indonesia, Myanmar, Malaysia, the Philippines, and Thailand | Panel (FMOLS, DOLS) |
| **EKC not supported** | Alam et al. (2016) | 1970–2013 | Brazil, China, India, Indonesia (BRIIs) | Time series (ARDL bound test) |
| | Al-mulali et al. (2015) | 1980–2008 | 93 countries | Panel (FE, GMM) |
| | Ben Jebli and Ben Youssef (2015) | 1980–2009 | Tunisia | Time series (ARDL, VECM) |
| | Charfeddine and Kahia (2019) | 1980–2015 | 24 MENA countries | Panel (PVAR) |
| | Frodyma, Papież and Śmiech (2022) | 1970–2017 | 28 EU countries | Time series (ARDL, ECT) |
| | He and Richard (2010) | 1948–2004 | Canada | Time series (VECM) |
| | Jaunky (2011) | 1980–2005 | 36 high-income countries | Panel (GMM) |
| | Knight and Schor (2014) | 1991–2007 | 29 high-income countries | Panel (Prais-Winsten regression, Driscoll-Kraay) |
| | Mensah et al. (2021) | 1990–2018 | 26 African economies | Panel (CCEPMG, CS-ARDL, AMG) |
| | Shah, Naqvi and Anwar (2020) | 1980–2017 | Pakistan | Time series (ARDL, VECM) |
| | Shahbaz, Bhattacharya and Ahmed (2017) | 1970–2012 | Australia | Time series (ARDL, ECM) |
| | Sinha and Sen (2016) | 1992–2012 | BRIC countries | Panel (GMM) |

Scholars have also pointed to several limitations of EKC hypothesis, which challenge both its empirical validity and theoretical foundation (Kaika and Zervas, 2013). First, from a policy viewpoint, the EKC has been accused of encouraging a "grow first, clean up later" mindset. Proponents of this view, such as Beckerman (1992), have argued that economic growth should be the primary focus for developing countries, under the assumption that environmental improvements will naturally follow increasing incomes. However, critics argue that this is a dangerous oversimplification. The progress seen in high-income countries was not a natural by-product of growth, but the result of deliberate and often costly environmental policies (Dasgupta, Laplante and Wheeler, 2002). Even more concerning, this narrative ignores the possibility of irreversible damage—such as biodiversity loss or toxic chemical accumulation—that cannot be undone later by income growth (Arrow *et al.*, 1995). Second, the traditional EKC is limited by its narrow focus on production-based emissions. In a globalized economy, many high-income countries have reduced their domestic emissions, partly by outsourcing pollution-intensive production to developing nations, while continuing to consume carbon-heavy goods through imports. As a result, their production-based emissions may appear to decline, while their consumption-based carbon footprint continues to grow (Peters *et al.*, 2011; Knight and Schor, 2014). In this sense, the EKC may create a misleading picture of decoupling. One methodological limitation is the assumption of homogeneity in many early studies, where data are pooled into aggregated panels. Individual country characteristics—such as institutional quality, energy mix, and technological capabilities—play a key role in shaping emissions (Stern, 2017). Therefore, this approach is prone to pooling bias, producing a misleading average curve that does not accurately reflect a specific country or group of countries (Dijkgraaf and Vollebergh, 2005). Acknowledging these limitations has directly motivated this research.

### 2.2 Production-based versus consumption-based emissions

As mentioned, one limitation of the traditional EKC framework is its reliance on production-based emissions (PCO2). These emissions, also known as territorial emissions, are only counted within the geographical boundaries of a country. While this is still a standard measure in national reports and international climate agreements, it does not account for the environmental effects of international trade. High-income countries, which are often subject to stringent environmental regulations, tend to shift polluting industries to developing economies. This process is referred to as carbon leakage. As Rothman (1998) argued, the environmental progress may be misleading, achieved not by domestic decarbonization but by shifting the pollution burden elsewhere. This pattern is also related to the Pollution Haven Hypothesis (PHH), which suggests that trade liberalization enables more developed countries to reduce domestic emissions by importing goods produced in countries with weaker environmental standards.

To address this gap, researchers have turned to consumption-based emissions (CCO2) as an alternative indicator of environmental degradation. CCO2 adjusts PCO2 for international trade. To be more specific, CCO2 accounts for all emissions associated with the final consumption of goods and services within a country, regardless of where they were produced. It is calculated by taking production emissions, adding the emissions embodied in imports, and subtracting those embodied in exports. Pioneering work by Hertwich and Peters (2009) and Davis and Caldeira (2010) was instrumental in quantifying these global emission transfers.

In response, a growing body of research has compared the EKC hypothesis using both metrics, revealing a scholarly debate with divergent findings. Some studies find that the inverted U-shaped relationship holds for both emission types. For instance, Danish, Ulucak and Erdogan (2022) found EKC support for 15 OECD countries under both emissions, using Driscoll-Kraay regression. Similarly, Sun *et al.* (2021) confirmed the EKC in China from 1990 to 2017, using both production- and consumption-based metrics. By contrast, some studies reject the EKC hypothesis under both emission metrics. Frodyma, Papież and Śmiech (2022), in their study of EU countries, rejected the EKC hypothesis for both production and consumption emissions, arguing that economic growth remains tightly coupled with emissions regardless of accounting method. Similarly, Dong, Wang and Guo (2016) in their study of global EKC emphasized that neither metric consistently supports the EKC pattern across diverse regions.

However, the most common finding among the literature supports the notion of "decoupling illusion," whereby the EKC often holds for production emissions but not for consumption emissions. These studies consistently show that, when the effects of international trade are considered, consumption emissions either continue to increase or have extremely high turning points. Knight and Schor (2014), for example, found that in 29 high-income countries, the EKC was supported for PCO2 but not for CCO2, undermining claims of sustainable growth. Similarly, Mir and Storm (2016) argued that while production emissions in advanced economies showed signs of decoupling, consumption emissions either kept increasing or re-coupled with growth.

Schröder and Storm (2020) expanded on this by arguing that growth-oriented policies risk locking economies into "hothouse earth" trajectories, as consumption patterns in wealthy nations offset efficiency gains. Leal and Marques (2022) observed the same divergence in OECD economies, noting that the EKC pattern for CCO2 is much weaker in highly globalized countries. More recently, Makarov and Alataş (2024), using a large panel of 85 countries from 1990 to 2020, demonstrated that while net exporters sometimes exhibited EKC patterns for both PCO2 and CCO2, net importers consistently showed weaker or absent EKC relationships for CCO2.

Literature has therefore firmly established that focusing exclusively on PCO2 is insufficient and that the divergence between production-based and consumption-based emissions is a critical blind spot. Yet, much of the existing work comparing PCO2 and CCO2 remains fragmented. Many are limited to single-country analyses (e.g., He and Richard, 2010; Sun *et al.*, 2021) or regional analyses (e.g., Knight and Schor, 2014; Danish, Ulucak and Erdogan, 2022). Studies examining environmental degradation by income groups (e.g., Ulucak and Bilgili, 2018; Naqvi et al., 2021) have contributed to the understanding of EKC, but have typically relied on more aggregate indicators such as ecological footprints, and have not systematically compared PCO2 and CCO2. As a result, there has been little systematic investigation into how the relationship between income and emissions differs for production and consumption measures across stages of development. This is a gap that motivates this research.

### 2.3 Urbanization and emissions

To build a more robust model and reduce the risk of omitted variable bias, this study extends the standard EKC framework by incorporating key structural variables. In line with extensive practice in literature, urbanization is included as a core control variable due to its significant influence on the environment. The relationship between urbanization and $CO_2$ emissions has been widely examined and yielded mixed findings. A considerable amount of research indicates that urbanization is a major cause of environmental damage. An early cross-country study by Parikh and Shukla (1995) suggested that urbanization drives emissions in three ways: by shifting consumption from traditional to modern fuels, by increasing demand for energy-intensive goods, and through greater transport use. Similarly, Poumanyvong and Kaneko (2010), using data from 99 countries, found that urbanization increases emissions in all income groups, with the effect being most pronounced in the middle-income group. At a regional level, Wang et al. (2016)

showed that urbanization increased $CO_2$ emissions in BRICS economies, and Salahuddin et al. (2019) verified that it is a key long-run driver of emissions in Sub-Saharan Africa.

In contrast, another body of research emphasizes the mitigating impacts of urbanization. For example, Sharma (2011) analyzed 69 nations and showed that urbanization lowered $CO_2$ emissions in high, middle, and low income groups. Li and Lin (2015) further nuanced this picture, showing that while urbanization increases emissions in low-income nations, it has the opposite effect in middle and high-income countries, where efficiency gains dominate. This efficiency-based view is suggested in the "compact city" hypothesis. Glaeser and Kahn (2010) showed that dense urban living in U.S. cities leads to significantly lower emissions from driving and home heating compared to suburban patterns. Supporting this idea, Dodman (2009) argued that dense urban settlements can benefit from economies of scale in public transport, service-based industries, and energy-efficient infrastructure, all of which help to reduce per capita carbon footprints. Moreover, several studies report insignificant results, suggesting that the impact of urbanization cannot be easily generalized. For example, Lin et al. (2017), Wang et al. (2018 ), and Chen et al. (2019) found no statistically significant link between urbanization and $CO_2$ emissions.

**2.4 Energy consumption variables and emissions**

Besides urbanization, energy consumption is a critical variable in the EKC framework, as it represents the most direct channel linking economic activities to emissions (Leal and Marques, 2022). Specifically, the balance between fossil fuel and renewable energy consumption is central to the income–emissions relationship. Our comprehensive EKC model therefore distinguishes their roles explicitly. The literature suggests that fossil fuels emerge as the driver of industrial growth and emissions, while renewable energy often has a mitigation effect.

The link between fossil fuel consumption and $CO_2$ emissions is important in environmental economics. Globally, fossil fuels remain the primary driver of carbon emissions, accounting for nearly 89% of $CO_2$ released in 2018 (Shukla *et al.*, 2022). Scholars have begun to include fossil fuel consumption as an important determinant of emissions in the EKC framework. Among the first studies to do so, Lee, Chiu and Sun (2009) included fossil fuel in their cubic EKC model and found positive relationship across 89 countries over 1960–2000. Subsequent large-scale analyses have consistently confirmed this relationship. Mensah et al. (2021), in a study of 26 African economies, found fossil fuel use to be a significant long-run driver of environmental degradation across all regional sub-panels. Similarly, long historical analyses of OECD countries by Churchill et al. (2018) implicitly confirm the significant role of fossil fuels in driving emissions throughout the industrial era. More recent single-country research, such as Salari, Javid and Noghanibehambari (2021) for the United States and Ullah et al. (2021) for Vietnam, provide more support for this finding. Overall, these studies highlight that reliance on fossil fuels remains a fundamental barrier to long-term emissions reduction.

Given the significant environmental costs of fossil fuels, renewable energy sources such as wind, solar, and hydro are widely regarded as the most viable alternatives. These energy sources emit little waste and have minimal environmental externalities, thus playing a vital role in strategies to decouple economic growth from environmental degradation. Many empirical studies have confirmed the negative relationship between renewable energy use and emissions. For example, Dogan and Seker (2016), analyzing a panel of leading renewable energy countries, found that greater renewable consumption significantly reduced $CO_2$ emissions. Bilgili, Koçak and Bulut (2016) reached similar conclusions for 17 OECD countries, while Ben Jebli, Ben Youssef and Ozturk (2016) reported the same effect for 25 OECD countries. Evidence from emerging regions is equally supportive. For example, Ahmed *et al.*, (2022) showed that renewable adoption in South Asia enhances environmental quality, and Adams and Acheampong (2019) found significant mitigating effects in Sub-Saharan Africa from 1980–2015. Country-specific studies reinforce this picture, including Italy (Cerdeira Bento and Moutinho, 2016), Pakistan (Danish *et al.*, 2017), India (Sinha and Shahbaz, 2018) and China (Chen *et al.*, 2019), all of which found reductions in emissions associated with renewable energy consumption. Collectively, these findings highlight the consistent role of renewable energy in curbing carbon emissions across diverse regions and income groups. While the evidence is strong, its mitigating effect is sometimes rejected. Some studies, such as Charfeddine and Kahia (2019) for 24 MENA countries and Pata (2018) for Turkey, report weak or insignificant results. This suggests that the relationship can be sensitive to regional energy structures and model specifications.

Furthermore, growing evidence shows that the influence of renewable energy is not always straightforward. According to Mongo, Belaïd and Ramdani (2021), environmental improvements can reduce $CO_2$ emissions in the long term, but may also cause a short-term rebound effect. In these cases, efficiency gains lower energy costs, which in turn encourage higher consumption and temporarily increase emissions. Similarly, Yang et al. (2022) raises a caution that large-scale but poorly diversified renewable projects may unintentionally raise emissions by stimulating energy-intensive economic activity through multiplier effects. These findings underscore that while renewable energy is essential to global decarbonization efforts, its success is not automatic. Instead, its effectiveness depends on coherent policy frameworks that minimize unintended consequences and direct investment toward technologies capable of sustained emissions reduction.

This literature review reveals several key findings that directly guide the research framework of this thesis. First, while the EKC hypothesis has been widely investigated, results remain highly sensitive to countries, methodological approach, and the choice of emissions measure. Moreover, analyses treat economies as homogeneous, thereby obscuring differences across countries. Second, most studies focus on production-based emissions and therefore overlook the carbon embodied in trade, which can create a misleading picture of environmental progress. There has been little systematic investigation into how the relationship between income and emissions differs for production and consumption measures across stages of development. This study aims to fill this gap by testing the validity of the EKC for both production- and consumption-based $CO_2$ emissions across income groups, while accounting for important control variables including urbanization, fossil fuel, and renewable energy consumption. It provides a more granular understanding of how a nation’s role in the global economy shapes its environmental path at each stage of development.

## SECTION 3: DATA AND METHODOLOGY

This section outlines the empirical framework used to test the validity of the EKC hypothesis. It begins by describing the panel dataset and specifying the dependent and independent variables of the model. It then presents the model specification. The section proceeds to detail the multi-step econometric methods employed. This sequence includes pre-estimation diagnostics for cross-sectional dependence and slope homogeneity, second-generation panel unit root tests, the main estimation for long-run relationships, and a final robustness check.

### 3.1 Panel dataset and model specification

This study investigates the Environmental Kuznets Curve (EKC) hypothesis using a balanced panel dataset for 95 countries over the period 1990–2021. We retain countries with complete series on all variables, and no imputation is used. The countries are then classified into three income groups based on the World Bank's 2021 classifications: (i) high-income, (ii) upper-middle-income, and (iii) lower-middle-income. The low-income group was excluded due to significant data limitations. A complete list of the countries in each panel is presented in Appendix A.

This study will have two models with two dependent variables, per capita production-based emissions (PCO2), and per capita consumption-based emissions (CCO2). Both measures are obtained from the Global Carbon Budget (2024). The core independent variables to test EKC are Gross Domestic Product per capita (GDP) and its squared term, which together allow for the identification of potential non-linearities in the income–emissions relationship. The model is extended with three control variables: urbanization (URB), fossil fuel energy consumption (FEC), and renewable energy consumption (REC). The selection of these variables is grounded in established theory. The inclusion of GDP and squared GDP is fundamental for testing the inverted U-shaped EKC hypothesis. Urbanization is included as a key driver of structural change, energy demand, and consumption patterns that influence emissions (Murshed, Ali and Banerjee, 2021; Maranzano, Cerdeira Bento and Manera, 2022). Fossil fuel energy consumption is the primary direct source of emissions (Churchill *et al.*, 2018; Mensah *et al.*, 2021), while renewable energy consumption represents a mitigation effect (Bilgili, Koçak and Bulut, 2016; Dogan and Seker, 2016). Data for all independent variables is drawn from the World Bank’s World Development Indicators. A complete list of variables and data sources is summarized in Table 2.

**Table 2.** Description of variables (1990-2021)

| Variable | Description | Source |
| --- | --- | --- |
| PCO2 | Production-based $CO_2$ emissions per capita (tons) | Global Carbon Budget |
| CCO2 | Consumption-based $CO_2$ emissions per capita (tons) | Global Carbon Budget |
| GDP | Gross domestic product per capita (constant 2015 USD) | World Bank |
| URB | Urban population (% of total population) | World Bank |
| FEC | Fossil fuel energy consumption (% of total energy use) | World Bank |
| REC | Renewable energy consumption (% of total energy use) | World Bank |

To estimate the relationship, this study constructs two models for production and consumption emissions. All variables are transformed into natural logarithms, which helps to mitigate skewness. The log-linear specifications of the models are as follows:

$$\ln PCO2_{it} = \alpha_0 + \alpha_1 \ln GDP_{it} + \alpha_2 (\ln GDP)^2_{it} + \alpha_3 \ln URB_{it} + \alpha_4 \ln FEC_{it} + \alpha_5 \ln REC_{it} + \epsilon_{it} \quad (1)$$

$$\ln CCO2_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 (\ln GDP)^2_{it} + \beta_3 \ln URB_{it} + \beta_4 \ln FEC_{it} + \beta_5 \ln REC_{it} + \mu_{it} \quad (2)$$

where i denotes the country and t denotes the period. The terms $\alpha$ and $\beta$ represent the coefficients to be estimated, and $\epsilon$ and $\mu$ are the error terms. The validity of the EKC hypothesis depends on the signs and significance of the income coefficients. Specifically, an inverted U-shaped relationship is confirmed if the long-run coefficient for lnGDP ($\alpha_1$, $\beta_1$) is positive and for its squared term ($\alpha_2$, $\beta_2$) is negative. The relationships are summarized in Table 3.

**Table 3**. Potential relationships between economic growth and emissions

| Coefficients (α or β) from equation (1 or 2) | Relationship between per capita GDP and per capita CO2 emissions |
| --- | --- |
| $\beta_1 = 0, \quad \beta_2 = 0$ | No relationship |
| $\beta_1 > 0, \quad \beta_2 = 0$ | Linearly increasing |
| $\beta_1 < 0, \quad \beta_2 = 0$ | Linearly decreasing |
| $\beta_1 > 0, \quad \beta_2 < 0$ | Inverted U-shaped (EKC supported) |
| $\beta_1 < 0, \quad \beta_2 > 0$ | U-shaped |

### 3.2 Econometric approaches

To ensure the empirical results are robust and reliable, this study adopts a systematic, multi-step econometric strategy in line with modern panel data analysis. This analytical sequence is consistent with the approach in recent empirical studies on the EKC hypothesis (Naqvi *et al.*, 2021; Saqib *et al.*, 2022). The procedure unfolds in the following sequence:

a) Pre-estimation tests: The analysis begins by testing two fundamental properties of panel data, cross-sectional dependence (CD), and slope homogeneity. The outcomes of these tests are critical, as they determine the choice of appropriate panel unit root and estimation techniques in the subsequent steps.

b) Panel unit root tests: Based on results of pre-estimation tests, a second-generation panel unit root test is employed to determine the order of integration for each variable.

c) Long run estimation: The presence of mixed integration orders and heterogeneity justifies the use of the Panel Autoregressive Distributed Lag (ARDL) model to investigate the long-run relationships among the variables.

d) Robustness check: Finally, the long-run estimates are checked for robustness using the Driscoll and Kraay (1998) standard errors method.

This entire analytical sequence is applied to both PCO2 and CCO2 models for each of the three income groups to capture their distinct dynamics. Each step is detailed in the subsections below.

3.2.1 Cross-sectional dependence and slope homogeneity tests

In panel data analysis, it is crucial to test for cross-sectional dependence (CD). CD arises when shocks or unobserved factors in one country are correlated with those in other countries in the panel. This is a common feature in a globalized world with integrated markets and policy spillovers (Shahbaz and Sinha, 2019). Ignoring the presence of CD can lead to biased and inconsistent estimates. To formally test this, the study employs two widely used tests. The first is the Breusch and Pagan (1980) Lagrange Multiplier (BP-LM) test, which is suitable for panels with a fixed number of cross-sections (N) and a large time dimension (T). The null hypothesis is cross-sectional independence. The LM statistics are calculated as:

$$BP_{LM} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}$$

where $\hat{\rho}_{ij}$ is the sample estimate of the pairwise correlation of the residuals. When N is large, the LM test can be biased. Therefore, this study also employs the Pesaran (2004) CD test, which is robust to large N panels. The Pesaran CD statistics are given by:

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} \hat{\rho}_{ij}^{2} \rightarrow N(0,1)$$

The next diagnostic step is to assess the assumption of slope homogeneity. Conventional panel models often assume that the slope coefficients are identical across all cross-sectional units. However, this assumption is frequently violated in practice, as countries possess unique economic, institutional, and technological characteristics that can lead to heterogeneous responses. Imposing homogeneity when heterogeneity exists can result in aggregation bias and misleading inferences.

To investigate this, the study uses the delta tests developed by Hashem Pesaran and Yamagata (2008), which are improved on Swamy (1970) test. This test evaluates the null hypothesis of slope homogeneity against the alternative hypothesis of heterogeneity. The rejection of the null hypothesis will provide evidence for slope heterogeneity. The test produces two statistics, the standard delta tilde ($\tilde{\Delta}$) and the bias-adjusted version ($\tilde{\Delta}_{adj}$) specified as:

$$\tilde{\Delta} = \left(\frac{1}{N}\tilde{S} - k\right)\sqrt{\frac{N}{2k}} \qquad \tilde{\Delta}_{adj} = \left(\frac{1}{N}\tilde{S} - 2k\right)\sqrt{\frac{N(T+1)}{2k(T-k-1)}}$$

where $\tilde{S}$ is the Swamy's test statistics.

### 3.2.2 Second-generation panel unit root test

Determining the stationarity properties of the variables is essential for avoiding the risk of spurious regressions. However, traditional first-generation panel unit root tests, such as those proposed by Levin, Lin and James Chu (2002) and Im, Pesaran and Shin (2003), are built on the assumptions of cross-sectional independence and slope homogeneity. As the diagnostic tests in the preceding section confirm the presence of both cross-sectional dependence and slope heterogeneity in our data, these first-generation tests would yield unreliable and misleading results. Consequently, it is imperative to employ a second-generation panel unit root test that is robust to these issues.

To this end, this study utilizes the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test, developed by Pesaran (2007). This test is derived from the average of individual Cross-sectionally Augmented Dickey-Fuller (CADF) regressions. The CADF test enhances the standard Dickey-

Fuller regression by including the cross-sectional averages of lagged levels and first differences of the individual series. This augmentation serves as a proxy for unobserved common factors, thereby accounting for cross-sectional dependence. The CADF regression is specified as:

$$\Delta y_{it} = \alpha_i + p_i \bar{y}_{t-1} + \sum_{j=0}^{k} \gamma_{ij} \Delta \bar{y}_{it-1} + \sum_{j=0}^{k} \delta_{ij} y_{it-1} + \varepsilon_{it}$$

where $y_{it}$ is the variable of interest for country i at time t, $\bar{y}_{it}$ is its cross-sectional average, $\Delta$ is the first-difference operator, and $p$ is the number of lags. The CIPS statistics are then computed as the simple average of the individual CADF statistics for each country. This approach effectively addresses both cross-sectional dependence and slope heterogeneity, providing a reliable assessment of the integration order of each variable in our panel. CIPS statistics are specified as:

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

### 3.2.3 Panel autoregressive distributed lag (ARDL) estimation

This study employs the Panel Autoregressive Distributed Lag (ARDL) framework, developed by Pesaran and Smith (1995) and extended by Pesaran, Shin and Smith (1999). The choice of this approach has several advantages. First, it yields consistent and efficient estimates regardless of whether the variables are I(0), I(1), or a mixture of both. Second, it is possible to estimate both long-run and short-run dynamics within a single error correction model (ECM) framework. Third, by including sufficient lags of the regressors, the ARDL technique can reduce endogeneity problems and is robust in smaller samples (Haug, 2002). The ARDL Panel model has been used in many studies related to the EKC framework, demonstrating its suitability in analyzing the relationship between income and emissions. For instance, Azam and Khan (2016) applied ARDL in a panel of developing nations, while Shahbaz, Bhattacharya and Ahmed, (2017) used ARDL to investigate how energy consumption and financial development influence $CO_2$ emissions. More recently, Rahman, Alam and Velayutham (2022) and Aydin, Koc and Sahpaz (2023) used an ARDL panel to reassess EKC in emerging economies.

Panel ARDL model estimation is performed using one of two approaches: Mean Group (MG) or Pooled Mean Group (PMG). The MG estimator runs the regression separately for each country and then averages the coefficients, allowing all parameters to be heterogeneous. In contrast, the PMG estimator assumes that long-run coefficients are homogeneous across all nations whereas short-run coefficients are heterogeneous. The use of PMG is theoretically sound if there is reason to believe that a common long-run equilibrium relationship exists across the panel (EKC pattern). The decision between the two estimators is made empirically by conducting a Hausman test, which tests the null hypothesis of long-run slope homogeneity. If the null is rejected, the MG estimator is preferred; otherwise, PMG is chosen.

The panel ARDL (p,q,...,q) model for equation (1) and (2) can be expressed in its error correction form as:

$$\Delta Y_{it} = \phi_i(Y_{it-1} - \beta' X_{it}) + \sum_{j=1}^{p-1} \delta_{ij} \Delta Y_{it-j} + \sum_{j=0}^{q-1} \gamma'_{ij} \Delta X_{it-j} + \mu_i + \varepsilon_{it}$$

where $Y_{it}$ is the dependent variable, representing either lnPCO2 or lnCCO2 for country i at time t. $X_{it}$ is the vector of explanatory variables, including lnGDP, $(\text{lnGDP})^2$, lnURB, lnFEC, lnREC. The parameters p and q denote the number of lags of the dependent and independent variables, respectively.

In this study, an ARDL (1,1,1,1,1) specification was applied, meaning that the dependent variable and each of the five explanatory variables enter the model with one lag. The lag structure was determined using information criteria, AIC and BIC. Δ is the first-difference operator. The vector $\beta$ captures long-run coefficients, which are assumed to be homogeneous across countries within each income group. $\delta_{ij}$ and $\gamma_{ij}$ are the country-specific short-run dynamic coefficients. The term in the parenthesis, $(Y_{it-1} - \beta' X_{it})$, is the Error Correction Term (ECT). It represents the deviation from the long-run equilibrium in the previous period. The coefficient $\phi_i$ indicates the speed at which the system corrects back towards this long-run equilibrium following a short-run shock. A negative and statistically significant $\phi_i$ is essential for confirming a stable long-run relationship.

The key objective of the model estimation is to test the inverted U-shape of the EKC curve. This is confirmed if the long-run coefficient of lnGDP is positive and the coefficient of $(\text{lnGDP})^2$ is negative. From these estimated coefficients, the income level at which emissions begin to decline, known as EKC turning point, can be calculated. This represents the level of per capita income at which economic growth continues to improve the environment. It therefore serves as a policy-relevant benchmark, helping to determine whether a country is still in a highly polluting stage of development or has moved onto a sustainable growth path. The turning point is calculated as:

$$GDP = \exp\left(\frac{-\beta_1}{2\beta_2}\right)$$

### 3.2.4 Robustness check

To ensure the validity of the primary findings, this study conducts a robustness check using an alternative estimation strategy. Specifically, we apply a panel regression model with Driscoll–Kraay (DK) standard errors, developed by Driscoll and Kraay (1998). The Hausman test guides the choice between fixed effects (FE) and random effects (RE). The DK error correction method offers several advantages. Unlike conventional clustered standard errors, DK errors are robust to heteroskedasticity, serial correlation, and general forms of cross-sectional dependence, features that are common in global macroeconomic panels. This makes the method particularly suitable for testing results in cross-country studies where spillovers and interdependence between units are unavoidable. By applying DK standard errors, we can estimate the long-run relationship even when cross-country dependence and slope heterogeneity exist. Although this static model is built on different assumptions from the dynamic ARDL panel framework, it serves as an important benchmark. Most importantly, if the signs and significance of the main coefficients in the EKC model remain consistent between the two approaches, the reliability and generalizability of the research results will be strengthened. Once the model has been specified and the methodology justified, the next section presents the data and results.

# SECTION 4: EMPIRICAL RESULTS

This chapter presents the empirical findings of the study, following the econometric methodology in Section 3. The analysis begins with descriptive statistics to observe differences across the high, upper-middle, and lower-middle income panels. This is followed by the results of cross-sectional dependence, slope homogeneity , and panel unit roots. The core of the chapter details the long-run estimation results from the Panel ARDL model for each income group. The section concludes with a robustness check. While this section focuses on presenting the results, a detailed discussion and interpretation of these findings will be provided in Section 5.

## 4.1 Descriptive statistics

This section begins by exploring the summary statistics of the variables for High-income, Upper-middle-income, and Lower-middle-income countries. As shown in Table 4, the data reveals significant heterogeneity across groups, which motivates our decision to classify the dataset into three income groups.

The descriptive statistics reveal a clear income-based difference in emissions level. High-income countries display the highest average per capita emissions, with a mean of 8.898 tons for production-based emissions (PCO2) and 11.053 tons for consumption-based emissions (CCO2). The fact that consumption emissions are higher than production emissions suggest that, on average, high-income nations are net importers of embodied carbon emissions. This observation is consistent with literature on global trade and pollution outsourcing of developed countries (Peters *et al.*, 2011). By contrast, upper-middle-income countries show slightly higher production emissions (3.610 tons per capita) than consumption emissions (3.426 tons per capita), suggesting their role as net exporters of carbon in global supply chain. The lower-middle-income group has the lowest emissions, at approximately 1.5 tons per capita for both emission types. This group also exhibits the least variation in emissions, whereas the high-income group has high standard deviation for both PCO2 and CCO2, which highlights significant diversity and the presence of major emitter nations within that panel such as the US, Germany, Canada.

**Table 4.** Descriptive statistics

| Variable | Statistics | High-income | Upper–middle–income | Lower–middle–income |
|---|---|---|---|---|
| PCO2 | Mean | 8.898 | 3.610 | 1.465 |
| | Std. Dev. | 4.520 | 3.126 | 2.060 |
| | Min | 1.270 | 0.000 | 0.037 |
| | Max | 32.122 | 17.024 | 15.246 |
| CCO2 | Mean | 11.053 | 3.426 | 1.520 |
| | Std. Dev. | 5.603 | 2.253 | 1.817 |
| | Min | 1.576 | 0.000 | 0.059 |
| | Max | 47.559 | 16.311 | 15.242 |
| GDP | Mean | 30,819.620 | 5,457.240 | 1,778.470 |
| | Std. Dev. | 20,053.090 | 2,730.190 | 1,068.690 |
| | Min | 4,059.100 | 792.570 | 369.930 |
| | Max | 112,417.900 | 14,040.620 | 5,381.190 |
| URB (%) | Mean | 75.212 | 61.000 | 42.850 |
| | Std. Dev. | 12.757 | 14.268 | 17.402 |
| | Min | 47.915 | 26.442 | 8.854 |
| | Max | 100.000 | 92.229 | 91.626 |
| FEC (%) | Mean | 77.394 | 75.045 | 54.846 |
| | Std. Dev. | 15.566 | 18.327 | 28.258 |
| | Min | 25.120 | 20.140 | 3.780 |
| | Max | 100.000 | 99.900 | 99.660 |
| REC (%) | Mean | 15.666 | 24.070 | 46.401 |
| | Std. Dev. | 12.717 | 18.401 | 29.016 |
| | Min | 0.200 | 0.700 | 0.400 |
| | Max | 61.200 | 79.200 | 95.200 |

**Note:** PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption.

The mean per capita GDP in the high-income panel ($30,820) is more than five times that of the upper-middle-income group ($5,457) and more than 17 times that of the lower-middle-income group ($1,778). This economic disparity also reflects structural differences in urbanization and energy consumption. High-income countries are the most urbanized (75.2%) and most dependent on fossil fuels (77.4%), while upper-middle-income countries follow a similar, though less pronounced, pattern. In contrast, the lower-middle-income group reports the highest share of renewable energy in its mix (46.4%). It is important to note that much of the renewable share in lower-middle-income countries comes from traditional biomass rather than from modern, diversified renewable infrastructure. This reliance poses unique challenges for a sustainable energy transition (*World Energy Outlook 2023 – Analysis*, 2023). These differences in economic structure and emission profiles suggest that the EKC relationship is unlikely to be uniform across the panels.

Before moving to pre-estimation tests, the data was assessed for multicollinearity. The pairwise correlation matrix (Appendix B) confirmed that the relationships between variables align with theoretical expectations. GDP, URB, and FEC are generally positively correlated with emissions, while REC shows a strong negative correlation (Dogan and Seker, 2016; Wang *et al.*, 2016; Murshed, Ali and Banerjee, 2021). As some variables exhibited moderate correlations, a formal diagnostic using the Variance Inflation Factor (VIF) was performed. The VIF results indicate that the values for all regressors are well below 2.5. This provides a strong verdict that multicollinearity is not a significant concern and is unlikely to affect the stability and reliability of the regression estimates presented in the following sections.

**4.2 Cross-sectional dependence and slope homogeneity test results**

Two preliminary diagnostic tests were conducted to determine the properties of the panels, which are important to decide which technique to use for unit root and estimation. First, Breusch-Pagan Lagrange Multiplier (1980) and Pesaran (2004) CD tests were performed to test cross-sectional dependence. The results are displayed in Table 5. We can see that the statistics strongly reject the null hypothesis of cross-sectional independence at the 1% significance level across all variables and panels. Therefore, results confirm the existence of CD.

**Table 5.** Result of cross-sectional dependence tests

| | High-income | | Upper–middle–income | | Lower–middle–income | |
|---|---|---|---|---|---|---|
| Variable | BP-LM | CD | BP-LM | CD | BP-LM | CD |
| lnPCO2 | 8871.8*** | 59.421*** | 3829.4*** | 28.17*** | 5935.8*** | 40.926*** |
| lnCCO2 | 6359.2*** | 40.427*** | 3345.9*** | 39.57*** | 5424.1*** | 46.792*** |
| lnGDP | 17642*** | 131.600*** | 9261.1*** | 94.23*** | 8665.3*** | 82.439*** |
| $(\ln GDP)^2$ | 17617*** | 131.460*** | 9309.4*** | 94.467*** | 8678.4*** | 82.543*** |
| lnURB | 13132*** | 44.042*** | 10661*** | 74.536*** | 8297.4*** | 62.937*** |
| lnFEC | 11517*** | 73.662*** | 3606.4*** | 11.615*** | 4853.8*** | 27.780*** |
| lnREC | 11635*** | 85.850*** | 3431.2*** | 15.432*** | 5904.3*** | 34.920*** |

**Note:** BP-LM is Breusch-Pagan Lagrange Multiplier test; CD is Pesaran CD test. PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption. All variables are in natural logarithms (ln). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Second, the Pesaran and Yamagata (2008) test for slope homogeneity was conducted (Table 6). The null hypothesis of homogenous slopes was also rejected at the 1% level, confirming the presence of country-specific heterogeneity in the relationships between the variables. These joint findings are critical, as they violate the core assumptions of standard panel data models. The presence of strong CD and slope heterogeneity invalidates first-generation unit root tests and estimators. Therefore, this study proceeds with the second-generation panel unit root test and panel ARDL model.

**Table 6.** Result of slope heterogeneity test

| Model | Statistic | High-income | Upper–middle–income | Lower–middle–income |
|---|---|---|---|---|
| lnPCO2 | $\Delta$ | 35.910*** | 26.566 *** | 26.894 *** |
| | $\tilde{\Delta}_{adj}$ | 40.628*** | 30.060 *** | 30.450 *** |
| lnCCO2 | $\Delta$ | 30.728 *** | 23.338 *** | 24.079 *** |
| | $\tilde{\Delta}_{adj}$ | 34.765*** | 26.408 *** | 27.263 *** |

**Note:** PCO2 – Production-based emissions; CCO2 – Consumption-based emissions. Variables are in natural logarithms (ln). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

### 4.3 Second-generation panel unit root test results

Given the confirmed presence of cross-sectional dependence, the stationarity properties of each variable were examined using a second-generation panel unit root test. Specifically, CIPS test proposed by Pesaran (2007) was employed, as it is robust to both heterogeneity and cross-sectional dependence. The results of the CIPS tests at level and at first difference for all variables, are presented in Table 7. We also perform the test for some potential lags.

**Table 7.** Second-generation Panel Unit Root Test (CIPS)

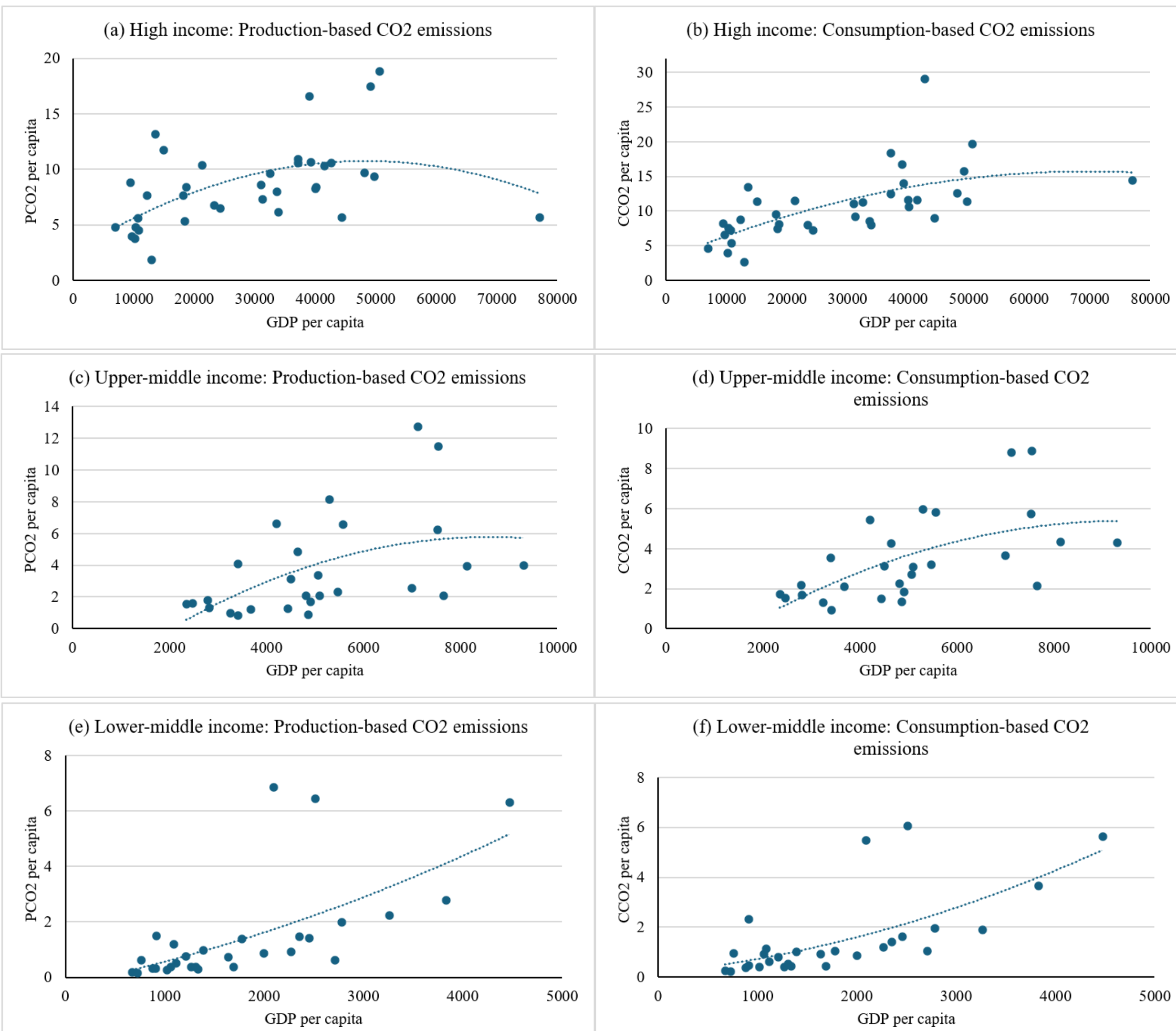
| | Level | | | First Difference | | |
|---|---|---|---|---|---|---|
| Lag | 0 | 1 | 2 | 0 | 1 | 2 |
| High-income | | | | | | |
| lnPCO2 | -1.599 * | -0.262 | 4.171 | -21.924 *** | -13.613 *** | -4.714 *** |
| lnCCO2 | -0.589 | 1.449 | 0.532 | -22.808 *** | -12.082 *** | -5.047 *** |
| lnGDP | -4.748 *** | -0.855 | 1.923 | -16.946 *** | -10.907 *** | -5.564 *** |
| $(\ln GDP)^2$ | -4.309 *** | -0.434 | 2.283 | -16.760 *** | -10.599 *** | -5.272 *** |
| lnURB | 1.166 | 2.631 | 4.728 | -0.232** | 0.833** | 2.792** |
| lnFEC | -1.995 ** | -1.224 | 1.558 | -23.037 *** | -14.355 *** | -7.559 *** |
| lnREC | -3.433 *** | -2.702 *** | -3.650 *** | -22.993 *** | -14.242 *** | -8.614 *** |
| Upper–middle–income | | | | | | |
| lnPCO2 | -0.810 | -0.775 | -0.292 | -16.180*** | -8.506*** | -4.969*** |
| lnCCO2 | -2.142 | -1.889* | 0.171 | -20.202*** | -14.355*** | -6.855*** |
| lnGDP | -0.024 | -1.804** | -0.551 | -11.113*** | -6.991*** | -5.020*** |
| $(\ln GDP)^2$ | 0.804 | -1.265 | -0.713 | -10.801*** | -6.603*** | -4.773*** |
| lnURB | 0.743 | 3.853 | 5.930 | -0.334 | 1.735 | 2.452 |
| lnFEC | 0.642 | -0.059 | 0.880 | -17.130*** | -10.067*** | -5.699*** |
| lnREC | 0.032 | 1.257 | 2.082 | -17.575*** | -9.811*** | -4.539*** |
| Lower–middle–income | | | | | | |
| lnPCO2 | -2.768 * | -1.202 | -0.983 | -20.181 *** | -11.879 *** | -7.012 *** |
| lnCCO2 | -1.639 | -0.568 | 0.415 | -21.851 *** | -13.894 *** | -7.136 *** |
| lnGDP | 4.289 | 1.884 | 0.751 | -11.687 *** | -6.135 *** | -3.695 *** |
| $(\ln GDP)^2$ | 4.476 | 2.131 | 0.822 | -11.448 *** | -5.830 *** | -3.532 *** |
| lnURB | 1.167 | 1.354 | 4.665 | 0.502 | -2.726 *** | 1.037 |
| lnFEC | 3.688 | 3.419 | 3.142 *** | -18.177 *** | -8.547 *** | -3.334 *** |
| lnREC | 2.532 | 3.456 *** | 4.161 *** | -16.903 *** | -9.100 *** | -4.785 *** |

**Note:** PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption. All variables are in natural logarithms (ln). Lag indicates the number of lags included in the unit root test. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

The findings provide evidence of a mixed order of integration across all three income panels. Some variables are stationary at their levels, I(0), while others only become stationary after being first-differenced, I(1). This mixed integration order has a crucial implication for the subsequent analysis. It invalidates the use of traditional cointegration techniques (such as the Johansen or Engle-Granger methods) which require all variables to be integrated of the same order. Consequently, this finding further justifies the selection of the Panel Autoregressive Distributed Lag (ARDL) approach. The ARDL framework is ideally suited for this context, as it can robustly estimate long-run relationships even when variables are a mixture of I(0) and I(1).

### 4.4 Panel ARDL estimation results

**Figure 2.** Income - Emissions relationship for each income group




**Note:** Each data point is the country-level average over the period 1990-2021. Dotted lines are second-order polynomial fits to visualize the EKC. They are descriptive only, not model estimates.

Prior to the main estimation, a graphical visualization of the income-emissions correlation provides some preliminary insights into the distinct EKC patterns for each income group. Figure 2 plots the relationship between per capita GDP and both per capita production-based (PCO2) and consumption-based (CCO2) emissions. First, for the high-income countries (panels a and b), the visuals seem to follow the EKC hypothesis for both emission types, with the polynomial trend lines clearly showing an inverted U-shape. However, the downward slope for PCO2 is steeper than for CCO2, and the turning point for PCO2 appears to occur earlier, at a lower income level. Second, for the upper-middle-income countries (panels c and d), the patterns of EKC appear less apparent than in high income group, but the trend line still has a slight curvature. Third, for the lower-middle-income countries (panels e and f), the visual evidence shows no EKC pattern, as both panels depict a positive and linear relationship between income and emissions.

**Table 8.** Estimation results (Panel ARDL)

| | High-income | | Upper–middle–income | | Lower–middle–income | |
|---|---|---|---|---|---|---|
| Dependent variable | PCO2 | CCO2 | PCO2 | CCO2 | PCO2 | CCO2 |
| lnGDP | 2.401*** | 1.045*** | 3.086*** | 3.937*** | 0.386** | -0.424 |
| $(\ln GDP)^2$ | –0.114*** | –0.040** | -0.157*** | -0.202 | 0.019 | 0.065* |
| lnURB | –0.069** | –1.084*** | 0.064 | 0.012 | -0.384*** | 0.351** |
| lnFEC | 1.962*** | 1.651*** | 1.027*** | 0.910*** | 0.748*** | 0.426*** |
| lnREC | –0.198*** | –0.122*** | -0.106*** | -0.074** | -0.234*** | -0.334*** |
| ECT | -0.310*** | -0.322*** | -0.372*** | -0.335*** | -0.348*** | -0.332*** |
| Hausman Test | p > 0.10 | p > 0.10 | p > 0.10 | p > 0.10 | p > 0.10 | p > 0.10 |
| Log likelihood | 2076.70 | 1630.27 | 1200.34 | 910.71 | 1160.37 | 878.72 |
| EKC supported | Yes | Yes | Yes | No | No | No |
| Turning point (constant 2015 USD) | $37,448 | $470,946 | $18,546 | - | - | - |

**Note:** Estimation results are based on the ARDL(1,1,1,1,1) specification using the Pooled Mean Group (PMG) estimator. Each income group is estimated separately for PCO2 and CCO2 models. PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption. All variables are in natural logarithms (ln). EKC is supported when results for lnGDP > 0 and for $(\ln GDP)^2 < 0$. Turning point = $\exp(-\beta_1 / (2 * \beta_2))$. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

These visual patterns set preliminary expectations for our main estimation analysis. Table 8 presents the long-run coefficients of the panel ARDL model, using the Pooled Mean Group (PMG) estimator. The choice of estimator is supported by the Hausman test, which failed to reject the null hypothesis of long-run slope homogeneity ($p > 0.10$) in all six models. A critical finding from the ARDL specification is the error-correction term (ECT), which quantifies the speed of adjustment back to the long-run equilibrium following a short-run shock. The ECT coefficient is negative and statistically significant at the 1% level across all six models, ranging from -0.372 to -0.310. This confirms the existence of a stable long-term relationship between the variables.

#### 4.4.1 High-income countries

For the panel of high-income countries, the results provide supporting evidence for the Environmental Kuznets Curve (EKC) hypothesis for both production-based (PCO2) and consumption-based (CCO2) emissions. In the long run, the coefficients for lnGDP are significantly positive, while the coefficients for quadratic terms are significantly negative, confirming the inverted U-shaped relationship. In the PCO2 model, the coefficient of lnGDP is 2.401 and that of $(\text{lnGDP})^2$ is −0.114. In the CCO2 model, the corresponding values are 1.045 and −0.040. Importantly, the analysis reveals a critical gap in the turning points of the two models. While the turning point for production emissions is calculated at a GDP per capita of \$37,448, the turning point for consumption emissions is \$470,946, which is economically unattainable. This shows that, while high-income countries have successfully decoupled domestic production from growth, they have not accomplished a decoupling of their consumption footprint. This is an expected conclusion and is consistent with our preliminary results from Figure 2.

The analysis of the control variables reveals that fossil fuel consumption (lnFEC) emerges as the most powerful and significant driver of both PCO2 and CCO2, with coefficients of 1.962 and 1.651, respectively. Conversely, renewable energy consumption (lnREC) has a significant mitigating effect on both production (-0.198) and consumption (-0.122) emissions. Urbanization (lnURB) is also found to have statistically significant mitigating effects on PCO2 (-0.069) and on CCO2 (-1.084).

#### 4.4.2 Upper-middle-income countries

The analysis for the upper-middle-income countries shows that the relationship between income and emissions differs when comparing the production and consumption approaches. For production-based emissions (PCO2), the long-run coefficient for lnGDP is significantly positive (3.086), while the coefficient for its quadratic term is significantly negative (-0.157). This confirms a classic inverted U-shaped relationship. The estimated turning point for production emissions is \$18,546. As this income level is just above the maximum observed in the panel, it suggests these nations are still on the upward slope of the EKC curve. In contrast, the EKC hypothesis is rejected for consumption emissions (CCO2). The results show a linear increasing relationship between income and emissions. Specifically, the coefficient of lnGDP is positive and highly significant (3.937), while the squared term is statistically insignificant. This implies that a 1% increase in GDP is associated with a 3.9% increase in consumption-based emissions, with no evidence of a decline in the future.

Unlike the high-income panel, urbanization (lnURB) is found to have no statistically significant impact on either emission type for upper-middle income group. As expected, fossil fuel consumption (lnFEC) is a powerful and significant driver of both production (1.027) and consumption (0.910) emissions. Conversely, renewable energy consumption (lnREC) is found to have significant mitigating effects on production (-0.106) and consumption (-0.074) emissions.

### 4.4.3 Lower-middle-income countries

The analysis for lower-middle-income countries shows that the EKC hypothesis is not supported for either production or consumption-based emissions. For production-based emissions (PCO2), the results show a monotonically increasing relationship with economic growth. The coefficient on lnGDP is positive and significant (0.386), while the quadratic term is insignificant. For consumption-based emissions (CCO2), the relationship with economic growth is less defined and lacks a clear systematic pattern. The coefficient for lnGDP is statistically insignificant, while the squared term is marginally significant. This absence of an EKC pattern is visually depicted in Figure 2 (panels e and f), where we see a positive or U-shaped relationship with no sign of a turning point. The finding indicates that these economies are in a fundamentally earlier stage of development than the previous two income groups.

The control variables reveal a complex and dual role for urbanization. For production emissions, urbanization has a strong mitigating effect (-0.384) while for consumption emissions, urbanization has an increasing effect (0.351). Moreover, as in the other income groups, the energy variables remain powerful. Fossil fuel consumption significantly increases PCO2 (0.748) and CCO2 emissions (0.426), while renewable energy provides significant mitigating effects for both emission types (-0.234 and -0.334, respectively).

### 4.4.4 Robustness check

A comparison with the Driscoll-Kraay fixed effect robust model (Appendix C) confirms that the central findings of EKC patterns and the role of energy variables are highly reliable across all three income groups. Robust results broadly mirror PMG signs and significance; minor magnitude differences do not alter substantive conclusions. For high-income countries, the existence of a strong inverted U-shaped EKC relationship for both production and consumption emissions is supported. For the upper-middle-income group, the EKC is robustly confirmed for PCO2, while the monotonically increasing relationship is confirmed for CCO2. For the lower-middle-income group, the absence of an EKC pattern for both emission types is also a robust finding. Furthermore, the positive impact of fossil fuels and the mitigating effect of renewable energy remain consistent and statistically significant across all models and income groups. However, the impact of urbanization is sensitive to estimation methods. For high-income countries, the significant mitigating effects found in the main ARDL model lose their significance in the static model. For the upper-middle-income group, the relationship is insignificant in the ARDL model but becomes significant and positive in the static fixed effect model. For lower-middle-income countries, the results are mixed. The mitigating effect of urbanization on production emissions (PCO2) is robust, while its positive effect on consumption emissions (CCO2) is not supported by the robust check.

This discrepancy in the role of urbanization highlights the fundamental difference between dynamic and static estimation. The ARDL model captures long-run processes, such as investments in public transport, infrastructure efficiency, and structural shifts in urban economies. The static fixed-effects model, by contrast, reflects immediate, within-period correlations while controlling for country-specific characteristics. Because urbanization encompasses multiple and often competing mechanisms, its measured impact may be more sensitive to these methodological differences than the energy variables, which exhibit direct physical relationships with emissions. This methodological sensitivity is consistent with the wider literature. Empirical studies generally agree on the unidirectional role of fossil fuels and renewable energy (Cole, Rayner and Bates, 1997; Dogan and Seker, 2016; Mensah *et al.*, 2021; Ullah *et al.*, 2023). However, urbanization–emissions link has produced mixed findings. Research on industrializing economies typically finds urbanization to be a strong driver of emissions (Parikh and Shukla, 1995; Poumanyvong and Kaneko, 2010; Wang *et al.*, 2016), while work on developed economies emphasizes its potential mitigating effects through compact-city efficiencies and technological improvements (Dodman, 2009; Glaeser and Kahn, 2010; Sharma, 2011). This apparent contradiction is often referred to as the "urban paradox" (Heinonen and Junnila, 2011), whereby cities appear environmentally efficient in terms of local, production-based emissions, yet their higher consumption and reliance on global supply chains drive up emissions elsewhere. This helps explain why the estimated impact of urbanization on emissions is more sensitive to accounting methods and model specification.

## SECTION 5: DISCUSSION AND IMPLICATIONS

The empirical results of this study provide a nuanced and multidimensional view of the relationship between economic growth and emissions. This section discusses these findings based on two main research questions. We analyze the differences between production- and consumption-based emissions (RQ1) in the EKC models for each income group (RQ2). We also assess the role of control variables in shaping emissions outcomes. Finally, the section concludes by highlighting important theoretical and practical policy implications of the analysis.

### 5.1 Revisiting the EKC: Production vs. Consumption Emissions by Income Group

The findings for high-income countries reveal a mature economy that has successfully achieved the traditional EKC for emissions produced within its own borders. For production-based emissions (PCO2), there is a clear inverted U-shaped relationship with a turning point of $37,448 per capita GDP. This figure is well within the observed income levels of this group (Table 4), suggesting that there are high-income countries that have achieved successful decoupling of domestic economic activity from production-based emissions. This result aligns with a significant body of literature. For instance, Matei (2022) supported a similar EKC pattern for 34 OECD countries over the period 1997–2015, with turning points ranging from $10,774 to $44,494. Churchill et al. (2018) also supported the EKC in OECD countries over the period 1870–2014, with estimated turning points ranging from $18,955 to $89,540 (in 1990 USD). Similarly, van Beek (2019) documented the existence of a production-based EKC in developed countries from 1995 to 2009, with a threshold of $72,767.5. This success in reducing domestic emissions may be the result of a combination of strict environmental policies, technological innovation, and a structural shift of the economy toward the service sector (Stern, 2004).

However, for high-income countries, the EKC model faces challenges from the consumption-based model. Although an inverted U-shaped relationship for consumption-based emissions (CCO2) is also statistically confirmed, the implied turning point of $470,946 per capita is economically unattainable. The gap between the two turning points is an important finding, highlighting the phenomenon of "carbon leakage." It demonstrates that while high-income nations have curbed domestic pollution, their high-consumption lifestyles are sustained by importing carbon-intensive goods produced elsewhere (Hertwich and Peters, 2009; Peters *et al.*, 2011). Furthermore, it is important to note that the presence of EKC pattern in high-income countries is not universally established in the literature and that it can be sensitive to sample composition and regional characteristics. For instance, Jaunky (2011) found a monotonically increasing relationship between emissions and income for a panel of rich nations, while Tachega et al. (2021) also failed to find an EKC for their panel of high-income African economies. Despite these discrepancies, a broad consensus remains that decoupling consumption-based emissions is far more challenging than decoupling production-based emissions in high-income countries.

The findings for upper-middle-income countries reflect their role as global manufacturing hubs. Within these economies, domestic pressures from industrialization, together with global consumption demand, have created a sharp divergence between production-based and consumption-based emissions. For PCO2 emissions, the analysis confirms the existence of a clear EKC pattern, with a reasonable turning point of $18,546 per capita. Since this threshold is only slightly above the highest income for this group, it suggests that they are still on the upward slope of the EKC curve. This aligns perfectly with the "grow now, clean up later" paradigm often used to describe economies undergoing rapid industrialization (Panayotou, 1995; Saboori, Sulaiman and Mohd, 2012). Upper-middle-income countries also serve as suppliers in global value chains, producing manufactured goods for consumption in developed countries, while bearing the environmental costs domestically. Moreover, the findings affirm the results of studies by Bah, Abdulwakil and Azam (2020), who also validated the EKC in upper-middle-income Sub-Saharan African countries. Similar conclusions were drawn by Al-mulali et al. (2015) and Acheampong (2019), who found EKC evidence in panels of emerging economies once industrialization stabilizes and regulatory and technological capacities strengthen.

By contrast, for upper-middle-income countries, the EKC hypothesis is firmly rejected for CCO2 emissions. The results instead indicate a monotonically increasing relationship between income and emissions. This pattern may reflect limited environmental awareness, low demand for green products, and increasing consumption of energy-intensive goods as incomes expand. In the absence of strong institutions and policy interventions, consumption emissions rise proportionally with income in this group. The sharp increase in their CCO2 is highly likely linked to the explosive growth of a new domestic middle class. Poumanyvong and Kaneko (2010) and Wang et al. (2016) emphasize that rising incomes in industrializing economies shift lifestyles toward energy-intensive consumption patterns, particularly through vehicle ownership, housing, and electronics. In this sense, upper-middle-income countries face a double burden: they bear the environmental costs of production while also experiencing a rapid expansion of their own consumption footprint. This finding stands in contrast to Qiao *et al.* (2019), who argued that the EKC is present only in developed economies. Our results instead show that production-based EKC is clearly present in these industrializing nations, but the consumption-based EKC continues to rise unchecked. This reinforces the argument of Mir and Storm (2016) and Schröder and Storm (2020), who contend that once consumption-based accounting is considered, the pattern of decoupling in emerging economies largely disappears.

The findings for the lower-middle-income countries portray economies at an early stage of development, where the conventional EKC hypothesis fails to hold for either production or consumption emissions. For production-based emissions (PCO2), the analysis reveals a linear increasing relationship with economic growth. This suggests lower-middle-income nations are in a classic "scale effect" phase, where expanding economic activity, often based on agriculture, basic manufacturing, and resource extraction, directly increases pollution (Grossman and Krueger, 1991). These countries have not yet reached the stage of development where cleaner technologies, regulatory frameworks, and structural economic shifts toward more efficient industries can offset the scale effect. As a result, production-based emissions continue to rise proportionally with income, with no evidence of decoupling.

For CCO2 model, in lower-middle-income countries, the relationship with income is statistically weak and ambiguous, with no EKC or linear pattern established. One possible explanation is that much of the economic growth in these countries is driven by commodity exports and spending on basic necessities rather than on high-carbon, energy-intensive consumer goods. At the same time, weak environmental awareness and limited access to green consumption choices mean that upward trends in CCO2 are likely to emerge as incomes rise further. This conclusion aligns with studies by Narayan and Narayan (2010b) who also failed to find evidence of an EKC for a panel of developing countries. Our conclusion is also in line with broad regional study of Ogundipe, Olurinola and Odebiyi (2014), who determined that the EKC theory is unsupported for a large sample of African economies. However, our findings are a clear departure from the work of Azam and Khan (2016) who identified an EKC for low-income countries using a different methodology. This contrast highlights that the income-emissions nexus at this stage of development remains unsettled and may be sensitive to the sample, time period, and methodology employed.

Collectively, the analysis provides insights into the two research questions, showing a holistic picture of global emissions. The relationship between income and emissions is not uniform but is conditional on emissions types and development stage. For production-based emissions (PCO2), the results depict a sequential transfer of environmental burden. High-income countries have mitigated their domestic pollution problem and passed their EKC turning point. Upper-middle-income countries are in the process of industrialization and are now approaching their emissions peak. The lower-middle-income countries, meanwhile, exhibit a linear increasing relationship. This confirms that the production-based EKC is not a universal law but depends on the stage of economic development. Our findings are in line with recent meta-analyses of the literature by Leal and Marques (2022). For consumption-based emissions (CCO2), however, EKC pattern is more challenging to achieve. The analysis shows that no income group has a feasible path to reducing its consumption footprint through income growth alone. The EKC path for high-income nations is significant but economically unattainable, while it is rejected for both upper-middle- and lower-middle income groups. This production-consumption divergence is the most critical insight of this study. It lends strong empirical support to scholars such as Peters et al. (2011) and Knight and Schor (2014), who argue that in a globalized economy, the environmental burden of consumption is displaced rather than diminished. It demonstrates that the environmental progress of wealthy nations is not an absolute decoupling but rather a geographic outsourcing of pollution. Upper-middle-income countries serve as the workshops for this outsourcing, while lower-middle-income countries may follow a similar path.

### 5.2 Role of control variables

Besides the core income-emissions relationship, the examination of the control variables indicates their importance as structural drivers of emissions. The relationship between urbanization and emissions varies greatly by income levels. For high-income countries, urbanization is found to have a significant mitigating effect on both production and consumption emissions. This result is consistent with the "compact city" hypothesis, which posits that the efficiencies of dense, mature urban environments in developed nation can significantly lower per capita carbon footprints (Glaeser and Kahn, 2010). It is noteworthy that the magnitude of this effect is larger for consumption-based emissions than for production-based emissions. This suggests that while urbanization contributes to making domestic industry more efficient, its primary environmental benefit comes from shaping less carbon-intensive lifestyles. The efficiencies gained through dense living, extensive public transport, energy distribution and service-based economies appear to have a profound dampening effect on the overall consumption footprint of their urban populations (Dodman, 2009).

In contrast, upper-middle-income countries see no significant long-run relationship between urbanization and both emission types. This finding diverges from studies that find a positive link in industrializing nations (e.g. Wang et al., 2016; Poumanyvong and Kaneko, 2010). However, it aligns with the view that the urbanization–emissions relationship is non-linear and context-dependent. Upper-middle-income countries are in a transitional stage. On the one hand, they face the emissions-increasing effects of industrial concentration and growing consumption. On the other hand, like high-income nations, they are beginning to benefit from density-related efficiencies, such as economies of scale in public services and the expansion of service-based industries (Sharma, 2011). Li and Lin (2015) further show that the impact of urbanization can shift from positive to negative as a country develops. The statistically insignificant relationship we find suggests that the opposing forces of degradation from industrial expansion and mitigation from structural efficiency are in balance, producing a net-neutral long-run effect.

Finally, the dynamic nature of urbanization is most visible in lower-middle-income countries, where it plays an entirely divergent role. The results show that urbanization significantly mitigates production emissions while simultaneously driving consumption emissions. The mitigating effect on production aligns with theories of industrial efficiency, where shift from rural and agricultural economies to more efficient, centralized urban industries helps reduce the carbon intensity of production (Henderson, 2003; Sharma, 2011). In contrast, the positive effect on consumption is consistent with literature showing that urbanization in early-stage developing nations is a primary driver of emissions as populations transition from subsistence to consumer-based lifestyles (Poumanyvong and Kaneko, 2010).

Regarding energy variables, the analysis shows consistent results across all income groups. Fossil fuel consumption (FEC) is found to be the largest and most statistically significant contributor to production and consumption-based emissions across all three income panels. This is an expected result and is consistent with many previous studies that confirm the central role of fossil fuels in environmental degradation, from developed countries (Churchill *et al.*, 2018) to developing countries (Saqib *et al.*, 2022). A noteworthy finding is that the impact of fossil fuel consumption is consistently greater for production-based emissions (PCO2) than for consumption-based emissions (CCO2) across all income groups. This highlights the crucial role of fossil fuels in the industrial and energy production sectors. Since these activities are critical to a country's economic base, changes in fossil fuel dependence have their most immediate and powerful impact on production-related emissions. Moreover, the overall magnitude of this impact is highest in the high-income countries This suggests that despite their economic development, their production and energy systems remain extremely carbon intensive. Therefore, even a small increase in fossil fuel dependence would have a disproportionate impact on the environment, underscoring the enormous challenge of decarbonizing their existing infrastructure.

For renewable energy consumption (REC), the analysis shows that it significantly reduces both production-based and consumption-based emissions across all three income groups. This finding underscores the crucial role of renewable energy in global climate strategies. These findings are strongly aligned with a broad body of literature that identifies renewable energy as a crucial tool for achieving sustainable growth (Ben Jebli and Ben Youssef, 2015; Cerdeira Bento and Moutinho, 2016; Dogan and Seker, 2016). More recent evidence confirms that REC reduces emissions across all stages of development, with particularly strong effects in emerging economies where new renewable power can directly substitute for fossil fuels (Ahmed *et al.*, 2022; Ullah *et al.*, 2023). Our results also highlight this point, which indicates that lower-middle-income nations experience the greatest reduction in emissions from renewable energy sources. This implies that most substantial environmental benefits can be obtained by making investments in renewable energy early in the development process. It offers these nations a clear pathway to "leapfrog" the most pollution-intensive phases of industrialization by building a fundamentally cleaner energy system from the outset.

## 5.3 Implications of the study

The findings of this research have several important theoretical and practical implications for understanding and addressing the global challenge of CO2 emissions.

### 5.3.1 Theoretical implications

Theoretically, this study refines the Environmental Kuznets Curve (EKC) hypothesis in two crucial ways. First, it demonstrates that the "decoupling" pattern observed in the production emissions of high-income countries is primarily the result of a geographic outsourcing of pollution through international trade. This provides strong empirical support for critiques, first raised by scholars like Rothman (1998) and later supported by Peters et al. (2011), who argued that traditional EKC studies were flawed for failing to account for the global net effects.

Second, the study reinforces that the EKC is a conditional, stage-dependent phenomenon, not a universal law. It suggests that this economic-emissions hypothesis provides a good model for the production-based emissions of developed and industrializing nations but fails for economies in the early stages of development and for consumption-based emissions. Our findings therefore contribute to the growing body of literature showing that the validity of the EKC is contingent on both the emissions measure and the stage of development.

### 5.3.2 Practical implications

Our empirical results carry significant practical implications for climate policy. The results suggest that the current international climate framework, which is largely based on production emissions, is insufficient to address the global nature of consumption and the associated problem of carbon leakage. The absence of a universal EKC confirms that a more nuanced, tailored approach is required, with different policy priorities for each income group.

For high-income countries, the central policy challenge is to address the "decoupling illusion." Although data confirms that many advanced economies have passed the turning point for production-based emissions, their consumption-based emissions continue to rise. This indicates that decoupling has been achieved domestically, but not globally, due to outsourced production. To address this imbalance, high-income countries need to take the lead in developing and implementing policies that consider carbon footprint of imported goods. One useful tool is the Carbon Border Adjustment Mechanism (CBAM), which adjusts the environmental costs of domestically produced and imported goods and limits the tendency to shift emissions abroad (Mehling *et al.*, 2019). Complementary domestic measures, such as carbon labelling, green consumer incentives, and circular economy policies, can directly address the high levels of consumption identified in our results (Kirchherr, Reike and Hekkert, 2017). In addition, as major beneficiaries of outsourced production, high-income countries have a responsibility to facilitate the decarbonization of global supply chains by promoting and financing technology transfer to trading partners. Finally, our finding that urbanization exerts a strong mitigating effect on consumption emissions suggests that continued investment in sustainable urban infrastructure (e.g., public transport, energy-efficient housing, retrofitting of buildings) can further enhance the carbon-reducing potential of mature cities (Dodman, 2009).

For the upper-middle-income countries, which serve as global manufacturing hubs, policy must handle a dual challenge. Specifically, they must simultaneously de-carbonize their domestic industry while managing the environmental impacts of their consumption. This duality underscores that production-oriented policies must be complemented by demand-side interventions. On the production side, a primary goal should be to accelerate their progress along the EKC path to reach the turning point. Empirical results show that renewable energy is a powerful mitigator of production-based emissions, justifying policies that promote domestic energy transition and green industrialization. Effective means include creating favorable investment environments for renewable technologies, phasing out fossil fuel subsidies, and imposing stricter regulations for energy-intensive industries. According to the IEA (2024), these strategies are part of a larger call to develop sustainable energy innovation systems in emerging economies. From the consumption side, the increasing demand for energy-intensive products is leading to a constant rise in emissions. To tackle this issue, it is essential to implement policies that shape consumer behavior and promote environmental awareness. Key measures include setting stringent energy efficiency standards for vehicles and household appliances, expanding eco-labeling and certification schemes to guide consumer choice, and investing in public awareness campaigns to stimulate demand for low-emission goods and services (Thøgersen, 2010). Collectively, such initiatives can help mitigate consumption-based emissions and support the transition toward sustainable consumption patterns.

Finally, for the lower-middle-income countries, the findings reveal they are at a critical crossroads where immediate choices regarding energy consumption will determine their long-term environmental path. With no evidence of an EKC, these economies are firmly in the scale effect where growth directly drives emissions. The linear rise in production emissions and the powerful impact of energy variables mean that energy policy is the most effective and urgent lever for this group. The primary goal must be to invest in renewable energy infrastructure immediately to avoid being stuck in high-carbon systems for decades, a phenomenon known as “carbon lock-in” (Unruh, 2000). This lock-in occurs when long-term investments in fossil fuel technologies create a strong inertia that makes a later shift challenging and expensive. Importantly, these nations have a considerable chance to avoid the most carbon-intensive stages of modernization because they still have a very low percentage of fossil fuels in their energy mix (about 55% of their energy mix, compared to over 75% for higher-income groups) (Goldemberg, 1998). At the same time, our results reveal that urbanization mitigates production emissions through efficiency gains while risking an increase in consumption emissions through higher demand for goods and services. This highlights the need for proactive sustainable urban planning to harness these efficiencies while managing consumption growth. However, pursuing these strategies requires external support. International climate finance, for example through mechanisms such as the Green Climate Fund (GCF), will be essential to enable lower-middle-income countries to seize this opportunity and pursue a genuinely green growth path.

## SECTION 6: CONCLUSION

This research provides a comparative analysis of the Environmental Kuznets Curve (EKC) in a globalized world. Recognizing that traditional EKC studies often overlook the influence of emissions embedded in trade and assume a uniform development path, this research tackles two research questions: (1) To what extent does the EKC hold for production-based (PCO2) versus consumption-based (CCO2) emissions? and (2) How does this relationship vary across income groups? To answer these questions, the study applied the robust Panel ARDL method on a dataset of 95 countries over the period from 1990 to 2021.

The findings provide important insights into the research questions, showing that the income–emissions relationship is profoundly dependent on both the type of emissions and the stage of development. For high-income countries, evidence supports EKC patterns for both measures. The turning point for PCO2 model is feasible ($37,448) while for CCO2 is economically unattainable ($470,946). This indicates "decoupling illusion" consistent with outsourcing carbon-intensive production to other countries. Therefore, in high-income countries, production-based targets should be complemented by consumption-footprint instruments (e.g., CBAM, carbon labels).

For upper-middle-income countries, the EKC appears to hold for PCO2, with a plausible turning point of $18,546. This finding reflects their role as manufacturing hubs that still pursue a pollution-intensive growth path. They are bearing the environmental costs of producing carbon-intensive goods, many of which are consumed in high-income countries. By contrast, CCO2 emissions increase linearly with income. This divergence requires a dual policy challenge. They should promote green industrialization to de-carbonize production while investing in demand-side measures to manage growing consumption emissions.

For lower-middle-income countries, the EKC hypothesis is rejected for both emission types. Instead, production-based emissions rise linearly with growth. This indicates that they are in an early development stage where they grow at the cost of environment. The most urgent policy implication is the need to prioritize investments in sustainable urban planning and renewable energy. Achieving this will require substantial external support, particularly through international climate finance.

The study also provides insights into control variables. Fossil fuel consumption consistently is the most powerful driver of emissions, while renewable energy provides a significant mitigating effect for all income groups. However, the role of urbanization is conditional on developmental stage. It mitigates emissions in high-income countries while having no significant effects in the upper-middle-income group. In lower-middle-income countries there are mixed results, where it mitigates production emissions while driving consumption emissions.

By questioning the traditional EKC model in light of emission types and income levels, this study contributes to the design of more equitable and empirically sound climate policy. The main contributions of this study are twofold. First, by systematically testing the EKC model for PCO2 and CCO2 emissions, the study provides empirical evidence for the phenomenon of "decoupling illusion." The results show that environmental progress in developed countries is often achieved through shifting emissions abroad, rather than through absolute reductions in their environmental footprint. This supports critiques that traditional EKC studies are flawed for not accounting for emissions embodied in trade. Second, by disaggregating this analysis across three distinct income levels, the study shows that the income–emissions relationship is fundamentally conditional on development stage. This both sharpens the theoretical debate and underscores the need for tailored, rather than one-size-fits-all, climate policies.

The findings of this study should be considered in light of several limitations, which open valuable avenues for future research. First, while $CO_2$ emissions were selected as the primary environmental indicator in line with the EKC framework, this choice fails to capture other elements of environmental degradation, such as biodiversity loss, land degradation, or local air pollutants (e.g., $NO_x$, $SO_2$). Future studies applying this comparative framework to a wider range of indicators, such as ecological footprints or local air pollutants, would provide a more holistic view. Second, data availability for CCO2 constrained both the time period of the analysis (1990–2021) and the inclusion of low-income countries. Therefore, the current results cannot be generalized to the world's poorest countries, a group that has not been fully studied in the EKC literature. As CCO2 data become more comprehensive, future studies should extend the analysis to cover this group of countries. Third, although the disaggregation by income group is an important contribution, the analysis still treats each group as internally homogeneous. This may miss potential differences between resource-dependent, manufacturing, or service-based economies within the same income group. Therefore, country- or sector-specific studies could complement the panel data analysis and provide more detailed and practical policy implications, especially for sectors such as energy, transport, or heavy industry. Methodologically, the ARDL panel framework used in this study assumes a symmetrical relationship between variables. This means that a 1% increase in GDP will have the opposite effect of a 1% decrease. Such assumption may overlook potential nonlinear or asymmetric dynamics, in which economic recessions have a greater effect on emissions than equivalent expansions. A potential direction for future research is the application of more flexible econometric models, such as the nonlinear ARDL (NARDL) framework. This method would give researchers a more dynamic view of the income–emissions relationship by enabling them to examine whether economic booms raise emissions at a different rate than recessions decrease them.

# APPENDICES

## APPENDIX A. Country list (95 countries)

| Income group | Number of countries | Countries |
|---|---|---|
| High-income | 37 | Australia, Austria, Belgium, Canada, Chile, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Korea (Republic of), Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Poland, Portugal, Romania, Singapore, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom, United States, Uruguay |
| Upper-middle-income | 29 | Albania, Argentina, Armenia, Azerbaijan, Belarus, Botswana, Brazil, Bulgaria, China, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Georgia, Guatemala, Indonesia, Jamaica, Kazakhstan, Malaysia, Mauritius, Mexico, Namibia, Paraguay, Peru, Russian Federation, South Africa, Thailand, Turkiye |
| Lower-middle-income | 29 | Bangladesh, Benin, Bolivia, Cambodia, Cameroon, Cote d'Ivoire, Egypt (Arab Rep.), Ghana, Honduras, India, Iran (Islamic Rep.), Jordan, Kenya, Kyrgyz Republic, Mongolia, Morocco, Nepal, Nicaragua, Pakistan, Philippines, Senegal, Sri Lanka, Tajikistan, Tanzania, Tunisia, Ukraine, Viet Nam, Zambia, Zimbabwe |

**APPENDIX B. Correlation matrix**

| | lnPCO2 | lnCCO2 | lnGDP | lnURB | lnFEC | lnREC | VIF |
|---|---|---|---|---|---|---|---|
| High-income | | | | | | | |
| lnPCO2 | 1.0000 | | | | | | |
| lnCCO2 | 0.8593* | 1.0000 | | | | | |
| lnGDP | 0.5026* | 0.6429* | 1.0000 | | | | 1.34 |
| lnURB | 0.2001* | 0.2985* | 0.4921* | 1.0000 | | | 1.39 |
| lnFEC | 0.4675* | 0.2913* | -0.0713 | -0.0699 | 1.0000 | | 1.71 |
| lnREC | -0.4919* | -0.5302* | -0.1604* | -0.2023* | -0.6063* | 1.0000 | 1.78 |
| Upper-middle-income | | | | | | | |
| lnPCO2 | 1.0000 | | | | | | |
| lnCCO2 | 0.9297* | 1.0000 | | | | | |
| lnGDP | 0.4621* | 0.5596* | 1.0000 | | | | 1.44 |
| lnURB | 0.2891* | 0.3269* | 0.5426* | 1.0000 | | | 1.46 |
| lnFEC | 0.7592* | 0.6869* | 0.2009* | 0.1774* | 1.0000 | | 2.34 |
| lnREC | -0.8115* | -0.7245* | -0.2021* | -0.2414* | -0.7539* | 1.0000 | 2.38 |
| Lower-middle-income | | | | | | | |
| lnPCO2 | 1.0000 | | | | | | |
| lnCCO2 | 0.9606* | 1.0000 | | | | | |
| lnGDP | 0.7675* | 0.7531* | 1.0000 | | | | 2.31 |
| lnURB | 0.6912* | 0.6500* | 0.6596* | 1.0000 | | | 2.05 |
| lnFEC | 0.8405* | 0.8082* | 0.6355* | 0.5776* | 1.0000 | | 2.17 |
| lnREC | -0.8668* | -0.8489* | -0.6701* | -0.6403* | -0.6913* | 1.0000 | 2.49 |

**Note:** PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption. All variables are in natural logarithms (ln). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

**APPENDIX C. Robustness estimation results (FE with DK standard errors)**

| | High-income | | Upper–middle–income | | Lower–middle–income | |
|---|---|---|---|---|---|---|
| Dependent Variable | PCO2 | CCO2 | PCO2 | CCO2 | PCO2 | CCO2 |
| lnGDP | 1.817 *** | 0.960** | 3.147 *** | 2.191* | 1.290** | -0.644 |
| $(\ln GDP)^2$ | -0.082*** | -0.029* | -0.021** | -0.112 | 0.048 | 0.165 |
| lnURB | 0.193 | -0.350 | 0.397** | 0.960*** | -0.157*** | 0.133 |
| lnFEC | 1.144*** | 0.816*** | 0.797*** | 0.413*** | 0.510*** | 0.403*** |
| lnREC | -0.151*** | -0.173*** | -0.195*** | -0.051** | -0.334*** | -0.215*** |
| R-squared (within) | 0.71 | 0.67 | 0.68 | 0.56 | 0.83 | 0.71 |
| Hausman Test (p-value) | (0.023) | (0.022) | (0.015) | (0.000) | (0.017) | (0.023) |

**Note:** Results from fixed effects regression using Driscoll-Kraay standard errors. Each income group is estimated separately for PCO2 and CCO2 models. PCO2 – Production-based emissions; CCO2 – Consumption-based emissions; GDP – Gross domestic product; URB - Urbanization; FEC – Fossil fuel energy consumption; REC – Renewable energy consumption. All variables are in natural logarithms (ln). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

## REFERENCE LIST

Acheampong, A.O. (2019) 'Modelling for insight: Does financial development improve environmental quality?', *Energy Economics*, 83, pp. 156–179. Available at: https://doi.org/10.1016/j.eneco.2019.06.025.

Adams, S. and Acheampong, A.O. (2019) 'Reducing carbon emissions: The role of renewable energy and democracy', *Journal of Cleaner Production*, 240, p. 118245. Available at: https://doi.org/10.1016/j.jclepro.2019.118245.

Ahmed, F., Kousar, S., Pervaiz, A., Trinidad-Segovia, J.E., Casado-Belmonte, M. del P. and Ahmed, W. (2022) 'Role of green innovation, trade and energy to promote green economic growth: a case of South Asian Nations', *Environmental Science and Pollution Research*, 29(5), pp. 6871–6885. doi:10.1007/s11356-021-15881-4.

Alam, Md.M., Murad, M.W., Noman, A.H.M. and Ozturk, I. (2016) 'Relationships among carbon emissions, economic growth, energy consumption and population growth: Testing Environmental Kuznets Curve hypothesis for Brazil, China, India and Indonesia', *Ecological Indicators*, 70, pp. 466–479. Available at: https://doi.org/10.1016/j.ecolind.2016.06.043.

Al-mulali, U., Weng-Wai, C., Sheau-Ting, L. and Mohammed, A.H. (2015) 'Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation', *Ecological Indicators*, 48, pp. 315–323. Available at: https://doi.org/10.1016/j.ecolind.2014.08.029.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B-O., Levin, S., Mäler, K.-G., Perrings, C. and Pimentel, D. (1995) 'Economic growth, carrying capacity, and the environment', *Ecological Economics*, 15(2), pp. 91–95. Available at: https://doi.org/10.1016/0921-8009(95)00059-3.

Aydin, M., Koc, P. and Sahpaz, K.I. (2023) 'Investigating the EKC hypothesis with nanotechnology, renewable energy consumption, economic growth and ecological footprint in G7 countries: panel data analyses with structural breaks', *Energy Sources, Part B: Economics, Planning, and Policy*, 18(1), p. 2163724. Available at: https://doi.org/10.1080/15567249.2022.2163724.

Azam, M. and Khan, A.Q. (2016) 'Testing the Environmental Kuznets Curve hypothesis: A comparative empirical study for low, lower middle, upper middle and high income countries', *Renewable and Sustainable Energy Reviews*, 63, pp. 556–567. Available at: https://doi.org/10.1016/j.rser.2016.05.052.

Bah, M.M., Abdulwakil, M.M. and Azam, M. (2020) 'Income heterogeneity and the Environmental Kuznets Curve hypothesis in Sub-Saharan African countries', *GeoJournal*, 85(3), pp. 617–628. Available at: https://doi.org/10.1007/s10708-019-09985-1.

Balaguer, J. and Cantavella, M. (2016) 'Estimating the environmental Kuznets curve for Spain by considering fuel oil prices (1874–2011)', *Ecological Indicators*, 60, pp. 853–859. Available at: https://doi.org/10.1016/j.ecolind.2015.08.006.

Beckerman, W. (1992) ‘Economic growth and the environment: Whose growth? whose environment?’, *World Development*, 20(4), pp. 481–496. Available at: https://doi.org/10.1016/0305-750X(92)90038-W.

van Beek, M. (2019) ‘The Environmental Kuznets Curve: Examining the relationship between income and technology-adjusted consumption-based $CO_2$ emissions’. Available at: http://lup.lub.lu.se/student-papers/record/8984944 (Accessed: 12 August 2025).

Ben Jebli, M. and Ben Youssef, S. (2015) ‘The environmental Kuznets curve, economic growth, renewable and non-renewable energy, and trade in Tunisia’, *Renewable and Sustainable Energy Reviews*, 47, pp. 173–185. Available at: https://doi.org/10.1016/j.rser.2015.02.049.

Ben Jebli, M., Ben Youssef, S. and Ozturk, I. (2016) ‘Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries’, *Ecological Indicators*, 60, pp. 824–831. Available at: https://doi.org/10.1016/j.ecolind.2015.08.031.

Bilgili, F., Koçak, E. and Bulut, Ü. (2016) ‘The dynamic impact of renewable energy consumption on $CO_2$ emissions: A revisited Environmental Kuznets Curve approach’, *Renewable and Sustainable Energy Reviews*, 54, pp. 838–845. Available at: https://doi.org/10.1016/j.rser.2015.10.080.

Cerdeira Bento, J.P. and Moutinho, V. (2016) ‘$CO_2$ emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy’, *Renewable and Sustainable Energy Reviews*, 55, pp. 142–155. Available at: https://doi.org/10.1016/j.rser.2015.10.151.

Charfeddine, L. and Kahia, M. (2019) ‘Impact of renewable energy consumption and financial development on $CO_2$ emissions and economic growth in the MENA region: A panel vector autoregressive (PVAR) analysis’, *Renewable Energy*, 139, pp. 198–213. Available at: https://doi.org/10.1016/j.renene.2019.01.010.

Chen, Y., Zhao, J., Lai, Z., Wang, Z. and Xia, H. (2019) ‘Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China’s $CO_2$ emissions: Evidence from a regional panel analysis’, *Renewable Energy*, 140, pp. 341–353. Available at: https://doi.org/10.1016/j.renene.2019.03.058.

Churchill, S.A., Inekwe, J., Ivanovski, K. and Smyth, R. (2018) ‘The Environmental Kuznets Curve in the OECD: 1870–2014’, *Energy Economics*, 75, pp. 389–399. Available at: https://doi.org/10.1016/j.eneco.2018.09.004.

Cole, M.A., Rayner, A.J. and Bates, J.M. (1997) ‘The environmental Kuznets curve: an empirical analysis’, *Environment and Development Economics*, 2(4), pp. 401–416. Available at: https://doi.org/10.1017/S1355770X97000211.

Danish, Zhang, B., Wang, B. and Wang, Z. (2017) ‘Role of renewable energy and non-renewable energy consumption on EKC: Evidence from Pakistan’, *Journal of Cleaner Production*, 156, pp. 855–864. doi:10.1016/j.jclepro.2017.03.203.

Danish, Ulucak, R. and Erdogan, S. (2022) ‘The effect of nuclear energy on the environment in the context of globalization: Consumption vs production-based $CO_2$ emissions’, *Nuclear Engineering and Technology*, 54(4), pp. 1312–1320. Available at: https://doi.org/10.1016/j.net.2021.10.030.

Dasgupta, S., Laplante, B. and Wheeler, D. (2002) ‘Confronting the Environmental Kuznets Curve’, *Journal of Economic Perspectives*, 16, pp. 147–168. Available at: https://doi.org/10.1257/0895330027157.

Davis, S.J. and Caldeira, K. (2010) ‘Consumption-based accounting of $CO_2$ emissions’, *Proceedings of the National Academy of Sciences*, 107(12), pp. 5687–5692. Available at: https://doi.org/10.1073/pnas.0906974107.

Davis, S.J., Peters, G.P. and Caldeira, K. (2011) ‘The supply chain of $CO_2$ emissions’, *Proceedings of the National Academy of Sciences*, 108(45), pp. 18554–18559. Available at: https://doi.org/10.1073/pnas.1107409108.

Destek, M.A. and Sarkodie, S.A. (2019) ‘Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development’, *Science of The Total Environment*, 650, pp. 2483–2489. Available at: https://doi.org/10.1016/j.scitotenv.2018.10.017.

Dijkgraaf, E. and Vollebergh, H.R.J. (2005) ‘A test for parameter homogeneity in $CO_2$ panel EKC estimations’, *Environmental and Resource Economics*, 32(2), pp. 229–239. Available at: https://doi.org/10.1007/s10640-005-2776-0.

Dodman, D. (2009) *Urban density and climate change: Analytical review of the interaction between urban growth trends and environmental changes*. Analytical Review Paper 1. New York: United Nations Population Fund (UNFPA).

Dogan, E. and Seker, F. (2016) ‘The influence of real output, renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries’, *Renewable and Sustainable Energy Reviews*, 60, pp. 1074–1085. Available at: https://doi.org/10.1016/j.rser.2016.02.006.

Dong, B., Wang, F. and Guo, Y. (2016) ‘The global EKCs’, *International Review of Economics & Finance*, 43, pp. 210–221. Available at: https://doi.org/10.1016/j.iref.2016.02.010.

Driscoll, J.C. and Kraay, A.C. (1998) ‘Consistent covariance matrix estimation with spatially dependent panel data’, *The Review of Economics and Statistics*, 80(4), pp. 549–560. Available at: https://doi.org/10.1162/003465398557825.

Frodyma, K., Papież, M. and Śmiech, S. (2022) ‘Revisiting the Environmental Kuznets Curve in the European Union countries’, *Energy*, 241, p. 122899. Available at: https://doi.org/10.1016/j.energy.2021.122899.

Glaeser, E.L. and Kahn, M.E. (2010) ‘The greenness of cities: Carbon dioxide emissions and urban development’, *Journal of Urban Economics*, 67(3), pp. 404–418. Available at: https://doi.org/10.1016/j.jue.2009.11.006.

Global Carbon Project (2024) *Territorial vs. consumption-based $CO_2$ emissions per capita*. Our World in Data. Available at: https://ourworldindata.org/grapher/prod-cons-co2-per-capita (Accessed: 13 August 2025).

Goldemberg, J. (1998) 'Leapfrog energy technologies', *Energy Policy*, 26(10), pp. 729–741.

Grossman, G.M. and Krueger, A.B. (1991) 'Environmental impacts of a North American Free Trade Agreement'. *NBER Working Paper* No. 3914. Cambridge, MA: National Bureau of Economic Research. Available at: https://doi.org/10.3386/w3914.

Hashem Pesaran, M. and Yamagata, T. (2008) 'Testing slope homogeneity in large panels', *Journal of Econometrics*, 142(1), pp. 50–93. Available at: https://doi.org/10.1016/j.jeconom.2007.05.010.

Haug, A.A. (2002) 'Temporal aggregation and the power of cointegration tests: A Monte Carlo study', *Oxford Bulletin of Economics and Statistics*, 64(4), pp. 399–412. Available at: https://doi.org/10.1111/1468-0084.00025.

He, J. and Richard, P. (2010) 'Environmental Kuznets curve for $CO_2$ in Canada', *Ecological Economics*, 69(5), pp. 1083–1093. Available at: https://doi.org/10.1016/j.ecolecon.2009.11.030.

Heinonen, J. and Junnila, S. (2011) 'Implications of urban structure on carbon consumption in metropolitan areas', *Environmental Research Letters*, 6(1), p. 014018. Available at: https://doi.org/10.1088/1748-9326/6/1/014018.

Henderson, V. (2003) 'The urbanization process and economic growth: The so-what question', *Journal of Economic Growth*, 8(1), pp. 47–71. Available at: https://doi.org/10.1023/A:1022860800744.

Hertwich, E.G. and Peters, G.P. (2009) 'Carbon footprint of nations: A global, trade-linked analysis', *Environmental Science & Technology*, 43(16), pp. 6414–6420. Available at: https://doi.org/10.1021/es803496a.

IEA (2024) *Clean energy innovation policies in emerging and developing economies*. Available at: https://www.iea.org/reports/clean-energy-innovation-policies-in-emerging-and-developing-economies (Accessed: 27 August 2025).

Im, K.S., Pesaran, M.H. and Shin, Y. (2003) 'Testing for unit roots in heterogeneous panels', *Journal of Econometrics*, 115(1), pp. 53–74. Available at: https://doi.org/10.1016/S0304-4076(03)00092-7.

Jaunky, V.C. (2011) 'The $CO_2$ emissions-income nexus: Evidence from rich countries', *Energy Policy*, 39(3), pp. 1228–1240. Available at: https://doi.org/10.1016/j.enpol.2010.11.050.

Kaika, D. and Zervas, E. (2013) 'The environmental Kuznets curve (EKC) theory. Part B: Critical issues', *Energy Policy*, 62, pp. 1403–1411. Available at: https://doi.org/10.1016/j.enpol.2013.07.130.

Kasman, A. and Duman, Y.S. (2015) '$CO_2$ emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: A panel data analysis', *Economic Modelling*, 44, pp. 97–103. Available at: https://doi.org/10.1016/j.econmod.2014.10.022.

Kirchherr, J., Reike, D. and Hekkert, M. (2017) ‘Conceptualizing the circular economy: An analysis of 114 definitions’, *Resources, Conservation and Recycling*, 127, pp. 221–232. Available at: https://doi.org/10.1016/j.resconrec.2017.09.005.

Knight, K.W. and Schor, J.B. (2014) ‘Economic growth and climate change: A cross-national analysis of territorial and consumption-based carbon emissions in high-income countries’, *Sustainability*, 6(6), pp. 3722–3731. Available at: https://doi.org/10.3390/su6063722.

Kuznets, S. (1955) ‘Economic growth and income inequality’, *American Economic Review*, 45(1), pp. 1–28.

Leal, P.H. and Marques, A.C. (2022) ‘The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective’, *Heliyon*, 8(11), e11521. Available at: https://doi.org/10.1016/j.heliyon.2022.e11521.

Lee, C.-C., Chiu, Y.-B. and Sun, C.-H. (2009) ‘Does one size fit all? A reexamination of the Environmental Kuznets Curve using the dynamic panel data approach’, *Applied Economic Perspectives and Policy*, 31(4), pp. 751–778. Available at: https://doi.org/10.1111/j.1467-9353.2009.01465.x.

Levin, A., Lin, C.-F. and Chu, C.-S. J. (2002) ‘Unit root tests in panel data: asymptotic and finite-sample properties’, *Journal of Econometrics*, 108(1), pp. 1–24. Available at: https://doi.org/10.1016/S0304-4076(01)00098-7.

Li, K. and Lin, B. (2015) ‘Impacts of urbanization and industrialization on energy consumption/$CO_2$ emissions: Does the level of development matter?’, *Renewable and Sustainable Energy Reviews*, 52, pp. 1107–1122. Available at: https://doi.org/10.1016/j.rser.2015.07.185.

Lin, S., Wang, S., Marinova, D., Zhao, D. and Hong, J. (2017) ‘Impacts of urbanization and real economic development on $CO_2$ emissions in non-high income countries: Empirical research based on the extended STIRPAT model’, *Journal of Cleaner Production*, 166, pp. 952–966. Available at: https://doi.org/10.1016/j.jclepro.2017.08.107.

Lindmark, M. (2002) ‘An EKC-pattern in historical perspective: Carbon dioxide emissions, technology, fuel prices and growth in Sweden 1870–1997’, *Ecological Economics*, 42(1), pp. 333–347. Available at: https://doi.org/10.1016/S0921-8009(02)00108-8.

Lorente, D.B. and Álvarez-Herranz, A. (2016) ‘Economic growth and energy regulation in the environmental Kuznets curve’, *Environmental Science and Pollution Research*, 23(16), pp. 16478–16494. Available at: https://doi.org/10.1007/s11356-016-6773-3.

Makarov, I. and Alataş, S. (2024) ‘Production- and consumption-based emissions in carbon exporters and importers: A large panel data analysis for the EKC hypothesis’, *Applied Energy*, 363, p. 123063. Available at: https://doi.org/10.1016/j.apenergy.2024.123063.

Maranzano, P., Cerdeira Bento, J.P. and Manera, M. (2022) 'The role of education and income inequality on environmental quality: A panel data analysis of the EKC hypothesis on OECD countries', *Sustainability*, 14(3), p. 1622. Available at: https://doi.org/10.3390/su14031622.

Matei, I. (2022) 'The environmental Kuznets curve: Empirical evidence from OECD countries', in *Energy consumption, conversion, storage, and efficiency*. IntechOpen. Available at: https://doi.org/10.5772/intechopen.108631.

Mehling, M.A., van Asselt, H., Das, K., Droege, S. and Verkuijl, C. (2019) 'Designing border carbon adjustments for enhanced climate action', *American Journal of International Law*, 113(3), pp. 433–481. Available at: https://doi.org/10.1017/ajil.2019.22.

Mensah, I.A., Sun, M., Omari-Sasu, A.Y., Gao, C., Obobisa, E.S. and Osinubi, T.T. (2021) 'Potential economic indicators and environmental quality in African economies: new insight from cross-sectional autoregressive distributed lag approach', *Environmental Science and Pollution Research*, 28(40), pp. 56865–56891. doi:10.1007/s11356-021-14598-8.

Mir, G.-U.-R. and Storm, S. (2016) 'Carbon emissions and economic growth: Production-based versus consumption-based evidence on decoupling', *Institute for New Economic Thinking Working Paper Series*, 41. Available at: https://doi.org/10.2139/ssrn.2772131

Mongo, M., Belaïd, F. and Ramdani, B. (2021) 'The effects of environmental innovations on $CO_2$ emissions: Empirical evidence from Europe', *Environmental Science & Policy*, 118, pp. 1–9. Available at: https://doi.org/10.1016/j.envsci.2020.12.004.

Murshed, M., Ali, S.R. and Banerjee, S. (2021) 'Consumption of liquefied petroleum gas and the EKC hypothesis in South Asia: Evidence from cross-sectionally dependent heterogeneous panel data with structural breaks', *Energy, Ecology and Environment*, 6(4), pp. 353–377. Available at: https://doi.org/10.1007/s40974-020-00185-z.

Murshed, M. and Dao, N.T.T. (2022) 'Revisiting the $CO_2$ emission-induced EKC hypothesis in South Asia: The role of export quality improvement', *GeoJournal*, 87(2), pp. 535–563. Available at: https://doi.org/10.1007/s10708-020-10270-9.

Naqvi, S.A.A., Shah, S.A.R., Anwar, S., Ali, M., Ashfaq, M. and Shafique, M. (2021) 'Renewable energy, economic development, and ecological footprint nexus: Fresh evidence of renewable energy environment Kuznets curve (RKC) from income groups', *Environmental Science and Pollution Research*, 28(2), pp. 2031–2051. Available at: https://doi.org/10.1007/s11356-020-10485-w.

Narayan, P.K. and Narayan, S. (2010) 'Carbon dioxide emissions and economic growth: Panel data evidence from developing countries', *Energy Policy*, 38(1), pp. 661–666. Available at: https://doi.org/10.1016/j.enpol.2009.09.005.

Ogundipe, A., Olurinola, O. and Odebiyi, J.T. (2014) 'Examining the validity of EKC in Western Africa: Different pollutants option'. *SSRN Working Paper*. Rochester, NY: Social Science Research Network. Available at: https://doi.org/10.2139/ssrn.2512152.

Our World in Data (2024) *$CO_2$ emissions per capita*. Available at: https://ourworldindata.org/grapher/co-emissions-per-capita (Accessed: 31 August 2025).

Panayotou, T. (1995) ‘Environmental degradation at different stages of economic development’, in Ahmed, I. and Doeleman, J.A. (eds.) *Beyond Rio*. London: Palgrave Macmillan UK, pp. 13–36. Available at: https://doi.org/10.1007/978-1-349-24245-0_2.

Parikh, J. and Shukla, V. (1995) ‘Urbanization, energy use and greenhouse effects in economic development: Results from a cross-national study of developing countries’, *Global Environmental Change*, 5(2), pp. 87–103. Available at: https://doi.org/10.1016/0959-3780(95)00015-G.

Pata, U.K. (2018) ‘Renewable energy consumption, urbanization, financial development, income and $CO_2$ emissions in Turkey: Testing EKC hypothesis with structural breaks’, *Journal of Cleaner Production*, 187, pp. 770–779. Available at: https://doi.org/10.1016/j.jclepro.2018.03.236.

Pesaran, M.H. (2007) ‘A simple panel unit root test in the presence of cross-section dependence’, *Journal of Applied Econometrics*, 22(2), pp. 265–312. Available at: https://doi.org/10.1002/jae.951.

Pesaran, M.H., Shin, Y. and Smith, R.P. (1999) ‘Pooled mean group estimation of dynamic heterogeneous panels’, *Journal of the American Statistical Association*, 94(446), pp. 621–634. Available at: https://doi.org/10.1080/01621459.1999.10474156.

Pesaran, M.H. and Smith, R. (1995) ‘Estimating long-run relationships from dynamic heterogeneous panels’, *Journal of Econometrics*, 68(1), pp. 79–113. Available at: https://doi.org/10.1016/0304-4076(94)01644-F.

Peters, G.P., Minx, J.C., Weber, C.L. and Edenhofer, O. (2011) ‘Growth in emission transfers via international trade from 1990 to 2008’, *Proceedings of the National Academy of Sciences*, 108(21), pp. 8903–8908. Available at: https://doi.org/10.1073/pnas.1006388108.

Poumanyvong, P. and Kaneko, S. (2010) ‘Does urbanization lead to less energy use and lower $CO_2$ emissions? A cross-country analysis’, *Ecological Economics*, 70(2), pp. 434–444. Available at: https://doi.org/10.1016/j.ecolecon.2010.09.029.

Qiao, H., Zheng, F., Jiang, H. and Dong, K. (2019) ‘The greenhouse effect of the agriculture-economic growth-renewable energy nexus: Evidence from G20 countries’, *Science of The Total Environment*, 671, pp. 722–731. Available at: https://doi.org/10.1016/j.scitotenv.2019.03.336.

Rahman, M.M., Alam, K. and Velayutham, E. (2022) ‘Reduction of $CO_2$ emissions: The role of renewable energy, technological innovation and export quality’, *Energy Reports*, 8, pp. 2793–2805. Available at: https://doi.org/10.1016/j.egyr.2022.01.200.

Rothman, D.S. (1998) ‘Environmental Kuznets curves—real progress or passing the buck?: A case for consumption-based approaches’, *Ecological Economics*, 25(2), pp. 177–194. Available at: https://doi.org/10.1016/S0921-8009(97)00179-1.

Saboori, B., Sulaiman, J. and Mohd, S. (2012) ‘Economic growth and $CO_2$ emissions in Malaysia: A cointegration analysis of the Environmental Kuznets Curve’, *Energy Policy*, 51, pp. 184–191. Available at: https://doi.org/10.1016/j.enpol.2012.08.065.

Salahuddin, M., Gow, J., Ozturk, I., Sohag, K. and Akbar, M. (2019) ‘The effects of urbanization and globalization on $CO_2$ emissions: Evidence from the Sub-Saharan Africa (SSA) countries’, *Environmental Science and Pollution Research*, 26(3), pp. 2699–2709. Available at: https://doi.org/10.1007/s11356-018-3790-4.

Salari, M., Javid, R.J. and Noghanibehambari, H. (2021) ‘The nexus between $CO_2$ emissions, energy consumption, and economic growth in the U.S.’, *Economic Analysis and Policy*, 69, pp. 182–194. Available at: https://doi.org/10.1016/j.eap.2020.12.007.

Saqib, N., Usman, M., Radulescu, M., Sinisi, C.I., Secara, C.G. and Tolea, C. (2022) ‘Revisiting EKC hypothesis in context of renewable energy, human development and moderating role of technological innovations in E-7 countries?’, *Frontiers in Environmental Science*, 10, 1077658. doi:10.3389/fenvs.2022.1077658.

Schröder, E. and Storm, S. (2020) ‘Economic growth and carbon emissions: The road to “Hothouse Earth” is paved with good intentions’, *International Journal of Political Economy*, 49(2), pp. 153–173. Available at: https://doi.org/10.1080/08911916.2020.1778866.

Sephton, P. and Mann, J. (2016) ‘Compelling evidence of an Environmental Kuznets Curve in the United Kingdom’, *Environmental and Resource Economics*, 64(2), pp. 301–315. Available at: https://doi.org/10.1007/s10640-014-9871-z.

Shah, S.A.R., Naqvi, S.A.A. and Anwar, S. (2020) ‘Exploring the linkage among energy intensity, carbon emission and urbanization in Pakistan: Fresh evidence from ecological modernization and environment transition theories’, *Environmental Science and Pollution Research*, 27(32), pp. 40907–40929. Available at: https://doi.org/10.1007/s11356-020-09227-9.

Shahbaz, M., Bhattacharya, M. and Ahmed, K. (2017) ‘$CO_2$ emissions in Australia: Economic and non-economic drivers in the long-run’, *Applied Economics*, 49(13), pp. 1273–1286. Available at: https://doi.org/10.1080/00036846.2016.1217306.

Shahbaz, M. and Sinha, A. (2019) ‘Environmental Kuznets curve for $CO_2$ emissions: A literature survey’, *Journal of Economic Studies*, 46(1), pp. 106–168. Available at: https://doi.org/10.1108/JES-09-2017-0249.

Sharma, S.S. (2011) ‘Determinants of carbon dioxide emissions: Empirical evidence from 69 countries’, *Applied Energy*, 88(1), pp. 376–382. Available at: https://doi.org/10.1016/j.apenergy.2010.07.022.

Shukla, P.R., Skea, J., Slade, R., Fradera, R., Pathak, M., Al Khourdajie, A., Belkacemi, M., van Diemen, R., Hasija, A., Lisboa, G., Luz, S., Malley, J., McCollum, D., Some, S. and Vyas, P. (eds.) (2022) *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.

Sinha, A. and Sen, S. (2016) ‘Atmospheric consequences of trade and human development: A case of BRIC countries’, *Atmospheric Pollution Research*, 7(6), pp. 980–989. Available at: https://doi.org/10.1016/j.apr.2016.06.003.

Sinha, A. and Shahbaz, M. (2018) ‘Estimation of Environmental Kuznets Curve for $CO_2$ emission: Role of renewable energy generation in India’, *Renewable Energy*, 119, pp. 703–711. Available at: https://doi.org/10.1016/j.renene.2017.12.058.

Stern, D.I. (2004) ‘The rise and fall of the Environmental Kuznets Curve’, *World Development*, 32(8), pp. 1419–1439. Available at: https://doi.org/10.1016/j.worlddev.2004.03.004.

Stern, D.I. (2017) ‘The Environmental Kuznets Curve after 25 years’, *Journal of Bioeconomics*, 19(1), pp. 7–28. Available at: https://doi.org/10.1007/s10818-017-9243-1.

Sun, Y., Li, M., Zhang, M., Khan, H.S.U.D., Li, J., Li, Z., Sun, H., Zhu, Y. and Anaba, O.A. (2021) ‘A study on China’s economic growth, green energy technology, and carbon emissions based on the Kuznets curve (EKC)’, *Environmental Science and Pollution Research*, 28(6), pp. 7200–7211. doi:10.1007/s11356-020-11019-0.

Swamy, P.A.V.B. (1970) ‘Efficient inference in a random coefficient regression model’, *Econometrica*, 38(2), pp. 311–323. Available at: https://doi.org/10.2307/1913012.

Tachega, M.A., Appiah-Otoo, I., Li, L. and Nketiah, E. (2021) ‘Income heterogeneity and the Environmental Kuznets Curve turning points: Evidence from Africa’, *Sustainability*, 13(10), p. 5634. Available at: https://doi.org/10.3390/su13105634.

Thøgersen, J. (2010) ‘Country differences in sustainable consumption: The case of organic food’, *Journal of Macromarketing*, 30(2), pp. 171–185. Available at: https://doi.org/10.1177/0276146710361926.

Ullah, A., Murshed, M., Mahmood, H., Shah, S.A.A. and Younas, W. (2023) ‘Modeling the impacts of technological innovation and financial development on environmental sustainability: New evidence from the world’s top 14 financially developed countries’, *Energy Strategy Reviews*, 50, p. 101229. Available at: https://doi.org/10.1016/j.esr.2023.101229.

Ullah, S., Nadeem, M., Ali, K. and Abbas, Q. (2021) ‘Fossil fuel, industrial growth and inward FDI impact on $CO_2$ emissions in Vietnam: testing the EKC hypothesis’, *Management of Environmental Quality: An International Journal*, 33(2), pp. 222–240. doi:10.1108/MEQ-03-2021-0051.

Ulucak, R. and Bilgili, F. (2018) ‘A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries’, *Journal of Cleaner Production*, 188, pp. 144–157. Available at: https://doi.org/10.1016/j.jclepro.2018.03.191.

Unruh, G.C. (2000) ‘Understanding carbon lock-in’, *Energy Policy*, 28(12), pp. 817–830. Available at: https://doi.org/10.1016/S0301-4215(00)00070-7.

Vo, A.T., Vo, D.H. and Le, Q.T.-T. (2019) ‘$CO_2$ emissions, energy consumption, and economic growth: New evidence in the ASEAN countries’, *Journal of Risk and Financial Management*, 12(3), p. 145. Available at: https://doi.org/10.3390/jrfm12030145.

Wang, N., Zhu, H., Guo, Y. and Peng, C. (2018) ‘The heterogeneous effect of democracy, political globalization, and urbanization on PM2.5 concentrations in G20 countries: Evidence from panel quantile regression', *Journal of Cleaner Production*, 194, pp. 54–68. Available at: https://doi.org/10.1016/j.jclepro.2018.05.092.

Wang, Y., Han, R. and Kubota, J. (2016) 'Does urbanization lead to more carbon emission? Evidence from a panel of BRICS countries', *Applied Energy*, 168, pp. 375–380. Available at: https://doi.org/10.1016/j.apenergy.2016.01.105.

IEA (2023) *World Energy Outlook 2023*. Available at: https://www.iea.org/reports/world-energy-outlook-2023 (Accessed: 14 August 2025).

World Meteorological Organization (2023) 'Rate and impact of climate change surges dramatically in 2011–2020'. Available at: https://wmo.int/news/media-centre/rate-and-impact-of-climate-change-surges-dramatically-2011-2020 (Accessed: 31 August 2025).

Yang, Z., Shao, S., Yang, L. and Ma, S. (2022) 'Can renewable energy investment reduce carbon dioxide emissions? Evidence from scale and structure', *Energy Economics*, 112, p. 106181. Available at: https://doi.org/10.1016/j.eneco.2022.106181.