Exploring the Drivers of Carbon Dioxide Emissions in G7 Countries: An Empirical Study

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Abstract

This study explores the short-run drivers of carbon dioxide emissions in G7 countries from 1971 to 2022, focusing on the role of economic growth and renewable energy consumption. Three fixed-effect panel regressions are estimated, with the inclusion of relevant control variables. The regressions analyse whether growth alone can directly help mitigate the rise in carbon dioxide levels with a direct link to the Environmental Kuznets Curve hypothesis. To test the consistency of the results, robustness checks are conducted using nitrous oxide as an alternative emissions measure. The results show no evidence to support the Environmental Kuznets Curve hypothesis. Instead, indirect outcomes of growth, particularly increased renewable energy consumption, are more effective at reducing carbon dioxide emissions. Additionally, the findings suggest that different factors drive alternative greenhouse gases. Overall, this study advocates for policymakers to implement strategic and targeted renewable energy policies to reduce carbon dioxide emissions, rather than relying on economic growth alone to achieve collective climate targets.

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1. Introduction

CO_2 emissions have risen steadily since the beginning of the Industrial Revolution, primarily driven by increasing global energy demand. It is widely recognised that CO_2 emissions are one of climate change's leading causes and primary indicators. The IPCC (2023) report states that "Global warming is more likely than not to reach 1.5 Celsius between 2021 and 2040" (Lee & Romero, 2023), with the costs of further inaction being "enormous" (IEA, 2023). This exemplifies the problem the world currently faces. Whilst countries have varying amounts of power and capability to deal with the problem, those that do and can have the responsibility to act. The G7 have the opportunity to lead the way in limiting the alarming statistics of the IPCC report. This is because the G7 are responsible for 30% of world energy demand as of 2022 and, as such, has the "power to inspire successful energy transitions" worldwide (IEA, 2022). Given the influence that the G7 has, understanding what drives CO_2 emissions in the G7 is crucial to implementing effective policies, which will then help pave the way for other countries to similarly contribute to mitigating the problem.

This paper aims to empirically examine the primary drivers of CO_2 emissions in G7 countries from 1971 to 2022. In addition, it will provide evidence as to whether policies aimed at increasing renewable energy consumption can significantly reduce CO_2 emissions and offset the environmental impact associated with economic growth. This paper will also contribute to the existing literature by including an alternative measure for emissions, specifically N_2O and by using updated data. In addition, we will include a variety of suitable controls to further improve the robustness of the results. The limitation of the approach of this paper is that it will not provide country-specific results, but instead, it examines the G7 collectively. However, this allows generalised trends to be made, which may be applicable to a wide range of similarly developed countries. This paper will continue in the following order: Section 2 addresses relevant literature, including economic models and previous research on the explanatory and control variables. Section 3 outlines and justifies the use of the data. Section 4 constructs the empirical model. Section 5 summarises the results. Section 6 conducts robustness tests. Lastly, Section 7 provides a justified conclusion.

2. Empirical Literature Review

As concerns over climate change intensify, precise research on mitigation strategies is crucial for informing policymakers on how to meet international climate goals, such as those set in the Paris Agreement of 2015. Since countries are continually growing and expanding their energy requirements to maintain this growth, they need to find ways to develop sustainably. As such, the G7 provide a suitable focus for this paper. This is because, historically, they have been large energy consumers, given they are advanced economies and have been at the forefront of driving change for a more sustainable future. Furthermore, their efforts can serve as a blueprint for emerging economies, which often lack the same level of resources but face mounting pressure to reduce emissions.

2.1 Environmental Kuznets Curve

One key debate in sustainable growth is the relationship between economic growth and environmental degradation. The Environmental Kuznets Curve (EKC) proposes a theoretical framework that helps explain this dynamic. It argues that economic growth can be separated into three distinct sections. The first argues that pollution increases early in a country's economic growth. This is because of factors such as industrialisation, lack of awareness and prioritising income. However, as an economy grows, there is a gradual shift towards producing lower pollution levels as technologies improve and society's ideologies change. At a certain threshold of GDP per capita, this environmental degradation begins to reverse, and environmental quality improves. This is because the model claims a wealthy country will have the resources to solve the problem. Eventually, the model argues that an increase in GDP per capita will reverse all environmental degradation. **Figure 1** illustrates the basic EKC. The model gained traction by the early 1990s, with the idea even being conceptualised in the World Development Report 1992, which argued that economic development is sustainable and could help improve environmental conditions (World Bank, 1992).

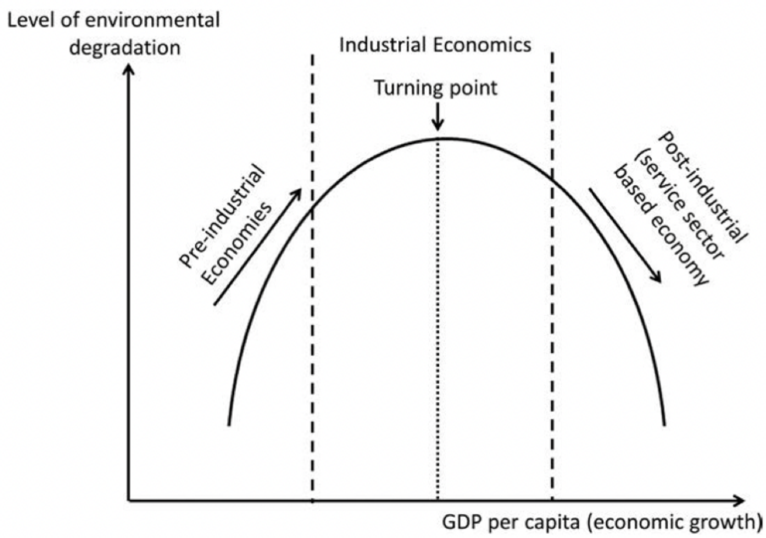

Figure 1. The Environmental Kuznets Curve (Prasad, 2023).

However, more recently, the EKC hypothesis has been criticised. Research suggests that countries taking this growth approach incur huge environmental costs that won't easily be absorbed in the future, as the EKC suggests (Gill, et al., 2017). Additionally, Stern, et al. (1996) argue that the model is subject to unrealistic assumptions, such as the ignorance of a feedback effect, suggesting that the EKC is not a justification for policy inaction. Given this criticism, we must explore alternative approaches to reducing CO_2 emissions, such as renewable energy consumption. This also plays a vital role in creating a less polluting future, which is examined next.

2.2 Renewable Energy

As countries pursue sustainability, their reliance on renewable energy is expected to increase. However, this does not explicitly imply a decline in non-renewable energy consumption. Instead, renewables may supplement rather than act as a substitute by replacing existing energy sources. Mirziyoyeva and Salahodjaev (2022) provide a direct analysis of the relationship between renewable energy and CO_2 emissions. They focused on the top 50 carbon-intensive economies from 2000 to 2015. Using both a fixed-effect regression and a two-step GMM estimator, they found that renewable energy has a significant and negative effect on CO_2 emissions, with a 1% increase in renewable energy reducing CO_2 emissions by 0.98%. This suggests that high-producing carbon countries successfully used renewable energy as a substitute to transition away from using non-renewable resources. Beyond quantifying relationships, the paper offers recommendations to policymakers. For example, providing financial incentives such as low-interest loans and subsidies to accelerate renewable energy adoption. Additionally, they recommend that further studies should examine the indirect relationship that renewable energy might have on CO_2 through GDP.

Building on this, Apergis and Payne (2012) explore the relationship between renewable and non-renewable energy consumption across 80 countries from 1990 to 2007. They employ a panel error correction model (ECM) and found a negative causal relationship between renewable and non-renewable energy sources, suggesting a degree of substitutability. They argued that this makes renewable energy sources a tool to mitigate the environmental damage that fossil fuels cause. However, they also caution that non-renewable energy cannot be completely disregarded as an energy source just yet. This is because structural investment and government policies to improve sustainability need to be strategically imposed to incentivise the development of the renewable energy sector. Additionally, they found a bidirectional causality between renewable energy consumption and economic growth in both the short and long run. This is evidence that investment in the renewable energy sector is economically worthwhile. They summarise by suggesting that developed economies, like those in the G7, have the institutional and financial capacity to lead the transition and should set an example for global energy policy.

In much of the literature, including work by Mirziyoyeva and Salahodjaev (2022) and our study, renewable energy is measured as a percentage of total primary energy. This choice allows insight into each county's own transition towards the total use of renewable energy and makes it comparable to other papers on this topic. It could also act as a proxy for the strength and effectiveness of renewable energy policies. However, it does come with limitations. Firstly, it does not represent absolute terms. This means that although the share of renewable energy in the overall energy mix can grow, the absolute consumption of non-renewable energy can still rise if total energy demand increases, which is misleading. Moreover, there are different types of renewable energy, some more sustainable than others. For example, hydropower has a "rather large environmental footprint," (European Commission , 2021), and an increase in this, over others, may lead to an overestimation of environmental progress and distort estimates of the actual effect of renewable energy consumption on CO_2 emissions.

2.3 Economic Growth

While there may be evidence that renewable energy consumption can be used as a substitute to help mitigate CO_2 emissions, renewable energy consumption is often influenced by broader economic conditions. For example, economic growth, often measured in GDP per capita, is commonly seen as a driver for renewable energy investment. As the previous section shows, some studies have suggested that economies with ample resources can invest more heavily in renewable energy. However, these studies do not establish whether countries will utilise their capability effectively.

Work produced by Sadorsky (2009) examines the impacts of GDP, oil prices and CO_2 emissions on renewable energy consumption within G7 countries between 1985 and 2005. The paper's sample period is relatively short and ends before many countries begin to invest aggressively in renewable energy, as seen in **Figure 2**. However, it offers a good comparison for this paper as it covers the G7 countries. His paper incorporates both Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) for modelling the long-term impacts and an error correction model (ECM) to establish any relationships in the short term. He found robust results to suggest increases in both GDP and CO_2 emissions are associated with increases in renewable energy consumption. Specifically, a 1% increase in real GDP per capita increases per capita renewable energy consumption by 8.44%. This shows that increases in GDP have the potential to reduce CO_2 emissions through an increase in renewable energy consumption. Interestingly, a 1% increase in CO_2 emissions per capita increases renewable energy consumption per capita by 5.23%. This suggests that as CO_2 emissions rise, there is a greater emphasis on transitioning towards renewable energy sources. Although this paper will study this relationship in the opposite direction, it does provide insight into a possible feedback loop.

A similar paper by Apergis & Payne (2010) investigates the relationship between renewable energy consumption and GDP in the short and long-term using 20 OCED countries from 1985-2005. They use a panel cointegration and vector error correction model (VECM) and provide evidence of economic growth having a positive and significant impact on renewable energy consumption in both the long and short term. They also found the relationship to be bi-directional, suggesting the presence of mutual reinforcement. They conclude by suggesting that increasing renewable energy consumption will help alleviate the environmental degradation caused by CO_2 emissions.

Upon establishing that previous literature points towards a direct link between renewable energy and GDP, the focus turns to whether GDP can influence CO_2 emissions. As previously discussed, the EKC hypothesis, while criticised, provides a theoretical foundation for this relationship. The following segment examines the empirical evidence of GDP's actual impact on CO_2. While there is a limited amount of recent literature investigating this relationship in developed countries, Onofrei, et al. (2022) explore the relationship between CO_2 and economic growth for 27 EU countries between 2000 and 2017. They employ a panel dynamic ordinary least squares (DOLS) model to analyse the long-term relationship between the two. They reveal a positive and statistically significant relationship, specifically that a 1% increase in GDP per capita leads to a 0.072% increase in CO_2 emissions. While the study helps to contribute to existing literature, it is limited by the omission of other relevant variables, such as renewable energy and energy consumption, amongst others. Therefore, the explanatory power of the paper may be limited. To address this, our approach will include a variety of key controls.
Another paper that contributes to the literature is written by Schroder and Storm (2020), who assessed the relationship between CO_2 and economic growth. They implement a FE model using a panel of 58 OECD countries between 2007 and 2015 for their main results. While the time scale of this paper is relatively small, which limits the scope of the results, they improve robustness in several ways. Most importantly, they use various measures of CO_2 emissions while also including additional countries to extend their analysis. Both alterations improve the reliability of their results. They observe that GDP has a positive and strongly significant impact on CO_2 emissions. To conclude, they challenged the EKC hypothesis, finding no evidence of a clear turning point. Instead, they argue that the economic growth trajectory will likely lead to an increase in global temperatures that surpasses the 1.5 degrees Celsius target, consistent with the IPCC report earlier. These findings justify the need to examine whether the adoption of renewable energy can counteract the emissions caused by economic growth.

2.4. Control Variables

A range of control variables are introduced to improve the accuracy and reliability of this paper's empirical results. These controls help isolate the causal effects of renewable energy consumption and GDP on CO_2 emissions by accounting for other important factors. This helps reduce omitted variable bias, improving the validity of the results.

One relevant control variable is population growth, which has long been theorised to impact levels of environmental degradation. One early perspective comes from the Malthusian theory, later updated to the Neo-Malthusian theory, which argued that population growth could put pressure on natural resources, contributing to a higher level of environmental degradation. While this idea is often considered outdated, the link between population growth and climate change is still relevant and theorised in the IPAT equation. Including population growth as a control variable allows this paper to account for increases in CO_2 emissions that stem from rising energy demand driven by population expansion. Many empirical papers follow a similar approach. For instance, Zoundi (2017) includes population growth as a control to assess how demographic differences shape CO_2 emissions. Also, Ochi and Saidi (2024) directly investigate the impact of population growth on global warming, covering the 33 most polluting countries from 1996 to 2019. Using a VAR model, they find that population significantly increases greenhouse gas emissions. Similarly, Shi (2001) uses data from 93 countries and interestingly finds that the effect of population growth on emissions is conditional on a country's wealth. Specifically, the effect of population growth on emissions is much smaller in high-income countries. This is relevant because our paper focuses exclusively on developed countries. Whilst this might imply that population plays a reduced role, failing to control for it risks omitting a potentially important influence on CO_2 emissions.

The next control variable that this paper considers is oil prices. Oil prices have been historically volatile and are impacted by various factors such as supply, demand, geopolitical events and macroeconomic factors. Importantly, oil prices can affect energy consumption behaviour and then CO_2 emissions indirectly. When oil prices rise, consumers are often incentivised to shift towards a more cost-effective energy source, in some instances, renewable energy. Additionally, governments can implement policies to make these alternatives more attractive. A notable case was the Danish government's introduction of grants for the creation of wind turbines following the 1970's oil crisis (IRENA and GWEC, 2013). This sparked a shift away from non-renewable energy sources, resulting in a reduction of CO_2 emissions countrywide. Apergis and Payne (2014) investigate the relationship between oil prices, renewable energy consumption and CO_2 emissions. They focus on 25 OCED countries using data from 1980 to 2011 and implement a panel ECM to examine long and short-term relationships. Their results suggest that oil price has a positive and significant impact on both renewable energy and CO_2

emissions in both the short and long term. While this might seem contradictory, it suggests that the substitution effect between oil prices and renewables is not strong enough to offset the broader rise in energy demand and therefore, CO_2 emissions continue to increase. Since this paper will use a longer time frame, it may be able to capture whether this substitution effect has become stronger in recent years as renewable technologies have progressed.

This study also considers foreign direct investment as a control variable. It tests two contrasting theories: the pollution haven hypothesis, which states that polluting firms will relocate to countries with less stringent environmental regulations, thereby increasing pollution in the host country, and the pollution halo hypothesis, which suggests that foreign investment can reduce pollution in a country through the transfer of green technology. A range of previous studies have empirically examined the impact of foreign investment on the levels of emissions a country produces. For example, Mirziyoyeva and Salahodjaev (2022) included foreign direct investment as a variable while studying the top carbon-intensive countries from 2000-2015. They find positive and significant results of foreign direct investment in CO_2 emissions.

A further relevant control variable is urbanisation. Urbanisation could increase emissions through greater energy demand from construction, but it could also reduce them through more efficient infrastructure. Sadorsky (2014) researches the net effect of urbanisation on CO_2 emissions. He finds evidence to suggest that both effects offset each other, and the net effect is statistically insignificant from 0. However, his study focuses on emerging economies, and as such, the effect of urbanisation on the G7 could provide alternative but equally interesting results.

The final control variable this paper will include is primary energy consumption. Fossil fuels currently remain dominant in the energy mix, and as such, energy demand plays a significant role in the production of CO_2 emissions. Including this variable helps to differentiate the effects of renewable energy consumption and GDP from the overall influence of increased energy demand.

3. Data

This paper uses strongly balanced panel data covering the G7 countries (Canada, France, Germany, Italy, Japan, United Kingdom and the United States). Using panel data allows for heterogeneity across all countries. Annual data for each country has been collected for each variable between 1971-2022. The data is limited by frequency due to difficulties sourcing many of the variables at a higher frequency and by duration because of a lack of available data. However, this ensures consistency and comparability of the analysis. **Table A** describes our variables. It includes relevant macroeconomic and environmental indicators, specifically GDP, renewable energy consumption (REC), oil price (OP), population growth (POP), primary energy consumption (TEC), foreign direct investment (FDI) and urbanisation (URB). Together, these will provide a foundation for our regression analysis in the next section, which will help to provide an understanding of the drivers of CO_2 emissions. Much of the data has been sourced and processed from the non-profit research organisation Our World in Data (OWID). OWID, based at the University of Oxford, is seen as a reputable source that features in a variety of articles from trustworthy news companies, including the Financial Times (Wolf, 2024), alongside data from the World Bank, from which our remaining data comes.

Much of the data is displayed in the following figures. **Figure 1** visually represents the variation in CO_2 emissions per capita over time for each country. Both Canada and the USA show comparably high CO_2 emissions per capita rates at the start of the period, likely due to being historically two of the largest producers of fossil fuels per capita (Our World in Data, 2024). **Figure 1** also exhibits a clear reduction in CO_2 emissions since 1971 for France, Germany, the UK and the USA. This paper aims to uncover why this has happened and how similar countries should base policy decisions to reduce their CO_2 emissions.

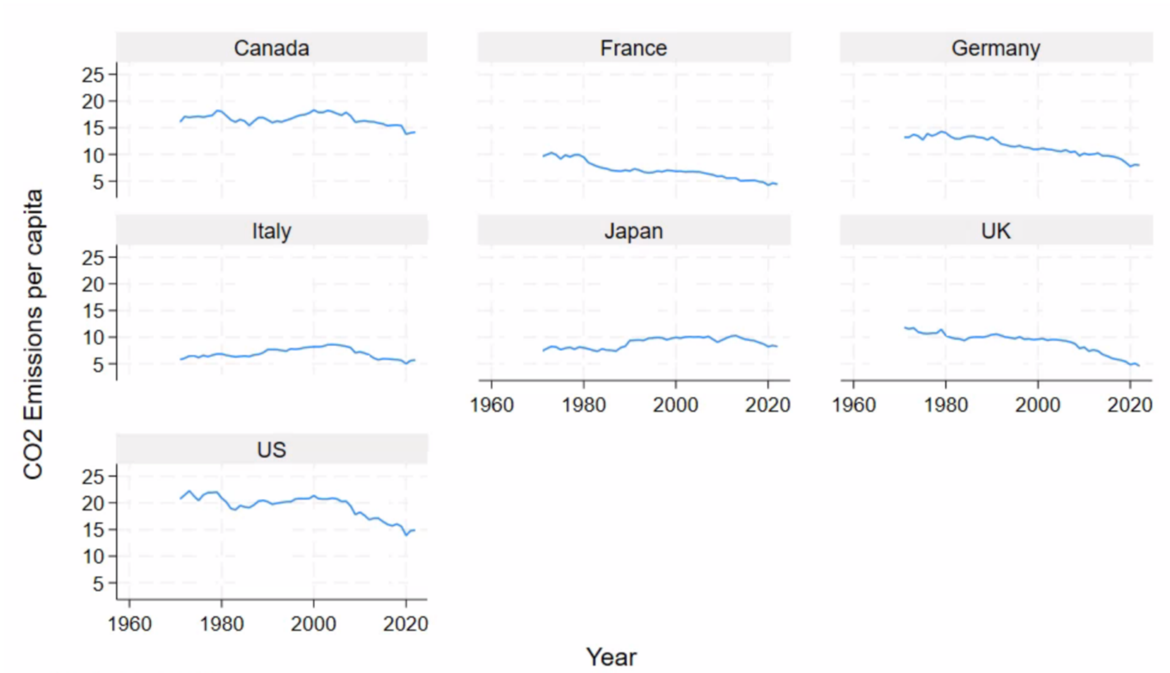

Figure 1: Carbon dioxide emissions per capita for G7 countries (1971-2022)

This paper proposes that some of the decline in CO_2 emissions in **Figure 1** can be explained by the increase in renewable energy consumption shown in **Figure 2**. This graph illustrates the steady growth of total renewable energy consumption over the last 50 years. Since 2010, most countries in the G7 have intensified their renewable energy consumption, displaying an increased awareness of the need for renewable energy and potentially a shift away from traditional energy sources. One exception to this is Canada. Their renewable energy consumption as a percentage of total consumption was higher at the beginning of our data coverage than any other country throughout. This shows how Canada was well ahead of any other country in terms of renewable energy consumption. However, their renewable energy consumption growth as a percentage of total energy consumption has stalled in recent years. This could be due to a lack of technological progress or regional constraints on the availability of renewable resources.

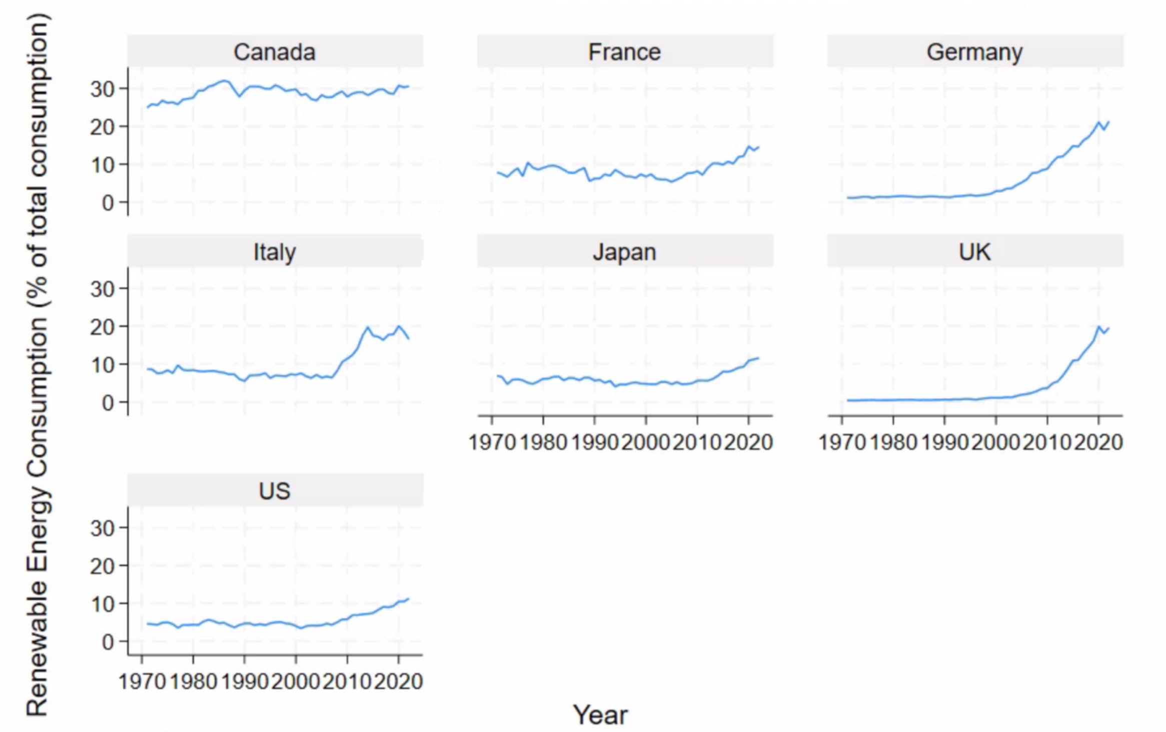

Figure 2: Percentage of energy consumption from renewables in G7 countries (1971-2022)

Figure 3 follows a similar approach to the previous two but depicts the real GDP per capita change throughout the dataset. As expected, countries experience different growth paths. This is because countries experience different productivity rates and stagnations in growth. Although, each country displays an overall increase over time. The trends in **Figure 3** combined with CO_2 emissions displayed in **Figure 1** provide the basis for analysing the EKC hypothesis. While recent studies have begun to speculate on the validity of the EKC (Gill, et al., 2017), it is still recognised as a way of explaining the relationship between economic growth and pollution. These figures collectively help visualise the foundation of the empirical model presented in the next section.

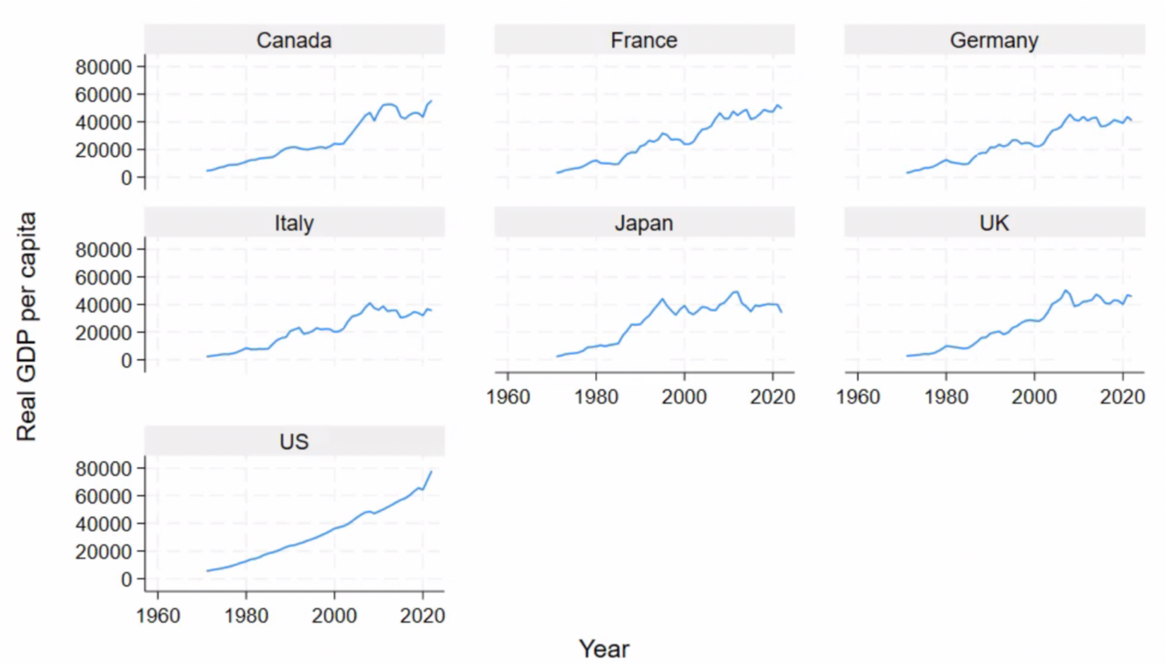

Figure 3: Real GDP per capita for G7 countries (1971-2022)

4. Methodology

To empirically analyse the drivers of CO_2 emissions in G7 countries, three equations have been introduced using annual panel data from 1971 to 2022. The three baseline equations are shown below:

$$\Delta \ln REC_{it} = \alpha_t + \beta_1 \ln GDP_{it} + \varepsilon_{it} \quad \textbf{(1)}$$

$$\Delta \ln CO2_{it} = \alpha_t + \beta_1 \Delta \ln REC_{it} + \varepsilon_{it} \quad \textbf{(2)}$$

$$\Delta \ln CO2_{it} = \alpha_t + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \Delta \ln REC_{it} + \varepsilon_{it} \quad \textbf{(3)}$$

Where:

$i = 1,\ldots, 7$ for each country and $t = 1971,\ldots, 2022$ for each period. α_t captures year-specific effects such as economic trends. Δ denotes the first difference operator, introduced as a measure to meet stationarity requirements. ε_{it} represents the error term capturing unobserved elements of the model. Moreover, variables have been transformed into natural logarithmic forms to enhance the interpretability of the results. At this point, control variables have been excluded to establish core relationships.

Each equation examines the effect of key explanatory variables on their respective dependent variables to allow isolation of their individual and combined influences on emissions and renewable energy adoption. Equation **(1)** tests whether GDP growth influences renewable energy consumption, assessing whether economic growth influences renewable energy adoption. This tests the idea that wealthy countries can afford to invest more substantially in renewable energy. Equation **(2)** tests the impact of renewable energy consumption on CO_2 emissions, assessing whether increased renewable energy adoption leads to lower emissions. This allows us to evaluate a potential substitution effect in the G7's energy transition towards renewables and away from fossil fuels. The final equation **(3)** combines economic growth and renewable energy consumption to determine if renewable energy adoption can help offset the CO_2 emissions associated with the economic development of a country. At the same time, the squared GDP term gives insights into the EKC hypothesis.

Now that the baseline equations have been introduced and explained, suitable controls have been added in line with the literature review. Like the explanatory variables, the control variables have been transformed into natural logarithmic form. Population growth rate is no exception to this because it is calculated as a log difference rate. The same control variables are included in each equation to enable comparisons among the equations. The next step is to conduct panel unit root tests to confirm stationarity. This is vital because non-stationary data can lead to spurious regression results. **Table B** provides the results of our panel unit root tests for our model with included controls. To ensure the reliability of our results, four separate panel unit root tests are conducted for each variable in the model. Also, the optimal lag length for our unit root tests was determined using the Akaike Information Criterion (AIC) statistical measure on STATA. This was implemented to improve the accuracy of the tests. Initially, the tests were carried out using data in level form for each variable. Results that indicate a p-value > 0.05 fail to reject the null hypothesis that the data is non-stationary at the 5% level. This was the case for $\ln(CO_2)$, ln(REC), ln(TEC) and ln(URB). The lack of stationarity found with these variables was expected because each commonly forms a long-run trend rather than having short-term fluctuations. However, other variables, like ln(GDP), indicated stationarity in level form, potentially due to factors like recessions causing the data to revert towards the mean. Additionally, stationarity tests on ln(OP), ln(FDI) and P, provided evidence of stationarity in their level form. Whilst we found evidence that some variables were stationary in level form, not all tests were consistent. The Breitung test repeatedly opposed the results of the other tests. However, each time, the three other tests gave evidence of stationarity. Since most tests gave evidence of stationarity, any inconsistencies with the Breitung test are ignored, and stationarity is assumed overall. Since the tests conclusively found evidence of non-stationarity for $\ln(CO_2)$, ln(REC), ln(TEC) and ln(URB), they need to be transformed, and the tests need to be reconducted. For each of these, the first difference is taken. By re-running the tests, there is now evidence to support the hypothesis that the data is stationary. At this point, all the data is now stationary.

Next, cointegration tests are conducted to test whether a long-run equilibrium relationship exists between the non-stationary variables in their level form. In this case, this includes $\ln(CO_2)$, ln(REC), ln(TEC) and ln(URB). The test requires each variable to be non-stationary in level form, which is confirmed by the panel unit root tests and indicated in **Table B**. If cointegration is present, it suggests that there is a long-run relationship between the variables tested. This means that a regression model that will produce results for both short and long-run relationships could be selected. Alternatively, if there is no evidence of cointegration, a short-run model would be sufficient. Using the Pedroni test for cointegration, it finds no evidence of cointegration. This result is highlighted in **Table C**. It showed that each of the three statistics failed to reject the null hypothesis of no cointegration. This means it is unlikely that there will be a long-term relationship between $\ln(CO_2)$, ln(REC), ln(TEC), and ln(URB). As a result, the empirical scope of this paper will be limited to focus on short-term relationships and incorporate a short-run model.

The next step is determining which short-run model to implement for each equation. Two of the most common short-run regression models are the fixed effect (FE) and the random effect (RE) models. The FE model uses a "within transformation" to remove time-invariant heterogeneity, such as differences in cultural attitudes towards CO_2 emissions between countries, which could bias estimates by being correlated to the explanatory variables (Wooldridge, 2019). Also, the FE model is always consistent even under such correlations but may not be the most efficient. In contrast, the RE model is generally more efficient but relies on the assumption that individual effects are uncorrelated with the explanatory variables (Wooldridge, 2019). If this assumption is violated, which, given the focus of this paper, is likely, the RE model becomes inconsistent. To determine which one is appropriate given the data, both FE and RE regressions are estimated and compared using the Hausman test. When running the Hausman test on equations (1), (2) and (3), we find a p-value > 0.05 for each, as seen in **Table E**. This means we fail to reject the null hypothesis for each equation, assuming that the RE model is appropriate. However, this paper will use the FE model despite this result. This decision reflects the importance of controlling for unobserved country-level characteristics, therefore reducing omitted variable bias and allowing for a clearer analysis of the relationship between CO_2 emissions and the explanatory variables.

Further diagnostic tests need to be run to help improve the robustness of results. Firstly, the modified Wald test was used to assess the presence of heteroskedasticity. **Table E** shows that p-values of 0.00 were found for each equation, which led to rejecting the null hypothesis of homoscedasticity. This suggests that heteroskedasticity is likely present and must be accounted for in the model. Secondly, the Wooldridge test for serial correlation was conducted. Similarly, the results are found in **Table E**. The test found a p-value < 0.05 for equation (1), which meant we rejected the null hypothesis of no serial correlation with the test suggesting its presence. Contrastingly, a p-value > 0.05 was found for equations (2) and (3), meaning we failed to reject the null hypothesis of no serial correlation, indicating no evidence of its existence. Thirdly, Pearson's CD test was used to investigate cross-sectional dependence. Equation (1) yielded a p-value > 0.05, suggesting no evidence of cross-sectional dependence, whereas equations (2) and (3) gave p-values < 0.05, which indicated evidence of cross-sectional dependence. Given the presence of heteroskedasticity in each equation, autocorrelation in equation (1) and cross-sectional dependence in equations (2) and (3), suitable adjustments are required to account for these issues. Thus, Driscoll-Kraay's standard errors are applied to each equation. Although not essential for all equations, it ensures comparability across equations while mitigating biases that the issues arising from the diagnostic tests may present. Finally, variance inflation factors (VIFs) were used to assess multicollinearity within each equation. For equations (1) and (2), VIFs were below the generic threshold of five, indicating no multicollinearity problems. However, equation (3) showed a significantly higher VIF. This is because both the GDP and GDP-squared terms are included and inherently correlated. Despite this, including both variables is necessary to understand the mechanics of the EKC. Therefore, neither variable will be omitted. While this may reduce the precision of individual coefficient estimates, the overall model behaviour is still valid and theoretically justified.

Now that the empirical model has been established and all appropriate diagnostic tests have been addressed, the next section assesses the regression results and findings.

5. Results

This section breaks down the regression analysis, starting with the baseline results, then moving on to the main regression results and finally, robustness checks. Firstly, **Table D** shows the baseline results. This included only the main explanatory variables and their respective dependent variable. Each regression follows exactly the baseline equations produced in the previous section. Compared to the main regression, the baseline similarly uses an FE model with Driscoll-Kraay's standard errors to improve comparability but, contrastingly, excludes control variables to isolate core relationships. The baseline regression aimed to highlight the raw relationships that are key to understanding changes to CO_2 emissions within the G7. For equation (1) in **Table D**, GDP per capita has a positive and statistically significant (at the 1% level) impact on renewable energy consumption. The result suggests that a 1% increase in real GDP per capita is associated with an increase of 0.31% in renewable energy consumption as a fraction of primary energy consumption, ceteris paribus. This means that as G7 countries grow and become wealthier, they gradually shift towards a greater reliance on renewable energy. Results from equation (2) in **Table D** show that renewable energy consumption has a negative and statistically significant (at 1% level) effect on CO_2 emissions, ceteris paribus. Specifically, a 1% increase in renewable energy consumption as a fraction of primary energy consumption leads to a 0.17% decrease in per capita CO_2 emissions within the G7 countries. Equation (3) in **Table D** reintroduces GDP to help determine the combined effect of renewable energy consumption and GDP on CO_2 emissions. It also includes a squared GDP term to evaluate the EKC hypothesis. The coefficient of renewable energy consumption on CO_2 emissions remains negative and statistically significant (at 1% level) and of similar magnitude to equation (2). Similarly, GDP is found to impact CO_2 emissions negatively, but this result has considerably large standard errors and is not significant. Therefore, no meaningful relationship is established. The GDP squared term also produces insignificant results with a marginally positive coefficient. Again, no relationship has been proven here. As a result, the baseline model produces no evidence supporting the EKC hypothesis. These preliminary results prove that renewable energy consumption in the G7 is central to reducing CO_2 emissions, unlike GDP during the sample period.

The main regression model builds on the baseline model by including suitable controls to address omitted variable bias and explore how other variables may influence the respective dependent variable in accordance with the empirical literature. The main regression results are displayed in **Table E**. Compared to the baseline results, the main regression results show a much-improved R-squared value. Equation (1) explores the effect economic growth and control variables have on renewable energy consumption in the short term. Similarly to the baseline results, GDP is found to have a positive and statistically significant (at the 10% level) effect on renewable energy consumption. Specifically, a 1% increase in real GDP per capita is associated with a 0.016% increase in the fraction of renewable energy consumption in primary energy consumption in the short term. However, the magnitude of the coefficient has substantially reduced, suggesting a significant overestimation of its explanatory power in the baseline model in the absence of control variables. The reduction is likely due to the inclusion of primary energy consumption, which has a negative and significant (at 1% level) impact on renewable energy consumption. Specifically, a 1% increase in total primary energy consumption is associated with a decrease in the share of consumption from renewable energy sources by 1.12% in the short term. This represents that renewable energy becomes a smaller share of the overall output mix as a country's total energy consumption increases. As a result, evidence suggests that renewable energy is not increasing quickly enough to maintain its weight in the energy mix. As such, fossil fuels are continuing to fill the gaps. Therefore, policies must ensure that the renewable energy sector can expand quickly enough to maintain or grow its share in the energy mix. The remaining control variables are found to be insignificant in the short term, offering less insight. However, further research could be undertaken to confirm whether any longer-term relationships exist. Equation (2) examines the short-term effects of renewable energy consumption on CO_2 emissions. The results indicate that renewable energy consumption has a negative and statistically significant (at the 1% level) impact on CO_2 emissions. A 1% increase in renewable energy consumption as a share of primary consumption leads to a 0.079% decrease in CO_2 emissions per capita over the short run. This result is lower than the baseline results, suggesting that the control variables absorb some of the impact. However, the results show evidence that expanding renewable energy relative to non-renewable energy can help diminish CO_2 emissions, consistent with previous findings. The control variables also add interesting findings. Firstly, the results show FDI has a positive and significant (at the 5% level) impact on CO_2 emissions. Specifically, a 1% increase in FDI net inflows increases CO_2 emissions per capita by 0.077% in the short term. This suggests that investment in the G7 countries is linked to carbon-intensive activities. As a result, policymakers should be aware that foreign investment may have unintended environmental consequences, which should be addressed through suitable regulation. Another key finding is the impact of total primary energy consumption on CO_2 emissions. Specifically, a 1% increase in total primary energy consumption increases CO_2 emissions by 0.86%. This result is statistically significant (at the 1% level). As energy demand rises, so do CO_2 emissions. This is expected because much of the energy mix largely comprises of fossil fuels producing CO_2 emissions. Without policies to cut down the use of non-renewable energy sources, countries may struggle to meet their climate targets. Equation (3) builds on equation (2) but includes GDP and a squared GDP term. As with equation (2), renewable energy consumption remains negative and statistically significant (at 1% level). It remains that a 1% increase in renewable energy consumption as a share of primary consumption leads to a 0.079% decrease in CO_2 emissions per capita over the short run. Turning to both GDP variables, their coefficients resemble predictions of the EKC. GDP is positive, and GDP squared is negative. However, there are various observations to note. Both coefficients are statistically insignificant, which means any meaningful relationship cannot be justified. The reason behind this insignificance, which many previous papers fail to mention, is the extremely high multicollinearity observed due to both GDP terms being included. Additionally, the findings are both small in magnitude, which further limits meaningful interpretations to help support or reject the EKC hypothesis. We see results similar to those in equation (2) regarding the control variables. Firstly, oil prices and population growth have insignificant and marginally negative impacts on CO_2 emissions in the short run. The result of oil price suggests that the G7 are relatively less sensitive to oil price fluctuations due to a diversified energy mix. This relationship may differ in countries which have a higher dependence on oil. The finding of population growth suggests that short-term implications are minimal. However, this result may differ in a long-term model. Additionally, this paper is limited to CO_2 emissions per capita. If it were absolute emissions instead, population growth may present more impactful findings. Lastly, urbanisation yielded a positive yet insignificant result, suggesting no meaningful effect in the short run. One reason could be that urbanisation rates in the G7 were already high at the start of the sample period. Therefore, changes were marginal and didn't produce significant results. As a result, urbanisation may only be a suitable variable for studies focusing on countries with more varied urbanisation rates. However, FDI inflows and total primary energy consumption are statistically significant (at the 1% level). In particular, a 1% increase in FDI net inflows is associated with a 0.008% increase in CO_2 emissions in the short run. While marginal, it provides evidence that foreign investment in the G7 contributes to a rise in CO_2 emissions. This suggests that policies to increase foreign investment are insufficient to achieve climate goals unless policies also actively target regulations promoting low-carbon investments. Finally, the results show that a

1% increase in total primary energy consumption leads to a 0.862% increase in CO_2 emissions. This shows that energy demand significantly drives overall CO_2 emissions in the G7. This provides evidence to suggest that it is not enough for the share of renewable energy to increase, but a reduction in non-renewable energy sources must occur. As a result, policymakers must understand that the substitutability between renewable and non-renewable energy sources is crucial to reducing CO_2 emissions. In this respect, policies must improve the feasibility and incentives of producing renewable energy sources. Potential methods could include, but are not limited to, providing subsidies, grants or tax credits to renewable energy investment or implementing more stringent carbon pricing mechanisms aiming to phase out non-renewable energy sources.

In summary, the main regression results provide evidence to support the idea that renewable energy investment, and thus consumption, can drive down CO_2 emissions within the G7 in the short term. In contrast, the effectiveness of GDP growth alone in driving down CO_2 emissions is weak. This paper finds no evidence to suggest that the EKC hypothesis holds true in the countries considered. The study also finds evidence to suggest that policymaking plays a vital role. It is not enough to promote clean energy sources alone, but also to provide incentives for consumers to substitute away from the production of non-renewable energy sources as demand for energy grows.

6. Robustness Checks

This section examines the robustness of our core findings. An alternative emissions measure, specifically N_2O, is introduced to do this. It will replace CO_2 in the baseline equations. Equation (1) did not include a CO_2 variable, so it is disregarded. The focus now involves only equations (2) and (3). Similarly, panel unit root tests are conducted on N_2O, as seen in **Table B**. Evidence suggests N_2O is stationary when the log first difference is taken. Similarly to before, a FE model is applied with Driscoll-Kraay standard errors to ensure comparability between the two different emission measures. The same variables are also controlled to provide consistency with the previous models.

Firstly, the regression is run on equation (2), plus controls. This tests whether a relationship exists between renewable energy consumption and the alternative emissions measure N_2O. The results are provided in **Table F**. The key result here is that renewable energy consumption now yields positive and insignificant results on N_2O emissions in the short term. This indicates that there is no evidence to suggest that an increase in renewable energy consumption can help drive down N_2O emissions. This is likely because N_2O is largely produced from agricultural and industrial activities, less so from the use of fossil fuels. This means that the idea of substitutability of renewable energy sources is less relevant in the N_2O case. This highlights that drivers of emissions vary across pollutant types and that different greenhouse gases may respond differently to the same policy measures. As a result, this finding suggests there is no one-size-fits-all policy to reduce overall emissions and that policies must strategically target emissions individually. The control variables' results are similar for equations (2) and (3) and they will be interpreted simultaneously in the equation (3) discussion.

Equation (3) analyses whether GDP and renewable energy, combined with relevant controls, drive N_2O emissions. The results find that renewable energy has a negligible and insignificant effect on N_2O emissions. However, in contrast to findings of the drivers of CO_2 emissions, evidence suggests that GDP has statistically significant effects (at the 1% level). Specifically, a 1% increase in real GDP per capita decreases per capita N_2O emissions by 0.237% in the short run, and the GDP squared term has a positive effect. This suggests that N_2O emissions initially fall as income grows, but this effect reverses past a certain income level. This contradicts the EKC hypothesis, which predicted an inverted U-shaped relationship. Instead, the results imply that wealthy countries like the G7 experience a rise in N_2O emissions, potentially due to increased industrial use of fertilisers and chemicals as an economy develops, despite previous climate gains. Next, looking at the control variables, the results find that FDI net inflows have a marginally negative and statistically significant impact on N_2O emissions. This suggests that foreign investment into sectors like agriculture, which produces vast amounts of N_2O emissions, supports the use of cleaner technologies. Additionally, total primary energy consumption remains a strong and significant driver of emissions. Specifically, a 1% increase in total primary energy consumption is associated with increased N_2O emissions per capita of 0.396% in the short run. This likely reflects that energy-intensive industrial sectors indirectly drive N_2O emissions. The remaining control variables, oil price, population growth and urbanisation, remain consistent with the CO_2 modelling because they provide no significant results. In summary, these findings stress the need for pollutant-specific policy action. Additionally, the robustness check finds again no evidence to support the EKC hypothesis.

7. Conclusion

This paper examined previous data from 1971 to 2022 to determine what exactly drives CO_2 emissions within G7 countries, explicitly analysing the role of GDP and renewable energy consumption. As such, the EKC hypothesis was addressed to investigate whether GDP growth alone was sufficient to mitigate CO_2 emissions or whether indirect outcomes of GDP growth are necessary to help counteract rising CO_2 emissions, thereby reducing overall environmental degradation and contributing to meeting climate goals.

The results provide strong empirical evidence to suggest that renewable energy consumption reduces CO_2 emissions in the short run. As such, the findings consistently show that renewable energy has a negative and statistically significant impact on CO_2 emissions. This supports the idea that policymakers must provide a suitable framework that incentivises the transition towards renewable energy sources. For example, subsidies or grants on renewable investment. However, policies that provide a transition towards renewable energy sources are not in themselves sufficient. The findings also suggest that total primary energy consumption increases CO_2 emissions in the short run. Therefore, policymakers must also incorporate strategies to transition away from non-renewable energy sources and can do so by taxing the worst polluters, for example. In addition, this paper found no evidence to support the EKC hypothesis. This aligns with the growing literature that has begun to speculate on its validity. As a result, policymakers cannot rely on growth itself to solve the escalating problems. Another key finding was that FDI net inflows were associated with an increase in CO_2 emissions in the short run. This suggests that policies have not been stringent enough to prevent investment that has contributed to environmental degradation. Therefore, policymakers should review the measures currently in place to tackle the effect that foreign investment has on the environment. Our results also tested for drivers of N_2O emissions, an alternative measure. The findings heavily contrasted that of CO_2 emissions. Renewable energy was not an important factor regarding drivers of N_2O. This suggested that while important for decarbonisation, it is less relevant for tackling other greenhouse gases. Additionally, while GDP produced significant results, it completely opposed the EKC hypothesis. The results highlight the importance that pollutant-specific strategies are necessary and that policymakers cannot assume that a singular mitigation tool will be the solution to climate change.

This paper has consistently stressed the need for policy action to address climate change. However, the analysis could not fully explore the most suitable policy instruments due to time constraints. In addition, given the currently high interest rates, any investment into renewable energy sectors may be delayed. Further research could include additional greenhouse gases to assess the tools policymakers should implement to mitigate their effects similarly. This analysis could also be extended to include a greater number of developed countries.

In summary, this paper finds no evidence of the EKC hypothesis within G7 countries. Economic growth alone is not enough to solve the climate problem. In contrast, improvements to the renewable energy sector are a useful mitigating tool for CO_2 emissions. However, this analysis cannot be extended to all emission types. These findings underline the need for targeted, well-designed policies, particularly those promoting renewable energy investment, to help countries meet climate commitments.

8. Appendix

Table A: Descriptive statistics.

Variable	Description	Mean	Std. Dev.	Min.	Max.	Source
CO_2 emissions	Annual total emissions of carbon dioxide (CO_2), excluding land-use change, measured in tonnes per capita.	11.37	4.75	4.26	22.26	(Global Carbon Budget, 2024)
Gross domestic product	GDP per capita in current US$.	26,697.57	15,709.70	2,310.92	78,035.17	(World Bank, 2024)
Renewable energy consumption	% Share of primary energy consumption that comes from renewables. Measured as a percentage of the total primary energy, using the substitution method.	9.73	8.87	0.39	32.05	(Energy Institute, 2024)
Oil price	Crude oil prices per cubic meter in 2023 US$.	450.15	229.87	106.02	947.91	(Energy Institute, 2024)
Urbanisation	Share of the population living in urban areas	76.54	5.43	64.75	91.96	(UN Population Division (via World Bank), 2025)

Table A: Descriptive statistics.

Variable	Description	Mean	Std. Dev.	Min.	Max.	Source
Foreign direct investment, net inflows	Net inflows of foreign direct investment from foreign investors to the reporting economy as a share of GDP.	1.46	1.78	-0.89	12.61	(World Bank, 2025)
Population growth rate	Average exponential rate of growth of the population over a given period. It is calculated as ln(P2/P1) where P1 and P2 are the populations on 1 January of subsequent years.	0.52	0.47	-0.99	1.85	(UN, World Population Prospects, 2024)
Primary energy consumption	Primary energy is the energy available as resources, before it has been transformed and was compiled using the substitution method. Measured in kilowatt-hours per person.	58,462.64	27,314.03	27,523.54	119,158.60	(U.S. Energy Information Administration, 2023)
N_2O emissions	Annual total nitrous oxide emissions, measured in tonnes of carbon dioxide-equivalents per capita	0.77	0.41	0.15	1.89	(Jones, 2024)

Table B: Panel unit root tests.

Variables	Levin, Lin & Chu (t*)	Breitung (λ)	Im, Pesaran and Shin (Z-t)	ADF Fisher (modified Pm)
Log (CO_2)	4.41	3.07	4.80	-2.07
Δ Log (CO_2)	-15.74***	-7.85***	-15.39***	59.42***
Log (GDP)	-6.78***	6.55	-4.15***	14.50***
Log (GDP^2)	-5.93***	6.63	-3.33***	8.36***
Log (REC)	5.03	4.47	4.96	-1.31
Δ Log (REC)	-19.10***	-11.12***	-17.67***	67.44***
Log (OP)	-2.31**	-0.65	-3.71***	4.53***
Log (FDI)	-7.09***	-4.64***	-7.40***	16.07***

Stars indicate significance levels: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table B: Panel unit root tests.

Variables	Levin, Lin & Chu (t*)	Breitung (λ)	Im, Pesaran and Shin (Z-t)	ADF Fisher (modified Pm)
P	-2.19**	1.29	-2.95***	6.20***
Log (TEC)	1.10	-0.40	1.00	0.66
Δ Log (TEC)	-16.82***	-6.83***	-16.59***	51.44***
Log (URB)	2.91	13.13	5.53	-2.62
Δ Log (URB)	-1.50*	-1.63*	-2.23**	0.88
Log (N_2O)	1.37	3.77	3.62	-2.35
Δ Log (N_2O)	-13.89***	-10.62***	-13.40***	42.48***

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table C: Pedroni test for panel cointegration with Ln(CO_2), Ln(REC), Ln(TEC) and Ln(URB).

Panel test statistics:	Statistic	P-value
Modified PP-statistic	0.72	0.24
PP-statistic	-0.14	0.44
ADF-statistic	0.26	0.40

Table D: Baseline regression results summary

	Equation (1)	Equation (2)	Equation (3)
Gross domestic product	0.31*** (0.01)	-	-0.022 (0.09)
Gross domestic product (squared)	-	-	0.001 (0.00)
Renewable energy consumption	-	-0.17*** (0.03)	-0.16*** (0.03)

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table E: Main regression results summary

	Equation (1)	Equation (2)	Equation (3)
N. of observations	357	357	357
Overall R^2	0.16	0.67	0.67
N. of countries	7	7	7
Hausman test Chi	6.20	4.69	2.39
Hausman p-value	0.40	0.58	0.94
Wald test Chi^2	272.92	237.14	276.84
Wald test p-value	0.00	0.00	0.00
Wooldridge test p-value	0.01	0.28	0.31
Pearson's CD test	0.32	0.00	0.00
Mean VIF	1.56	1.47	189.15

Table E: Main regression results summary

	Equation (1)	Equation (2)	Equation (3)
Gross domestic product	0.016* (0.01)	-	0.020 (0.04)
Gross domestic product (squared)	-	-	-0.001 (0.00)
Renewable energy consumption	-	-0.079*** (0.01)	-0.079*** (0.01)
Oil price	-0.014 (0.01)	-0.001 (0.00)	-0.002 (0.00)

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table E: Main regression results summary

	Equation (1)	Equation (2)	Equation (3)
Foreign direct investment, net inflows	0.002 (0.01)	0.077** (0.00)	0.008*** (0.00)
Population growth rate	-0.014 (0.06)	-0.002 (0.00)	-0.002 (0.05)
Primary energy consumption	-1.115*** (0.19)	0.861*** (0.04)	0.862*** (0.05)
Urbanisation	0.290 (1.47)	0.275 (0.46)	0.321 (0.43)

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table F: N_2O robustness check regression results summary

	Equation (2)	Equation (3)
Gross domestic product	-	-0.237*** (0.06)
Gross domestic product (squared)	-	0.012*** (0.00)
Renewable energy consumption	0.001 (0.02)	0.000 (0.02)
Oil price	0.008 (0.01)	0.007 (0.01)

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table F: N_2O robustness check regression results summary

	Equation (2)	Equation (3)
Foreign direct investment, net inflows	-0.012** (0.01)	-0.011** (0.00)
Population growth rate	0.002 (0.01)	0.000 (0.01)
Primary energy consumption	0.428*** (0.11)	0.396*** (0.10)
Urbanisation	-0.359 (0.66)	-0.712 (0.82)

Stars indicate significance levels: *** p<0.01, ** p<0.05, * p<0.1.

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