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The Response of CO2 Emissions to Macroeconomic Shocks - A Panel VAR Analysis

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The Response of CO_2 Emissions to Macroeconomic Shocks - A Panel VAR Analysis

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Abstract: Global efforts towards mitigating climate change gain momentum; reducing carbon dioxide (CO_2) emissions and aiming for zero emissions, or carbon neutrality, is the main goal. Economic factors are main determinants of CO_2 emissions coming from production and energy consumption. This paper aims to empirically estimate these economic effects. For this purpose, we employ an unbalanced panel of 78 countries using annual data between 1990 to 2022. We estimate a panel vector autoregression (VAR) model to show the dynamic response of CO_2 emissions to a large number of macroeconomic variables. These are: Population, GDP, investment, trade, oil price, renewable energy consumption, inflation, effective exchange rate, and nominal interest rate. Moreover, we perform extensive robustness checks to account for panel heterogeneity by splitting the sample based on: Geographical location, income level, population, and emission level. We find significant responses of CO_2 emissions to shocks from population growth, GDP growth, renewable energy consumption, and interest rates.

Keywords: CO_2 emissions, climate change, energy consumption, economic growth, panel VAR

JEL codes: Q54, F64

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1 Introduction

The world has been witnessing climate change and its consequences for the past decades. The rise of this global issue is mainly attributed to the rising level of industrialization, production, and population growth which inevitably equated to higher energy consumption which fuels the increase of greenhouse gas emissions in general, and CO_2 emissions in specific. Due to rising global temperatures there is now the urgency to substitute fossil fuel with renewable energy sources to meet the 1.5C target laid down in the Paris Agreement of 2015. This could be achieved via innovations to create ”greener” production methods (Dong et al., 2018; Rahman and Alam, 2022; Hao and Chen, 2023).

Greenhouse gas emissions have dramatically increased since the 1960s, with 81% of these emissions attributed to rising levels of CO_2 gas emissions, making it the most widely used climate change measure in econometric modelsChishti et al., 2021. The expected consequences of this phenomenon are wide-ranging and include the melting of polar ice caps, rising sea levels, deterioration in environmental quality, damage to agricultural crop production, and a range of natural disasters attributed to an increase in temperature, losses in human lives, and spread of diseases (Taha et al., 2022). As a result, environmental research aims to determine the contributing factors to CO_2 emissions (Chishti et al., 2021; Nguyen et al., 2022).

Rapid growth in population, globalization, production, and trade is suggested to be the main drivers behind climate change (Rahman and Alam, 2022). Additionally, economic policies, like monetary policy, were recently proposed to influence CO_2 emissions and therefore can be used to mitigate the climate change issue (Qingquan et al., 2020). In addition to monetary policy, other factors such as inflation rate, exchange rate, and oil prices, have been investigated empirically to test for their potential impact on CO_2 emissions (Mahmood et al., 2022; Shah et al., 2022; Okwanya et al., 2023; Grolleau and Weber, 2024).

This article contributes to the growing literature by first collecting data for 78 countries worldwide, since fighting climate change is a global challenge. Second, we estimate the effects of various macroeconomic variables simultaneously, to account for potential inter-dependencies. Third, we apply extensive robustness checks to account for potential heterogeneity among the sample countries. To do so, we employ a panel vector auto-regression (VAR) to allow for dynamic response of the macroeconomic variables on CO_2 emissions.

The remainder of this paper is structured as follows; Chapter 2 provides a review of previous empirical studies in our field of research. Chapter 3 presents the data sources and sample splits applied. In chapter 4 we explain the methodology used. In chapter 5 we present and discuss the results of our estimations. Finally, chapter 6 concludes.

2 Literature Review

Economic growth, population growth, and renewable energy consumption are the most researched determinants of CO_2 emission. A well-established strand of literature links economic growth to environmental damage. The Environmental Kuznets Curve (EKC) is an established concept that is usually used to model this relationship. Several studies have provided empirical evidence of this relationship. Similarly, population growth is linked to an increase in energy consumption and production and, ultimately, lower environmental quality. The relationship between renewable energy consumption and CO_2 emissions has been extensively investigated (Dogan and Seker, 2016; Ito, 2017; Shafiei and Salim, 2014; Bhattacharya et al., 2017; Dong et al., 2018; Salem et al., 2021). The consensus is that nonrenewable energy is the main cause of CO_2 emissions; therefore, an increase in renewable energy consumption (REC) improves environmental quality. In the remainder of this section, we report the results of previous empirical studies that investigated different macroeconomic factors affecting CO_2 emissions, mostly by applying a panel analysis.

Dogan and Seker (2016) investigate the EU-15 from 1980 to 2012 by applying a DOLS methodology. They find evidence of REC reduction of CO_2 emissions. Similar results were obtained by Ito (2017) for a panel of 42 developed countries. They applied GMM and PMG methodologies. Shafiei and Salim (2014) find similar results for REC, and report evidence of a positive influence from output and population on CO_2 emissions. In their study, Bhattacharya et al. (2017) investigate the effects of GDP growth and REC on CO_2 emissions for a panel of developing economies from 1991 to 2012. They utilized GMM and FMOLS in their analysis and found evidence of a positive impact of REC on output and a negative impact on the emission level. In another study, Dong et al. (2018) investigate a panel of twelve countries from 1990 to 2014. They use a CCEMG estimator and found that economic growth and population growth have a positive impact on CO_2 emissions and that REC leads to a decline. They explore subsamples based on regions and find that the impact of REC on CO_2 is more intense for South and Central America, as well as Europe and Eurasia, when compared to the rest of the sample. In

Salem et al. (2021), the authors cover a sample of the top ten highly carbon-emitting countries from 1991 to 2018. They apply a PMG model and found a significant negative impact of different types of renewable energy consumption on CO_2 emissions.

Mahmood et el. (2022) focus on a panel of GCC countries from 1980 to 2019. They apply the NARDL methodology and found that economic growth positively impacted CO_2 emissions. Rahman and Alam (2022) investigate a panel of 17 Asia-Pacific countries from 1960 to 2020 and find similar results with respect to economic growth. In another study, Hao and Chen (2023) investigate E7 countries from 1990 to 2020. They apply FMOLS, DOLS, ARDL, and CCR and found a significant negative impact of REC on CO_2 emissions and a positive impact from economic growth.

Other macroeconomic factors, such as trade and investment, contribute to emissions. However, empirical studies on these relationships have yielded mixed results, and it is agreed that it depends on the context of the study. Rahman and Alam (2022) also find trade to have a positive influence on CO_2 emissions, however, they still acknowledge that this link requires more attention as it is understudied and has inconclusive results. The opposite results were found by Ahmad et al. (2022) in the context of Pakistan from 1970 to 2018. Similar results were found in Dogan and Seker (2016) in the EU context.

There are only a few studies dealing with the impact of oil prices on CO_2 emissions. This is particularly important for the post-COVID-19 period and the Russian war in Ukraine that are affecting oil prices in the current years thus making it more volatile. Mahmood et al. (2022) find that oil prices have a negative influence on CO_2 emissions in GCC countries. Okwanya et al. (2023) investigate a sample of 30 African countries for the period from 1987 to 2019 and find that positive changes in oil prices are linked to a decrease in CO_2 emissions. They, moreover, find differences in the results between oil-importing and oil-exporting countries, where oil-importing countries seem to respond more positively to changes in oil prices in the long run. By contrast, oil-exporting countries respond more to negative changes in oil prices.

When it comes to the impact of inflation, interest rates, and exchange rates on CO_2 emissions there are only a few studies. As more channels are involved, the impact becomes indirect and complex. However, as expected, recent empirical studies have begun to investigate and the results are mixed. For inflation, very few studies have investigated the link. Grolleau and Weber (2024) investigate a panel of 189 countries for the period from 1970 to 2020 by applying a fixed effects regression model and found a minor negative impact of inflation on CO_2 emissions and concluded that the impact is too weak to make a statement for policy implications. However, Hao and Chen (2023) find that inflation increased CO_2 emissions. Shah et al. (2022) test the impact of exchange rate depreciation on CO_2 emissions and find it positive in Pakistan. The justification proposed is that due to the expansionary effect on output, devaluation has the side-effect of higher energy consumption.

Finally, there is a strand of literature investigating the influence of monetary policies on CO_2 emissions. This transmission is hypothesized to occur through energy consumption, innovation, aggregate demand consumption, financial development, and income levels (Qingquan et al., 2020; Chishti et al., 2021; Nguyen et al., 2022). Most studies have concluded that lowering the interest rate (expansionary monetary policy) is associated with a higher level of CO_2 emissions, whereas the opposite is true for increasing interest rates (contractionary monetary policy). E.g. Isiksal et al. (2019) find that the real interest rate negatively impacts CO_2 emissions in Turkey. Supporting this result, Qingquan et al. (2020) find long-term cointegration between monetary policy and CO_2 emissions in a selected sample of Asian economies. The coefficients support the idea that an expansionary monetary policy increases CO_2 emissions, whereas a contractionary monetary policy reduces CO_2 emissions in the long run. Similar results for the BRICS economies were found in Chishti et al. (2021) and Nguyen et al. (2022) for a sample of 14 emerging economies, Xin et al. (2022) for the context of the US, Aghabalayev and Ahmad (2023) for G7 states, Noureen et al. (2022) for a selected sample of developing countries, Huang et al. (2022) for a sample of EU countries, Liguo et al. (2022) for the context of the US, and Jiang et al.(2021) for Australia.

Contrary to the studies above, some studies have found expansionary monetary policy to be associated with a lower level of CO_2 emissions, while the opposite is true for contractionary monetary policy. These studies are: Pradeep (2021) shows that interest rates have a significant positive impact on per capita emissions in the long and short run. Muhafidin (2020), in the context of Indonesia, shows a positive significant relationship between the interest rate and CO_2 emissions. Finally, Zeraibi et al. (2022), in the context of China, conclude that an expansionary monetary policy lowered CO_2 emissions both in the long and short run.

In our study, we aim to contribute to previous literature by applying the VAR method with an extensive sample of 78 countries and adding multiple variables including monetary policy to have a realistic model of influential factors that contribute to CO_2 emissions. Furthermore, as sample heterogeneity is discussed in the literature, we account for this by conducting an extensive robustness check by splitting the sample based on different criteria: geography, population, emissions level, and income level. Based on the literature, we propose the following hypotheses:

H1: CO_2 emissions respond positively to GDP growth, trade, and population shock.

H2: CO_2 emissions respond negatively to oil prices and REC growth.

H3: The influence of inflation, exchange rate, and interest rate is minor if significant.

In the following section, we discuss the data and methods used to investigate the hypotheses in detail.

3 Data

In this article, we employ a panel VAR for 78 countries applying yearly data between 1990 to 2022. Even though we tried our best to balance the panel it was not possible to do so for all countries and variables. Therefore, the panel remains to some extent unbalanced. In total, we end up with 1820 observations across countries. A detailed description of which years for which country are available is given in Table A1 in the appendix.

All data are retrieved from the World Bank, except for some series for some countries that are retrieved from other sources. Some cross-sections are missing for interest rate data, hence they were retrieved from IMF and OECD, for: Saudi Arabia, Morrocco, Denmark, Poland, EA countries, Tunisia, and Türkiye. Those missing for the real effective exchange rate are retrieved from Bruegel, for Albania, Estonia, Egypt, Indonesia, India, Jordan, Kuwait, Lebanon, Lithuania, Madagascar, Mauritania, Mauritius, Oman, Peru, Rwanda, Thailand, and Türkiye. We retrieve oil prices from the US Energy Information Administration (EIA).

We include in our estimation the following variables: production, trade, inflation, oil price, renewable energy consumption, real effective exchange rate, investment, interest rate, and population. For production, we use GDP growth as our measure. For trade, we use the growth of the share of trade from GDP. For exchange rate, we employ the real effective exchange rate. For investment, we use gross fixed capital formation growth. For population, we use annual population growth. For the interest rate, we employ the nominal interest rate. For renewable energy consumption, we use renewable energy consumption as a share of total energy consumption. For inflation, we use the growth rate of the consumer price index (CPI).

On the one hand, we expect a positive shock from GDP growth, trade growth, and population growth, which will lead to an increase of CO_2 emissions. On the other hand, we expect a negative response to oil price growth and renewable energy consumption growth.

All variables included are converted to growth rates to guarantee stationarity, except for interest rate and inflation rate. Descriptive statistics of all variables along with stationarity test statistic (ADF) are shown in Table 1. All variables are stationary when using yearly growth rates. We only present the ADF test statistic in the table, however, we also checked other tests, namely: Levin -Lin-Chu (LLC), Im, Pesaran and Shin (IPS) W-stat, and Philips-Perron (PP) - Fisher Chi-square, and all yield similar conclusions.

Table 1: Descriptive Statistics

	CO_2	GDP	Population	Oil price	Renewable energy	Exchange rate	Interest rate	Inflation	Investment	Trade
Mean	1.133886	3.093155	0.848038	6.513519	3.302409	0.672105	13.59660	7.420749	190.6843	1.103805
Median	1.161538	3.233496	0.829763	2.290389	0.847063	0.615991	8.171145	3.128072	−41.02152	1.205064
Maximum	65.43459	24.37045	11.79402	58.65922	369.2308	84.84808	989.2672	1058.374	260377.5	71.77990
Minimum	−37.08456	−22.90000	−3.847671	−47.13550	−61.40351	−74.65392	−9.995215	−4.478103	−37477.65	−51.93908
Std. Dev.	6.864772	3.753954	1.118241	26.88014	18.85516	7.698574	35.84451	35.66302	7137.600	8.993722
Observations	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820
Stationarity test (ADF stat)	585.315	759.595	377.533	1251.98	750.450	949.631	400.937	622.425	757.099	1070.31

4 Methodology

In this section, we will first explain the VAR model specification, followed by a detailed description of the sample splits.

4.1 Model Specification

Our analysis is based on an estimated panel VAR model. We find the VAR structure suitable for this investigation as it controls for feedback between CO_2 emissions growth rate (CO_2g), population growth rate (POPg), GDP growth rate (GDPg), investment growth (GCFg), trade growth (TRADEg), oil prices growth (OILg), renewable energy consumption growth (RECg), inflation rate (INF), real effective exchange rate (RERg), and nominal interest rate (NIR).. The cross-sectional dimension covers country i = 1,...,N, while the time dimension is t = s + 1,...,T. The estimated model is:

$$Ay_{it} = d_i + F_1 y_{it-1} + ... + F_s y_{it-q} + \epsilon_{it}, (1)$$

Where Yt is a vector of all endogenous variables, y_{t-j} is a matrix of the lags of all included variables. We include an n x 1 vector cross-section with country fixed effects. The matrices

A and F contain the VAR coefficients, The structural shocks, which eventually drive all the endogenous variables, are collected in ϵ_{it} with $\epsilon_{it} \sim N(0, \sum \sum')$.

We estimate the VAR model with the following 10 × 1 vector of endogenous variables:

$$y_{it} = [POPg_{it}GDPg_{it}GCFg_{it}TRADEg_{it}OILg_{it}RECg_{it}INF_{it}RERg_{it}NIR_{it}CO2g_{it},]'(2)$$

The ordering of variables was determined as follows: We posit that the CO2 growth responds contemporaneously to all the other variables in the system. Whereas population growth is not contemporaneously affected by other variables in the system. As a check for robustness, we tested different orderings for the other variables for each of the following discussed trials, and no significant differences were to be reported. We determine the lag order (q) using information criteria, we go with the lowest number of lags suggested to preserve degrees of freedom [3]. Thus, we include q = 5 lags of the endogenous variables. In light of the large dimension of the data set across time and countries, the relatively large number of variables and parameters to be estimated should not be a concern.

We assume that A is lower-triangular such that the reduced-form model is:

$$y_{it} = c_i + B_1 y_{it-1} + ... + B_s y_{it-s} + A^{-1} \sum \epsilon_{it}, (3)$$

with $\epsilon_{it} \sim N(0, I_k)$, where c_i $A^{-1}d_i$ and $B_j = A^{-1}F_j$. $\sum$ is an n x n matrix with standard deviations on the main diagonal.

As we estimate the VAR model for 78 countries, we assume that the auto-regressive coefficients are identical across countries. This implies that we obtain one set of impulse response functions summarizing the information from all countries. However, to address potential heterogeneity in the cross-section, we split our country sample as described in the next section.

4.2 Sample Splits

To check for robustness and to address potential heterogeneity, we split the sample based on four different criteria: geographically, income level, population density, as well as emission level (overall increasing vs decreasing).

For the geographical split, we adopted the World Bank's classification: Middle East and North Africa (MENA), Europe and Central Asia, and Southeast Asia and Pacific. MENA sam-

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[3] The detailed results are available from the authors upon request.

ple include: Algeria, Egypt, Arab Rep., Iran, Islamic Rep., Jordan, Kuwait, Lebanon, Morocco, Tunisia. EA sample include: Austria, Belgium, Croatia, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Spain. Europe and Central Asia include: Albania, Armenia, Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Moldova, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russian Federation, Slovak Republic, Spain, Sweden, Switzerland, Turkiye, Ukraine, United Kingdom. Southeast Asia and the Pacific include: Australia, China, India, Indonesia, Japan, Korea, Rep., Malaysia, New Zealand, Pakistan, Philippines, Singapore, Thailand.

For the income level split, we also adopted the World Bank's income classification; we split the sample into two groups, the first is the high-income and upper-middle-income, and second is the low-middle-income and low-income countries. Defined as high and upper-middle income are: Albania, Armenia, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czechia, Denmark, Dominican Republic, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Indonesia, Ireland, Italy, Japan, Korea, Rep., Kuwait, Latvia, Lithuania, Luxembourg, Malaysia, Malta, Mauritius, Mexico, Moldova, Netherlands, New Zealand, North Macedonia, Norway, Paraguay, Peru, Poland, Portugal, Romania, Russian Federation, Saudi Arabia, Singapore, Slovak Republic, South Africa, Spain, Sweden, Switzerland, Thailand, Turkiye, United Kingdom, United States, Uruguay. Defined as low-middle and low-income are: Algeria, Bolivia, Congo, Dem. Rep., Cote d'Ivoire, Egypt, Arab Rep., India, Iran, Islamic Rep., Japan, Lebanon, Morocco, Nicaragua, Nigeria, Pakistan, Philippines, Tunisia, Ukraine, Venezuela, Zambia.

Moreover, we split our sample into two subsamples depending on the population density. The threshold for the division is whether a country has a population density above or below 100 people per sqm in the last data point for the respective country. Defined as high population density are: Albania, Austria, Belgium, China, Costa Rica, Cyprus, Czechia, Denmark, Dominican Republic, Egypt, Arab Rep., France, Germany, Hungary, India, Indonesia, Italy, Japan, Jordan, Korea, Rep., Kuwait, Lebanon, Luxembourg, Malaysia, Malta, Mauritius, Netherlands, Nigeria, Pakistan, Philippines, Poland, Portugal, Singapore, Slovak, Republic, Switzerland, Thailand, Turkiye, United Kingdom. Defined as low population density are: Algeria, Armenia, Australia, Bolivia, Brazil, Bulgaria, Canada, Chile, Colombia, Congo, Dem.

Rep., Cote d'Ivoire, Croatia, Estonia, Finland, Greece, Iceland, Iran, Islamic Rep., Ireland, Latvia, Lithuania, Mexico, Moldova, Morocco, New Zealand, Nicaragua, North Macedonia, Norway, Paraguay, Peru, Romania, Russian Federation, Saudi Arabia, South Africa, Spain, Sweden, Tunisia, Ukraine, United States, Uruguay, Venezuela, Zambia.

For the emission level classification, we calculated the difference between the first and last data point from the CO_2 emissions series for each country and split them into two groups: First, is the increasing emissions sub-sample where the last data point is higher than the first one, and, second, is vice versa for the decreasing emissions sub-sample. Defined as a decreasing emission level sample are: Albania, Armenia, Belgium, Bulgaria, Congo, Dem. Rep., Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Moldova, Netherlands, North Macedonia, Poland, Portugal, Romania, Russian Federation, Slovak Republic, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States, Venezuela.

Defined as an increasing emission level sample are: Algeria, Australia, Austria, Bolivia, Brazil, Canada, Chile, China, Colombia, Costa Rica, Cote d'Ivoire, Croatia, Cyprus, Dominican Republic, Egypt, Arab Rep., India, Indonesia, Iran, Islamic Rep., Ireland, Jordan, Korea, Rep., Kuwait, Lebanon, Malaysia, Mauritius, Mexico, Morocco, New Zealand, Nicaragua, Nigeria, Norway, Pakistan, Paraguay, Peru, Philippines, Saudi Arabia, Singapore, South Africa, Thailand, Tunisia, Turkiye, Uruguay, Zambia.

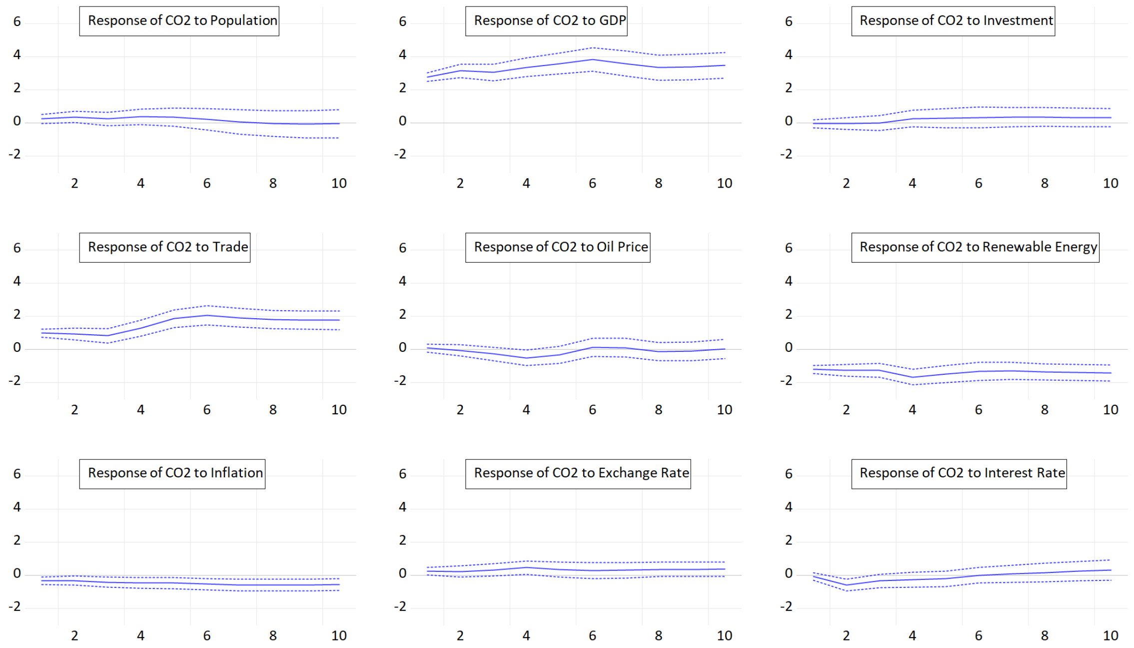
5 Empirical Results and Discussion

Our baseline model includes a yearly 10-variable, third-order Vector Auto-regressive model (VAR(10)) for 78 cross-sections with 5 lags and country fixed effects. As explained previously, we have assumed the following ordering: population growth rate (POPg), GDP growth rate (GDPg), investment growth (GCFg), trade growth (TRADEg), oil prices growth (OILg), renewable energy consumption growth (RECg), inflation rate (INF), real effective exchange rate (RERg), nominal interest rate (NIR), and CO_2 emissions growth rate (CO_2g). The robustness checks with the sub-samples follow the same specification. All of the discussed models are checked for stability and the models are found stable with the given number of lags. For this paper, our interpretation focuses on the response of CO_2 emissions to shocks from other variables [4].

5.1 Baseline Model

Figure 1 shows the accumulated impulse response function graphs of CO_2 emissions growth to all of the included variables. In this section, we report the results of the VAR model in terms of impulse response functions. We highlight the significance, and direction of the response of CO_2 emissions growth to a shock one standard deviation in size, and response magnitude.

Figure 1: Response of CO_2 to Macroeconomic Variables



Notes: Accumulated impulse response function to a one standard deviation shock for the next 10 years. Solid line = impulse response, dashed lines = 90% confidence interval.

In response to a positive shock in population growth, we see a small positive response for the first period that later dissipates. This is attributed to the population factor offsetting between our heterogeneous sample. A positive response was expected, as more people equals more consumption, production, and energy consumption. However, one would expect the impact to be larger. In response to a positive shock in GDP growth, there is an immediate lasting positive response peaking at 3.82% in the 6th period. When compared to other variables, GDP growth shock receives the largest CO_2 response.

In response to a positive trade growth shock, there is a positive response peaking at 2.05%

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[4] More detailed results are available from the authors upon request.

after six years. In response to a positive oil price growth shock, the response is not contemporaneous, however, a significant, yet small, negative response of -0.5% occurs after 4 years from the shock and later dissipates. In response to a positive shock in renewable energy consumption growth, CO_2 emissions had, as expected, an immediate lasting negative response with the lowest response in the 4th period at -1.67%.

The response to nominal interest rate shock is not contemporaneous, however, a significant negative shock of -0.6% occurs after 2 years from the shock and later dissipates. In response to a positive investment growth shock, there is no significant effect on CO_2 emission growth. Also, in response to an exchange rate shock, there is no significant response from CO_2 emission growth. In response to inflation shocks, CO_2 emission is negatively affected over the 10-year span, however, the effect is small (between -0.4% to -0.5%).

To sum up, the evidence supports the following; GDP growth, renewable energy consumption, and trade seem to receive the biggest shock response. These results are in line with the consensus of previous studies (Bhattacharya et al., 2017; Dong et al., 2018; Salem et al., 2021; Mahmood et al., 2022; Rahman and Alam, 2022, Hao and Chen, 2023). As expected, economic growth comes with the side effects of higher levels of CO_2 emissions. This can be attributed to the higher energy consumption that comes with higher production levels.

Concurrently, in support of previous research, switching to renewable energy is an effective mitigator of CO_2 emissions. For trade, in reference to the debate mentioned in Rahman and Alam (2022), our results support the argument that trade ultimately worsens environmental quality due to increasing industrial production. As for population growth, the impact seems to be not exactly as expected; we clarify these results further in the discussion of the sample split based on population density.

As for oil price, and interest rate, the results are as expected; for the oil price, as oil gets more expensive, the level of consumption is lower which in turn has a significant effect on the overall level of CO_2 emissions. Similar results were found in Mahmood et al. (2022) and Okwanya et al. (2023). For the nominal interest rate, it was also expected to see that a contractionary monetary policy leads to less demand, energy consumption, and hence, production and CO_2 emissions, which matches the framework discussed in Qingquan et al. (2020).

Lastly, investment and exchange rate have no significant impact on CO_2 emissions. The results for exchange rate are different from Shah et al. (2022) where found a significant impact in the Pakistani context, however, it seems that in a larger sample as in this article, it does not hold for most other economies. As for inflation, the results are in line with the minor effect found in Grolleau and Weber (2024). We elaborate on the policy implications of these effects in Chapter 6.

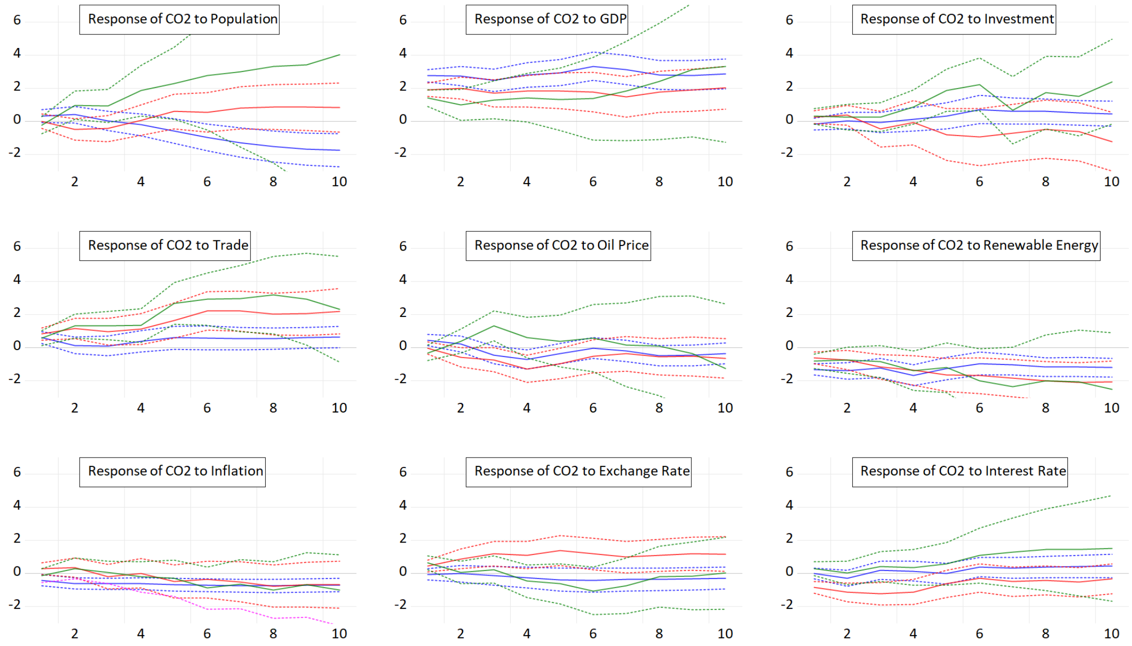
5.2 Robustness checks

Now we report the results of the sample splits. In comparison to the baseline findings, there are only minor differences in the response to shocks.

5.2.1 Geographical Classification

We now split the sample into MENA, Europe and Central Asia, and Southeast Asia and Pacific. Figure (2) shows the resulting impulse responses.

Figure 2: Response of CO_2 to Macroeconomic Variables: Geographical split



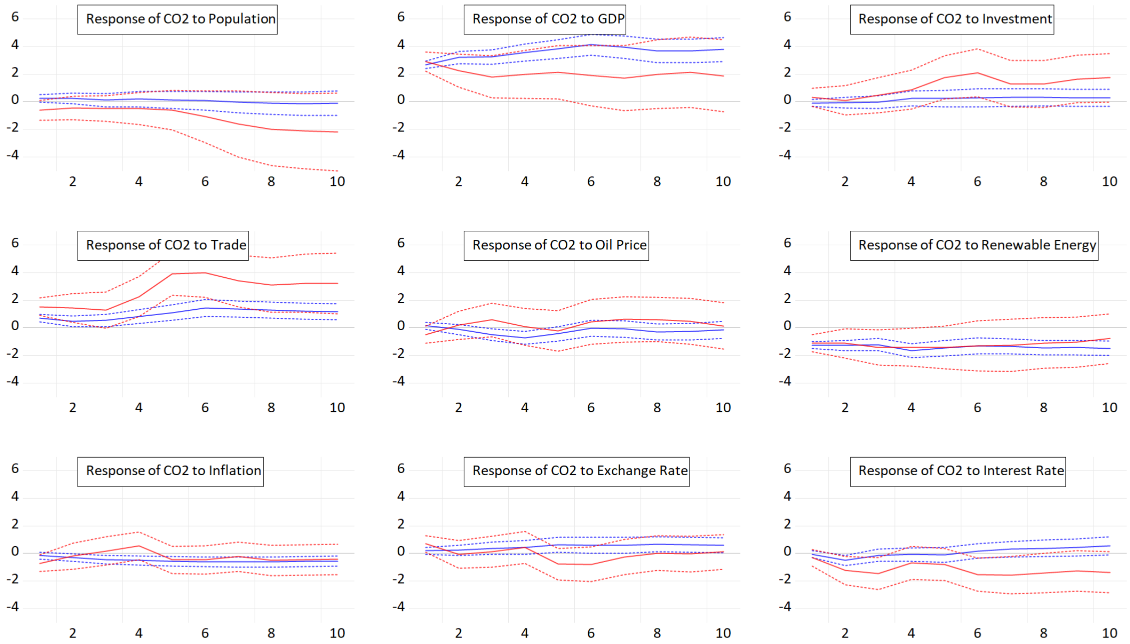
Notes: Accumulated impulse response function to a one standard deviation shock for the next 10 years. Solid line = impulse response, dashed lines = 90% confidence interval. Blue lines = Europe and Central Asia, red lines = Southeast Asia and the Pacific, green lines = MENA.

Due to the low number of countries in the MENA sample, the confidence intervals are generally quite large, so no significant differences to other regions can be detected. Also for the other two regions, there are almost no significant differences. The only exception is population growth. Here higher population growth rate in Europe and Central Asian countries leads to significantly lower CO_2 emissions after about six years. This finding is offset in the baseline results because of the non-significance of the other country groups.

5.2.2 Income Level Classification

Here, we split the sample into two groups; the first is the high-income upper-middle, and upper-middle income, and the second is the low-middle-income and low-income countries. Figure (3) shows the resulting impulse responses.

Figure 3: Response of CO_2 to Macroeconomic Variables: Income level split



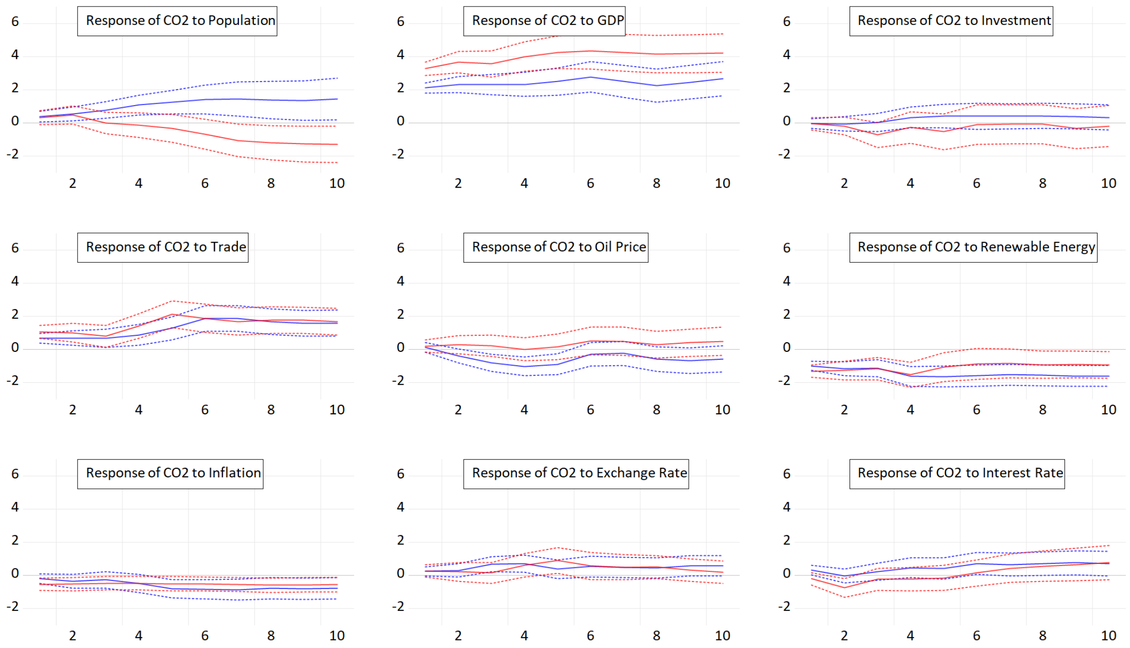
Notes: Accumulated impulse response function to a one standard deviation shock for the next 10 years. Solid line = impulse response, dashed lines = 90% confidence interval. Blue lines = high- and upper-middle income countries, red lines = lower-middle and low income countries.

As the lower-middle and low income countries sample have fewer number of countries, the confidence intervals appear to be larger than for the high and upper-middle income countries. Nevertheless, come significant differences occur. With respect to trade growth, the lower-middle and low income countries tend to have a larger CO_2 response after about four years. This may mirror the effect of higher pollution due to more transportation in the lower-middle and low income countries. Moreover, the response to interest rate changes differs. Here the high and upper-middle income countries show similar evolution as in the baseline results, while the lower-middle and low-income countries show the expected negative response for almost the entire sample period.

5.2.3 Population Density Classification

Here, we split the sample into two groups; above and below population density of 100 people per sqm of land as of the last data point for the respective country. Figure (4) shows the resulting impulse responses.

Figure 4: Response of CO_2 to Macroeconomic Variables: Population density split



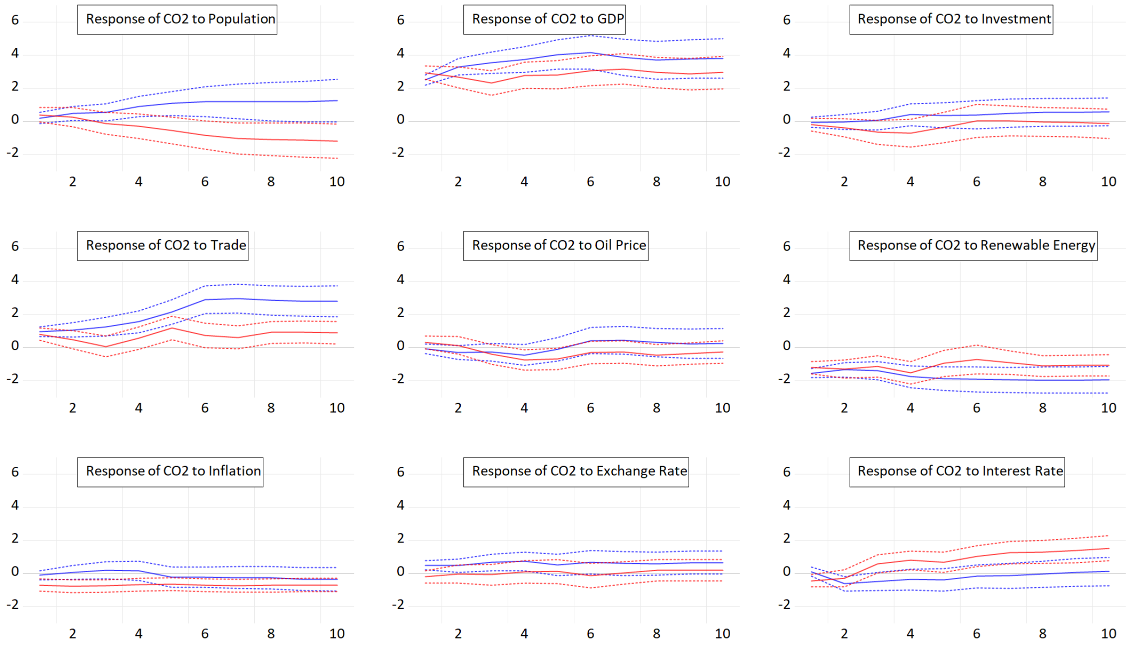
Notes: Accumulated impulse response function to a one standard deviation shock for the next 10 years. Solid line = impulse response, dashed lines = 90% confidence interval. Blue lines = high-density population countries, red lines = low-density population countries.

In comparison to the baseline findings, we find a significant difference in the response to population growth shock in high versus low population density economies. For economies with high population density, a positive shock in population growth leads to higher CO_2 emissions, whereas the opposite holds for countries with low population density. This provides us with a reason behind the insignificant response of CO_2 emission to population growth in the baseline sample results. Moreover, the response with respect to GDP growth differs. Here the response of low density countries is found to be significantly higher in the first two years than for the high density countries. An explanation for this may be the higher transportation costs associated with production and consumption in low density countries due to the more dispersed population.

5.2.4 CO_2 emission level Classification

Here, we split the sample into two groups; increasing and decreasing emission levels (as described in chapter 4.2). Figure (5) shows the resulting impulse responses. In comparison to the baseline findings, the significant difference was the response to population growth shock in both high-emission and low-emission economies. For the increasing emission economies, a positive shock in population growth leads to higher CO_2 emissions. Whereas the opposite holds for the decreasing emission economies. Similar to what we found in the population density split, this also explains the insignificant response of CO_2 emission to population growth in the full sample.

Figure 5: Response of CO_2 to Macroeconomic Variables: Emission level split



Notes: Accumulated impulse response function to a one standard deviation shock for the next 10 years. Solid line = impulse response, dashed lines = 90% confidence interval. Blue lines = increasing emissions countries, red lines = decreasing emissions countries.

When splitting the sample into CO_2 increasing and decreasing countries, two significant differences stand out. First, with respect to the response to population growth, the emission increasing countries tend to have a positive effect on CO_2 emissions while the reverse is true for emission decreasing countries. An explanation for this finding may be that the decreasing emission countries are also the more developed countries which transition their economies into more service sector intensive being more pollution friendly. The reverse is true for the emission increasing countries being mainly developing countries which still adopt less pollution friendly industrial production. Second, confirming that is the difference we find in the response of CO_2 with respect to trade shocks. Here the increasing emission countries are found to have a higher response to an increase in trade. Given the higher industrial production intensity in the increasing emission countries, more exports necessarily lead to higher emission levels compared to the exports from the decreasing emission countries which are mainly services.

In another robustness check, we remove the top polluting countries/or the largest contributors to global emissions as of 2022 (China, India, Russia, and the US) the results are robust and no significant difference is observed.

6 Conclusion

This paper employs a panel VAR model on an unbalanced panel of 78 countries. To address heterogeneity and check for robustness, we ran the sample twice: for the full sample and sample splits. We find robust significant responses of CO_2 emissions to shocks from population growth, GDP growth, renewable energy consumption, and nominal interest rate.

Aligning with the literature, the results confirm the environmental cost of economic growth. The controversial conclusion is to suggest de-growth, however, this is not the only solution. As a policy implication, we would like to address that rather than calling for de-growth, we call for innovation and the use of renewable energy. De-growth will have adverse effects, especially for less developed economies that inevitably need to target the exact opposite of de-growth to enhance their economic welfare. Hence, backed by our results for renewable energy consumption, we side with recent climate pacts (e.g. Glasgow, 2021) and favor the decoupling of growth from CO_2 emissions through innovation of greener production methods and switching to renewable energy as the remedy that can fit every economy regardless of its income or emission level. In addition, the results on trade may suggest that it contributes to the climate change issue. Based on this, we would like to direct policymakers to pave the way towards greening international trade.

We also conclude from the results, that increasing interest rates decreases CO_2 emissions.

As mentioned by Qingquan et al. (2020), the suggested channel is that in contractionary policies, credit is more expensive so less is produced. However, we should acknowledge the potential drawback that new green investments would also be discouraged, therefore the effect seems to be a trade-off and offset each other in a way. Hence, we would further suggest future research distinguishing between its effects on green versus dirty investments. There is significant support for central banks to get involved with the climate change issue on the policy level. However, given the small effect, it is not exactly beneficial to target CO_2 levels with the interest rate, given the side effects this may have on price and financial stability. Further, we would like to bring the trilemma, also known as, the impossible trinity into this discussion; adding climate change to this mix will just further complicate how we manage our monetary systems. Based on our results, we are in favor of not involving monetary policy in CO_2 emission targeting.

Finally, the results suggest that the impact of economic growth on CO_2 emissions is the same across all countries regardless of income level, emissions level, geographical location, or even population density. Based on this, we stress that it is equally important for all countries to participate and cooperate to work towards a better environment. Consequently, the conclusion is that it is not only the responsibility of the highest emitters, but any economy can take the lead and cooperate for a sustainable future.

To further extend this paper, some limitations can be addressed for future research. We favored a large sample over a small sample of countries, however, the available data was annual rather than a high-frequency sample (i.e. quarterly). This is mainly due to the scarcity of emissions data in quarterly form. Hence, we suggest repeating the study when higher frequency data is available. Moreover, we only used CO_2 emissions in metric tons as an indicator of climate change. We suggest future research exploring proxies such as CO_2 emissions per GDP to consider the size of the economy. To continue further with this topic, we would also suggest trying different sample splits and comparisons, for example: oil-exporting vs oil-importing economies, splitting countries based on the nature of trade, and high vs low share of renewable energy from total energy consumption. Finally, income inequality seems to be a potential addition to the model as suggested in Yang et al. (2022). It would also be interesting to explore it with the presence of monetary policy in the VAR model to see if there is a potential nexus between CO_2 emissions, income inequality, and monetary policy (previous studies discussing this nexus: Bai et al., 2020; Omar and Richter, 2021; Wang et al., 2023).

One final suggestion would be allowing for an asymmetric effect from oil prices, monetary policy, and growth rate. Few previous studies delved into this, however, for a small sample or a single country context. It would be enriching to understand the difference of the effect on CO_2 emissions between positive and negative shocks from GDP, interest rate, and oil price.

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Appendix

Table A1: Unbalanced Panel Detailed

	POPg	*GDPg*	*GCFg*	TRADEg	OILg	RECg	INF	RERg	NIR	CO2g
Albania	1990-2022	1990-2022	1998-2022	1990-2022	1991-2022	1991-2020	1992-2022	1993-2022	1992-2022	1991-2020
Algeria	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1995-2022	1991-2020
Armenia	1990-2022	1990-2022	1996-2022	1991-2022	1991-2022	1991-2020	1994-2022	1995-2022	1995-2022	1991-2020
Australia	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2019	1991-2020
Austria	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Belgium	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Bolivia	1990-2022	1990-2022	1990-2021	1990-2021	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Brazil	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1997-2022	1991-2020
Bulgaria	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1994-2022	1992-2022	1991-2020
Canada	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2017	1991-2020
Chile	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2018	1991-2020
China	1990-2022	1990-2022	2013-2021	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Colombia	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Congo, Dem. Rep.	1990-2022	1990-2022	1995-2022	1995-2022	1991-2022	1991-2020	1990-2016	1993-2022	2006-2016	1991-2020
Costa Rica	1990-2022	1990-2022	1990-2020	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Cote d'Ivoire	1990-2022	1990-2022	1998-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	2005-2017	1991-2020
Croatia	1990-2022	1996-2022	1997-2022	1996-2022	1991-2022	1991-2020	1990-2022	1998-2022	1996-2014	1991-2020

Table A1: Unbalanced Panel Detailed

	$POPg$	$GDPg$	$GCFg$	TRADEg	OILg	RECg	INF	RERg	NIR	CO2g
Cyprus	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Czechia	1990-2022	1991-2022	1992-2022	1991-2022	1991-2022	1991-2020	1992-2022	1992-2022	1993-2022	1991-2020
Denmark	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2021	1991-2020
Dominican Republic	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1991-2022	1991-2020
Egypt, Arab Rep.	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Estonia	1990-2022	1996-2022	1995-2022	1996-2022	1991-2022	1991-2020	1993-2022	1993-2022	1994-2021	1991-2020
Finland	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
France	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Germany	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Greece	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Hungary	1990-2022	1992-2022	1993-2022	1992-2022	1991-2022	1991-2020	1990-2022	1992-2022	1992-2022	1991-2020
Iceland	1990-2022	1996-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1996-2022	1991-2020
India	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Indonesia	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Iran, Islamic Rep.	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2021	1990-2022	2004-2016	1991-2020
Ireland	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Italy	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020

Table A1: Unbalanced Panel Detailed

	POPg	*GDPg*	*GCFg*	TRADEg	OILg	RECg	INF	RERg	NIR	CO2g
Japan	1990-2022	1990-2022	1990-2022	1990-2021	1991-2022	1991-2020	1990-2022	1990-2022	1993-2017	1991-2020
Jordan	1990-2022	1990-2022	2013-2019	1990-2019	1991-2022	1991-2020	1990-2022	1993-2022	1997-2022	1991-2020
Korea, Rep.	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1991-2021	1996-2022	1991-2020
Kuwait	1990-2022	1993-2022	2013-2019	1990-2019	1991-2022	1991-2020	1990-2021	1993-2022	1993-2021	1991-2020
Latvia	1990-2022	1996-2022	1997-2022	1996-2022	1991-2022	1991-2020	1992-2022	1994-2022	1994-2021	1991-2020
Lebanon	1990-2022	1990-2021	1992-2022	1990-2021	1991-2022	1991-2020	2009-2021	1993-2022	2009-2019	1991-2020
Lithuania	1990-2022	1996-2022	1997-2022	1996-2022	1991-2022	1991-2020	1992-2022	1993-2022	1994-2021	1991-2020
Luxembourg	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Malaysia	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Malta	1990-2022	1990-2022	2002-2022	1990-2022	1991-2022	2002-2020	1990-2022	1990-2022	1995-2013	1991-2020
Mauritius	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Mexico	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1993-2022	1991-2020
Moldova	1990-2022	1996-2022	1997-2022	1990-2022	1991-2022	1991-2020	1992-2022	1995-2022	1996-2022	1991-2020
Morocco	1990-2022	1990-2022	1990-2021	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2022	1991-2020
Netherlands	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1999-2021	1991-2020
New Zealand	1990-2022	1990-2022	1990-2021	1990-2021	1991-2022	1991-2020	1990-2022	1990-2022	1998-2017	1991-2020
Nicaragua	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	2000-2022	1990-2022	2000-2022	1991-2020

Table A1: Unbalanced Panel Detailed

	$POPg$	$GDPg$	$GCFg$	TRADEg	OILg	RECg	INF	RERg	NIR	CO2g
Nigeria	1990-2022	1990-2022	1990-2021	1990-2021	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
North Macedonia	1990-2022	1991-2022	1992-2020	1991-2022	1991-2022	1991-2020	1994-2022	1994-2022	2005-2022	1991-2020
Norway	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	2013-2022	1991-2020
Pakistan	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	2004-2021	1991-2020
Paraguay	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Peru	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Philippines	1990-2022	1990-2022	2002-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2019	1991-2020
Poland	1990-2022	1991-2022	1997-2022	1996-2022	1991-2022	1991-2020	1990-2022	1992-2022	1992-2021	1991-2020
Portugal	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Romania	1990-2022	1991-2022	1992-2022	1991-2022	1991-2022	1991-2020	1991-2022	1992-2022	1993-2022	1991-2020
Russian Federation	1990-2022	1990-2022	1992-2022	1990-2022	1991-2022	1991-2020	1993-2021	1995-2022	1997-2021	1991-2020
Saudi Arabia	1990-2022	1990-2022	2002-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1999-2017	1991-2020
Singapore	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2021	1991-2020
Slovak Republic	1990-2022	1993-2022	1994-2022	1991-2022	1991-2022	1991-2020	1992-2022	1991-2022	1994-2021	1991-2020
South Africa	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Spain	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1994-2021	1991-2020
Sweden	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1992-2006	1991-2020

Table A1: Unbalanced Panel Detailed

	$POPg$	$GDPg$	$GCFg$	TRADEg	OILg	RECg	INF	RERg	NIR	CO2g
Switzerland	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	2008-2022	1991-2020
Thailand	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Tunisia	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	2001-2017	1991-2020
Turkiye	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1993-2022	1990-2022	1991-2020
Ukraine	1990-2022	1990-2022	1992-2022	1990-2022	1991-2022	1991-2020	1993-2022	1994-2022	1993-2022	1991-2020
United Kingdom	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2014	1991-2020
United States	1990-2022	1990-2022	1990-2021	1990-2021	1991-2022	1991-2020	1990-2022	1990-2022	1990-2021	1991-2020
Uruguay	1990-2022	1990-2022	1990-2022	1990-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2022	1991-2020
Venezuela, RB	1990-2022	1990-2014	1990-2014	1990-2014	1991-2022	1991-2020	2009-2016	1990-2016	2009-2014	1991-2020
Zambia	1990-2022	1990-2022	2014-2021	1995-2022	1991-2022	1991-2020	1990-2022	1990-2022	1990-2020	1991-2020