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Emissions-output decoupling: evidence from long-run and short-run elasticities

Master's Thesis

Study Program : Corporate Strategy and Finance in Europe
Author : Trouble Elisa
Supervisor : Ph.D. Jaromír Baxa
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Trouble Elisa

Abstract

This thesis evaluates the evidence of decoupling of emissions and economic growth. More specifically, it draws upon previous literature and estimates both the short run and long run elasticities of emissions using an altering method. Most recent data for production and consumption based CO2 emissions on the world's top 23 emitters is used. The baseline model is extended to measure decoupling at the global level by using panel data analysis and by aggregating emissions and growth variables to create a world level time series. Further, the validity of the Environmental Kuznets Curve hypothesis is tested at the individual country and global levels. Results provide evidence of absolute decoupling in richer nations and relative decoupling in less developed countries. At the global level evidence of decoupling is mitigated. Comparison between consumption and production based elasticity estimates also provides evidence in favor of the Pollution Haven Hypothesis. Finally, sensitivity checks are conducted by estimating elasticities on a subsample and robustness checks suggest evidence is weak and not robust to the estimation method.

Keywords:: Emissions-output decoupling, HP filter, OLS, absolute decoupling, Environmental Kuznets Curve, emissions-output elasticity

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List of acronyms

ADF: Augmented Dickey Fuller test
CBA: Consumption based emissions
CO2: Carbon Dioxide
EKC: Environmental Kuznets Curve
HP: filter Hodrick-Prescott filter
IPCC: Intergovernmental Panel on Climate Change
GHG: GreenHouse Gases
OECD: Organisation for Economic Co-operation and Development
OLS: Ordinary Least Squares
PBA: Production based emissions
UNEP: United Nations Environment Program
UN: United Nations

Chapter 1

Introduction

During the 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 27) in November 2022, leaders of the world reaffirmed the importance of committing to the 1.5-degree limit and to “a fight for climate justice and climate ambition.” The United Nations (UN) secretary António Guterres concluded stating, “we can and must win this battle for our lives” (United Nations, n.d.). Climate change and environmental degradation are considered the biggest challenges of our times, centering on the question as to whether or not infinite growth can be sustained. The environment-economic growth nexus has been studied under different names including “Green Growth”, “Environmental Kuznets Curve” or even “decoupling" (which will be retained in this thesis). Amongst the various empirical studies, all ask the same question: is continued growth compatible with the environment in the long run?

Decoupling has been adopted as a key goal for several international organizations and governments across the world. In 2011, the Organisation for Economic Co-operation and Development (OECD) launched its “Green Growth Strategy”, turning decoupling as an all-encompassing strategy (OECD, 2011). In 2015, the United Nations Environment Program (UNEP) also brought decoupling as a core objective of its environmental strategy and sustainable development goals. As a matter of fact, United Nations secretary general Ki-moon called for the need to “decoupling economic growth from environmental degradation” (United Nations, n.d.). Decoupling is defined as “the process of separating economic growth from associated negative environmental impact” (UNEP, 2011, p.4). In other words, it can be understood as the ability to maintain a growing economy while reducing environmental degradation and emissions at the same time. According to this theory, investment and innovation improve technology efficiency and policy responses (taxes, subsidies, carbon pricing mechanisms…) allow for positive spillovers (Porter, 1991) which both lead to the decoupling of economic growth and environmental degradation in absolute or relative terms.

Several international organizations, governments and leaders rely on this strategy today. For instance, the European Union's initiatives rely on creating a competitive, sustainable and inclusive market (European Commission, 2011). What's more, the 2019 Going for Growth OECD report OECD identified 11 countries and the EU to be relying on this strategy, including China, Japan, Australia, India and others (OECD, 2019). Therefore, many national policies are still based on the idea that decoupling can be achieved in both the short and long run. Yet, according to the sixth IPCC assessment (AR6), decoupling and climate mitigations are not achievable, even by the most optimistic scenarios. Several obstacles arise such as path dependency, rebound effects or displacement effects through international trade. Some theorists are skeptical on the feasibility of decoupling and do not believe that economic growth and climate protection can be achieved simultaneously. Most notably, J.Hickel, J.Van Den Bergh and G.Kallis consider decoupling to be "unrealistic" (Den Bergh and Kallis, 2012) or "a political agenda" (Hickel and Kallis, 2019) and advocate for alternative pathways to growth (Van Den Bergh, 2011; Van Den Bergh and Kallis, 2012; Hickel and Kallis, 2019).

In front of such a crucial issue on managing long-term growth and mitigating climate risks, an increasing number of empirical studies have attempted to measure decoupling using various methods from decoupling indexes (Tapio, 2005), elasticities or even measures of Environmental Kuznets Curves (Grossman and Krueger, 1991). Yet, despite the vast number of studies and econometric or empirical methods, there is no consensus on whether or not decoupling is feasible or if it has been achieved. In contrast to previous literature, Cohen et al. (2018, 2022) estimate the emissions-income relationship on trend and cycle separately. They use the Hodrick-Prescott (HP) filter to extract trend and cycle from GDP per capita and GHG emissions per capita on the top 20 emitters in the world. With such data, they measure the emissions-output elasticity in two ways, one using the cycle component of both variables and the other one using the trend component of both variables. This approach has not been used in many studies (aside from Papiez et al., 2022). The authors themselves replicated their study in 2022 with another set of countries and focused on the differences in elasticities between developed and developing countries. Yet much has changed since 2014 as most countries have made significant efforts to reduce their emissions and invest in climate change mitigation strategies.

The aim of this thesis is to build on previous empirical literature and to verify whether decoupling is possible and if yes, whether it will be fast enough to deliver emission reduction consistent with 1.5° or 2°C pathways. It employs the method by Cohen et al. but uses the most recent data up to 2021 and focuses directly on the CO2 emissions that are in the center of all climate policy discussions. Besides, the framework implemented by Cohen et al. (2018) is extended by drawing the Environmental Kuznets Curve and calculating its turning point. World level decoupling is also estimated using panel data techniques and aggregated variables. Finally, this thesis also provides comparison with estimations on a subsample until 2015.

The rest of this thesis is structured as follows. Chapter 2 presents the literature review on decoupling and emissions-output elasticity, delving deeper into Cohen et al. work and how it contributes to measuring long term decoupling. Chapter 3 presents the data employed, its source and descriptive statistics. Chapter 4 addresses the empirical methodology applied to construct the econometric model. Chapter 5 presents and analyzes the results in the context of preexisting literature and provides details on robustness checks. Finally, Chapter 6 summarizes the findings and concludes.

Chapter 2

Literature review

In this chapter, we provide an overview of significant research in the literature of emissions-output decoupling. Numerous studies have been conducted on the topic that involve various statistical measures. We choose to focus on emissions-income elasticities, estimations of the Environmental Kuznets Curves and look into the cyclicality of emissions and trend-cycle decomposition. Finally, approaches that differentiate between long run and short run decoupling are also addressed.

2.1 Measures of elasticities and decoupling indexes

One of the most common measures of emissions-output decoupling is the Tapio decoupling index (Tapio, 2005), which measures the change in emissions or other environmental impact per change in output. Tapio provides several interpretations of the index from strong decoupling to expansive coupling. Wu et al (2018) test the decoupling trend of growth and CO2 emissions in developed and developing countries on a panel between 1965 and 2015. They use the OECD decoupling model, Tapio elasticity analysis and find strong decoupling in developed countries such as the United Kingdom (UK), the United States (US) or France. Tapio elasticity analysis (TEA) is used to estimate the index by regressing the natural logarithm of emissions on the natural logarithm of output which coefficient represents the Tapio elasticity. Tarabusi and Giurani (2018), Climent and Pardo (2007), Wang et al. (2017), Zhang et al. (2020) and many others also use this method.

The STIRPAT model is another model used to analyze the impact of one variable on the changes in emissions or environmental degradation. STIRPAT stands for Stochastic Impacts by Regression on Population, Affluence, and Technology, where Affluence is understood as income and often measured using GDP or GDP per capita. As argued by Fan et al. (2006), the coefficient for the Affluence or income factor in STIRPAT analysis can be understood as carbon elasticity of income. In their study, Fan et al. (2006) investigate more specifically the impact of population, affluence and technology on CO2 emissions on a panel of countries from 1975 to 2000. The coefficient elasticity for GDP per capita varies between 1.10 for high-income countries, 1.39 for low-income countries to 0.85 for middle-income countries. Thus, the study concludes that emissions income elasticity is high overall. Other models can be cited that conduct the same analysis such as Sadorsky (2014) who find an emissions income elasticity of 1.14 using Fixed Effects, Liddle (2013) who finds an elasticity of 0.44 for high income countries and 0.97 for low income countries, Jorgenson and Clark (2012) who find 0.93 on a panel of 86 countries or even York who finds an elasticity of 0.70 on a panel of 14 EU countries.

As Wu et al. (2018) point out; each method presents its own advantages. The OECD model requires less data but does not distinguish degrees of decoupling while the TEA is more refined. Those methods provide examples of indexes and other analysis that estimate decoupling of emissions and output. Nevertheless, these techniques lack reliability and diversity in their form and other estimations aim at measuring the emissions income relationship, as do many studies under the Environmental Kuznets Curve framework.

2.2 Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) is a conceptual framework that is used to analyze the relationship between environmental degradation and economic growth. The EKC hypothesis describes an inverted U-shaped relationship between economic growth or income and some measure of the environment. The concept originated from Kuznets' (1955) observation of an inverted U_shaped relationship between income inequality and economic growth and adapted by Grossman and Krueger (1991, 1995) and Stern and Common (2001). According to the EKC hypothesis, environmental degradation increases with income until a certain threshold or turning point after which it declines. Indeed, a meta-analysis conducted by Sarkodie and Strezov (2019) estimates the average turning point in the EKC literature to be around US$8910. Antweiler et al (2001) and Coxhead (2003) explain the shape of the EKC due to scale effects, composition effects and technological effects (Grossman and Krueger, 1991). The implications of the EKC are numerous and significant for environmental policies. Indeed, if the EKC is validated it implies that growth is not harmful to the environment to a certain extent and may even be necessary to limit environmental degradation (Beckerman, 1992; Bhagawati, 1993). Yet, the existence of an inverted U-shape relationship between income and the environment remains debated and results from empirical research are mixed.

According to Saqib and Benhmad (2021) meta-analysis, a major part of the literature on decoupling finds evidence in favor of an inverted U-shape EKC. Selden and Song (1994), Cropper and Griffiths (1994) and Shafik and Bandyopadhyay (1992) all find a U-shaped relationship between environmental pollution and economic growth. The EKC has also been validated by using other forms of environmental degradation or pollutants, CO2 emissions being the most frequently used one. For example, Stern and Common (2001), Stern et al (1996), Selden and Song (1994), Grossman and Krueger (1991) and Torras and Boyce (1998) apply fixed effects regression on a panel of countries and also find that sulfur emissions are an inverted U-shaped function of income. Other measures include Hettige et al. (1992) using "toxic intensity of industrial production", Khan et al., (2019) deforestation, while Selden and Song (1994) use suspended particulate matter.

In addition, several studies find evidence that supports the existence of the EKC both on cross country and panel data. Ang (2007) provides evidence for the existence of an inverted U-shaped relationship between emissions, energy consumption and output using cointegration analysis and Vector Error Correction Model (VECM) for France between 1960 and 2000, with a turning point of 9.55 (in logarithms). Iwata et al. (2010) also estimate the EKC for France by using Autoregressive Distributed Lag (ARDL) approach and cointegration. Their results, similar to Ang (2007), validate the hypothesis and find a turning point around 9.5. Such conclusions also hold for other countries. Beşe and Özden (2020) find validating results for Australia using coal consumption and ARDL model while Moosa (2017) shows weak result using CO2 emissions and econometric models. This result is also in line with Shahiduzzaman and Khorshed (2012) who investigate the existence of an inverted U-shape relationship between CO2 emissions and GDP over 50 years in Australia, using the same estimation method as Beşe and Özden (2020). Zambrano-Monserrate and Fernandez (2017) use nitrous oxide (N2O) emissions and agricultural land use in German using ARDL and confirm the existence of the EKC in Germany. Rafindadi (2016) shows that even with declining income and energy crisis, the EKC is validated in Japan, using ARDL bound testing. Thuis, evidence of the EKC in developed countries is numerous but can also be found in research focusing on developing countries.

Other examples include, Pata (2018) who validates the EKC in Turkey, Shahbaz et al. (2012) for Pakistan and Tiwari et al. (2013) for India, all using ARDL bounds testing approach for cointegration. In addition, Tiwari et al. (2013) also find presence of feedback relations between growth and CO2 emissions using Granger causality test. Aspergis and Ozturk (2015) use Generalized Method of Moments (GMM) in panel data for 14 Asian countries from 1990 to 2011 using a framework that includes population density, land and other value-added sectors. They also use Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Square

(DOLS) which account for the non-stationary and heterogeneity of the panel. The outcome of their study validates the EKC hypothesis for all 14 countries. Liu et al. (2017) use the same estimation method for Malaysia, Philippines, Indonesia and Thailand and conclude to the existence of an inverted U-shaped function, as do Lau et al. (2014) for Malaysia. Furthermore, Pao and Tsai (2010) use the ARDL model and find that CO2 in BRIC countries exhibit an inverted U-shape pattern with a turning point around 5.393 in logarithms. They find similar results in their 2011 study on Brazil. Lastly, Martinez-Zarzoso and Bengochea-Morancho (2004) apply pooled mean group (PMG) estimators to a panel of OECD countries from 1975 to 1998. Their results also validate the EKC with turning points between $4914 and $18,364.

Studies investigating the form of the relationship between income and emissions using panel data estimations are rarer. Dinda and Coondoo (2006) use short run dynamic models Error Correction Model (ECM) that corrects for non-stationarity of the variables for 88 countries grouped by income in the period 1960-1990. Farhani et al. (2014) examines the EKC for 10 MENA countries over the period 1990-2010 and finds positive results that show an inverted U-shape relationship. Al-Mulali et al. (2012) examine the EKC for a panel of 93 countries using ecological footprint and GDP growth but only finds validation for high-income countries. Finally, Dogan and Seker (2016) use CADF and CIPS cointegration tests, after accounting for non-stationarity of the variables and cross sectional dependence in their panel, and confirm the EKC hypothesis. Stern (2010) uses the between estimator and to measure long run elasticities of sulfur emissions and income. The outcome suggests an elasticity of 0.7 for the OECD panel and 1.06 for the global panel with a turning point of $19,008 (1990 Dollars).

Galeotti et al. (2006) find that evidence on the EKC is “at best mixed” and there are a number of studies that do not validate the hypothesis. Some studies find an N-shaped EKC by which emissions initially increase, reach a turning point and decrease before increasing again. Several author’s findings support the existence of an N-shaped EKC as do Taskin and Zaim (2000) (with turning points of $5000 and $12000) or Pao et al. (2011). Holtz-Eakin and Selden (1995) and Shafik (1994) find emissions to be a monotonically increasing function of GDP at the global scale. Similarly, Perman and Stern (1990, 1999) do not find evidence for the EKC using Sulfur emissions and cointegration analysis for most of the 74 countries in their study. Rather individual results of the panel show U-shaped or monotone functions. Further, Alam et al (2016) finds no evidence of delinking of income and CO2 emissions for India and China in the long run but do find evidence in favor for Brazil and Indonesia in the long and short run. Similarly, Liu and Bae (2018) and Yilanci and Pata (2020) find no evidence of EKC in China just as Mulali et al (2015) do for Vietnam, all using ARDL bound testing and VECM. Evidence on the EKC also differs from panel data to individual country analysis. Dijkgraaf and Vollebergh (1998) test both cases and find inverted U and U-shaped functions at the individual country level while their panel data result take an inverted U-shaped form. Finally, Lopez-Menendez et al. (2014) find evidence of the inverted U hypothesis only for countries using significant amounts of renewable energy in the EU 27. For other countries, the curve takes an N-shaped form with a turning point around 18,990 euros per inhabitant.

Overall, a large number of studies testing the EKC use cointegration analysis, with error correction dynamic models or models that accommodate for the non-stationarity such as FMOLS for panel data. It is also necessary to note that evidence on the existence of the EKC is mixed and the framework itself is not without its criticism. Wagner (2008) points out that EKC estimations in the literature suffer from "bad econometrics" such as cross-sectional dependence in panel data estimations which leads to spurious relations and non robust results. Dogan and Seker (2016) make similar remarks and highlight the need to apply second generation cointegration tests that account for cross-sectional dependance. Husnain et al. (2021) attribute the mixed results found in the literature to the differences in econometric techniques and sample sensitivity. Overall, while the EKC hypothesis has been studied a lot, results and estimates vary greatly in their conclusions.

2.3 Estimation of emissions-output decoupling: other added variables

In their meta-analysis on EKC studies, Saqib and Benhmad (2021) point out that GDP is the most important variable, followed by trade, population and energy, which each significantly improve the model's fit. In a more general way, the literature on emissions-output decoupling has been concerned with the question of the omitted variable bias (Farhani et al., 2014), which in the case of EKC could bring the turning point downward (Stern and Common, 2001). It is now common for studies to use additional variables into their models. Additional variables include urbanization

(Farhani et al., 2013.; Pao et al., 2012), financial development or financial globalization (Paroussos et al., 2020; Chen et al, 2023), investment and R&D (Wang and Zhang, 2020; Song et al. 2019; Wang and Wang, 2019), poverty (Liu, 2012), energy and energy price (Ang, 2007; Aspergis and Payne, 2009; Agras and Chapman, 1999); democracy (Usman et al. 2019), and trade (Farhani et al., 2014; Antweiler et al. 2001) or population growth (Alam et al. 2016)

Several studies have shown the importance of international trade in measures of decoupling (Burke et al., 2015; Cohen et al., 2018; Peters et al., 2011; Papiez et al., 2022). Kozul-Wright and Fortunato (2012), Lucas et al., (1992) and Low and Yeats (1992) argue that international trade and the practice of outsourcing energy and pollution intensive industries explains part of the decoupling that can be observed in developed countries. According to Moreaua et al. (2019) international trade creates an illusion of decoupling, a “virtual decoupling”. The pollution haven hypothesis (PHH), postulated by Copeland and Taylor, suggests the relocation of polluting industries in less regulated developing countries, creating a “pollution haven” effect. Therefore, international trade can result in a displacement effect whereby pollution intensive industries from developed countries shift to developing countries. To account for this possibility Khan et al., (2020); Cohen et al., (2018); Hasanov et al., (2018); use both production based and consumption based measures of emissions. While some research still uses production based emissions, the number of studies using consumption based emissions has increased (Jalles and Ge, 2020; Antweiler et al., 2001; Ang 2009).

2.4 Cyclicality of emissions

Several studies study the cyclicality of emissions and estimate short run emissions-output decoupling. Doda (2014) uses the HP filter to extract cyclical components from CO2 emissions and GDP and tests the procyclicality of emissions by using a correlation coefficient. Results show that emissions are procyclical with an average correlation coefficient of 0.297 but this result varies across countries (eg. the US has a coefficient of 0.6; India has a coefficient of -0.14). Burke et al. (2015) also explore the emissions-output elasticity during economic expansion and recession and introduce lags into their model. After performing a Dickey-Fuller unit root test, they estimate emissions income elasticity for 189 countries over the period 1961-2010. The mean elasticity is 0.5

and results show no signs of asymmetry of GDP and emissions during business cycles, contrary to Doda (2014). In addition, by introducing lags into the model, the study shows that emissions increase with a "delayed effects" in times of economic expansion. The study also estimated the effects of energy growth, energy efficiency and changes in trade flows from trading partners on GDP-CO2 emissions elasticities. Finally, short-term elasticities also vary across sectors, industries having the highest elasticity, followed by services and agriculture. On the same note, Sheldon (2017) notes that most forecasts rely on a constant growth rate rather than allowing it to fluctuate due to the existence of business cycles. Results are similar to Doda (2014) in that emissions decrease more when income decreases than they increase when income increases. Using US GDP and CO2 emissions, the outcome indicates that energy intensity, especially in the industrial sector, is the driver of this asymmetry.

Bowen et al. (2009), Peters et al. (2012) and Jotzo et al. (2012) look at the emissions implications of periods of extensions and contraction by detrending output and emissions and find that emissions tend to increase with high rates of GDP and decrease in times of financial crisis. Further, Doda (2014), Shahiduzzaman and Layton (2015) and Sheldon (2017) find evidence of asymmetric changes in CO2 emissions over business cycles and Peters et al. (2012) note that CO2 emissions decrease more permanently during economic contractions. On the other hand, York (2012) found contrary evidence using panel data and Prais-Winsten correction for autocorrelation. Whereas the aforementioned studies focus on the changes in emissions during business cycles, Heutel (2012) analyzes the optimal environmental policy response to output-emissions fluctuations due to productivity shocks by using a dynamic stochastic general equilibrium model for US CO2 emissions and GDP using monthly data. The outcome highlights that optimal environmental policy for CO2 emissions is procyclical, including for tax rates and quotas. Using ordinary least squares (OLS), Heutel (2012) estimates the cyclical elasticity to be between 0.5 and 0.9, irrespective of the filtering method used.

The literature on the cyclicality of emissions usually focuses on US country evidence and looks into short term emissions-output relationships. Alege et al. (2017) uses the Hodrick-Prescott (HP) filter on national data on Nigeria in a period from 1981 to 2015. Their results show evidence that GHG emissions are counter cyclical to output in Nigeria but procyclical if only looking at the industrial sector. Sarwar et al. (2021) apply the same method for South Asia and use impulse response functions (IRFS) and VECM to analyze the impact of GDP shocks on emissions. Similar to Doda (2014), results show that GHG emissions are procyclical for south asian countries but also highly volatile. Finally, Rodriguez et al. (2018) provide evidence of procyclicality of emissions for the EU 28 from 1950 to 2012 using dynamic factor analysis. Lastly, it's worth noting other models, mainly dynamic ones, investigate short run decoupling SVAR frameworks (Khan et al. 2019), impulse response functions (Jalles, 2019) or even Dynamic Ordinary Least Squares (DOLS) (Dogan and Seker, 2016; Zhang et al., 2017).

2.5 Trend-cycle decomposition analysis

So far literature on emissions-output decoupling has used various econometrics methods to either estimate decoupling indexes and Environmental Kuznets Curve or to measure the cyclicality of emissions by detrending the variables. Few studies investigate the long run elasticity of emissions and output and almost none distinguish between short term and long term elasticities. Cohen et al. (2018), Cohen et al. (2022) and Jalles and Ge (2020) argue that common measures of decoupling are "misleading" as they reflect both the long run trend embodying structural changes, as well as the short run, cyclical fluctuations. Cohen et al. (2018) and in their earlier IMF working paper (2017) propose a new framework based on the distinction between trend and cycle components to investigate cyclical elasticity and trend elasticity which they also call "Okun elasticity" and "Kuznets elasticity". Using the HP filter, they extract trends and cycles from real GDP per capita, consumption and production based GHG emissions for the top 20 emitters in the world from 1990 to 2014. Results show procyclicality of emissions with a mean cyclical elasticity equal to 0.4. However, some countries' cyclical elasticities show signs of delinking between the cycle component of GDP and the cycle component of GHG emissions. Results for Kuznets elasticities are heterogeneous and suggest signs of absolute decoupling (France, the UK or Germany), relative decoupling but also no signs of decoupling at all (Saudi Arabia). The mean Kuznets elasticity is 0.6 and Cohen et al. find evidence that decoupling is achieved by developed countries while developing countries only show signs of relative decoupling or coupling. Comparing both production based and consumption based emissions, they also reveal that consumption based emissions-output elasticities are higher, showing less signs of decoupling for developed countries.

On the other hand, they are lower for developing countries, aligning with the Pollution Haven Hypothesis.

In 2022, the same authors pursued their work and investigated the differences in CO2 emissions-real GDP decoupling between high-income countries, developing countries and low-income countries on a sample of 178 countries from 1960 to 2018. Results confirm their previous works and show stronger evidence of decoupling for developed countries and especially European ones, than for developing countries. The authors also investigate decoupling in the Global South and find evidence that trend elasticities are higher than those of the Global North but they also observe evidence of decoupling for most of the sub sample. Cohen et al. (2019) applied the same analysis to China at the national and provincial levels and found a decreasing trend elasticity of 0.6, lower in richer provinces. In addition, Jalles and Ge (2020) investigate the results of such a framework using GHG emissions for 46 commodity exporters' countries and find heterogeneous results amongst countries for the Kuznets elasticity with a mean of 0.6.

Very few studies have been conducted using this framework. Narayan and Narayan (2010) use an approach similar to Cohen et al. (2018) by differentiating between long run and short run elasticities. They test the EKC hypothesis on a panel of developing countries and compare long run and short run elasticities on the basis that if long run elasticity is lower than the short run one, then the country has decoupled. Using Pedroni panel cointegration regression and ECM they provide evidence that decoupling has been achieved in several regions of the world. In the Middle East, Iraq shows a long-term elasticity of -0.1 and a short-term elasticity of 0.33. In Africa, Nigeria has a long run elasticity of -0.65 and a short run elasticity of 0.34. Finally, in Asia, Vietnam has a long run elasticity of 0.95 and a short-term elasticity of 1.50. Since long run elasticities are lower than short term elasticities for all the examples mentioned, then according to Narayan and Narayan "emissions have fallen with a rise in income" or that these countries have achieved decoupling. Hu et al. (2019) also use a similar approach to Cohen et al. by controlling for the business cycle in their estimation of emissions-output elasticity. The authors use the HP filter to decompose variables into their trend and cycle components and then apply the ECM only on the trend component of each variable. Their findings suggest a strong relation between GDP and SO2 emissions in China in the long run. Finally, Papiez et al (2022) also apply this framework to investigate the efficiency of the EU's energy policy on a panel of EU countries using mixed effects models. and evaluate the effects of EU energy policy. They extend Cohen et al. (2018) model by testing additional variables that account for the effects of the EU energy policy on three types of emissions (production based, consumption based and emissions covered by the EU ETS). Similar to previous studies they find procyclicality of emissions but different results for long term decoupling between EU 15 and the new EU countries. Their results reveal a negative relationship between emissions and output from energy and industry sectors but this relationship reverses when using consumption-based emissions.

Chapter 3

Data and variables

This chapter describes the data used in this empirical study. The dataset comprises 23 countries with observations from 1990 to 2021. For the first part of our analysis, we estimate emissions-output elasticity for each individual country, creating 23 time series of 31 observations. For the second part of our analysis, we use the whole dataset as a panel and include additional variables. This section is divided into three parts: first, the variables and sources used are presented, second the criteria and rationale behind the selection of the dataset's countries is explained and lastly, descriptive statistics for both the time series and panel data are provided.

3.1 Data and sources

Data for output is taken from the October 2022 version of the IMF World Economic Outlook (WEO) database, using GDP per capita, PPP constant 2017 in international dollars. Many measures of environmental degradation exist which yield different results. GreenHouse Gases (GHG) emissions are the most common in the literature as they aggregate CO2 emissions and non-CO2 emissions such as methane, nitrous oxide and fluorinated gasses. Cohen et al. (2018) retrieved data on emissions from The World Resource Institute (WRI), the Carbon Dioxide Information Analysis Center (CDIAC) and the Eora Multi-Regional Input-Output (MRIO) database. In this thesis, we estimate decoupling by using CO2 emissions, which account for the vast majority (around 80%) of GHG emissions are less subject to limitations due to data availability. Hence, we retrieve production and consumption based CO2 emissions per capita from Our World in Data (https://ourworldindata.org) since it offers free access to reliable and recent data on emissions (including consumption based) for the period of interest. GHG emissions are retrieved from the same source to compare choice of countries with Cohen et al. (2017) in this chapter.

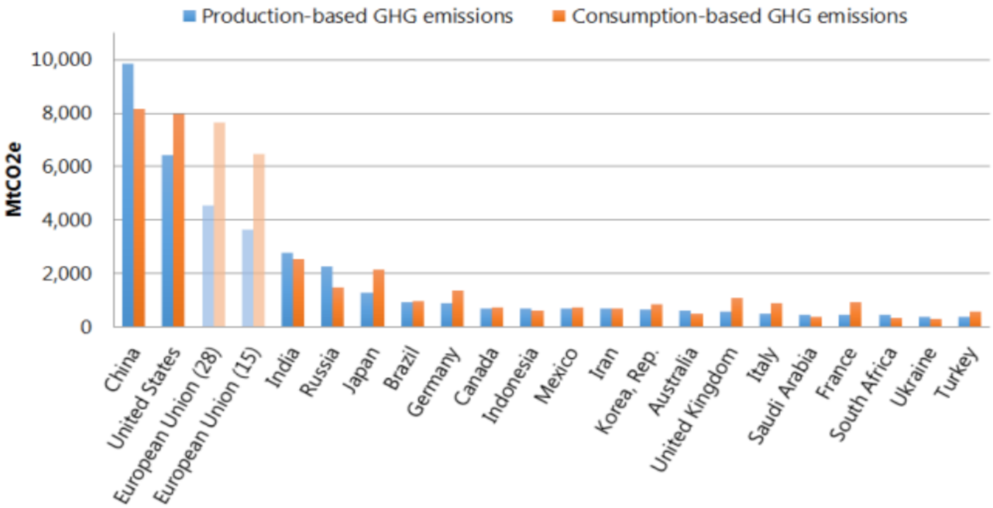
Finally, to differentiate between production and consumption based emissions, the acronyms PBA and CBA are used hereafter.

As an additional exercise, we add other variables to our analysis, which are often present in the literature and usually most relevant. According to Saqib and Benhmad (2021) trade and energy are the most important variables in decoupling analysis, aside from GDP. Openness to trade is usually used by most studies. However, it does not account for the distance of the main trading partners in the sense that a country can have a very high openness to trade but trade with bordering partners. Therefore, carbon emissions embodied in trade are used for this analysis, taken from the OECD database. The indicator is taken from the OECD online database and measures the volume of carbon emissions resulting from the burning of fossil fuels in imports and exports, expressed in mega tonnes of CO2 (MtCO2). It covers 63 countries and 34 industries..Energy is usually included in the form of energy use as kg of oil per capita. Nevertheless, the panel of 23 countries is very heterogeneous with different energy mixes for each country. Therefore, total electricity generation per capita in kilowatt-hours from all sources is chosen since it will account for a country's specific energy mix, including use of renewable energies that have a positive impact on reduction of CO2 emissions. This variable is retrieved from Our World in Data (https://ourworldindata.org).

3.2 Countries of the dataset

Cohen et al. (2018) estimate long run decoupling of GHG emissions and real GDP on the top 20 emitters in the world.

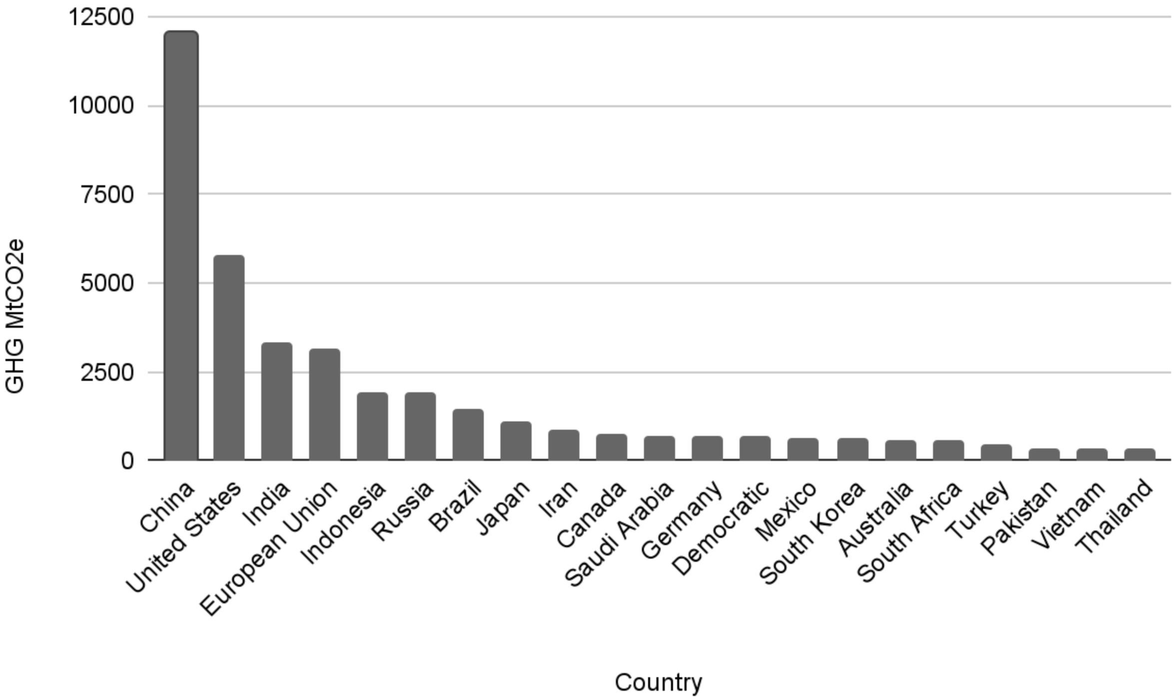
Figure 1.1: Top 20 World GHG emitters (Cohen et al., 2017)



Source: Cohen et al. (2017), based on WRI and Eora databases

Figure 1.1 shows the top 20 GHG emitters in the world as described and picked in Cohen et al. (2017; 2018) study. China, the US, India and the EU (28) are in leading positions in GHG emissions. In the original sample, the countries taken represent more than 70% of the world's emissions with an average higher than 33 000 MtCO2e per year. Since 2014, legislation and international agreement have been passed and countries have made significant efforts to reduce their emissions. To compare the top 20 emitters in 2014 and 2021 we use data on production based GHG emissions, production and consumption based CO2 emissions and plot them in figures 1.2 to 1.4.

Figure 1.2: Top 20 World emitters - GHG emissions (2021)

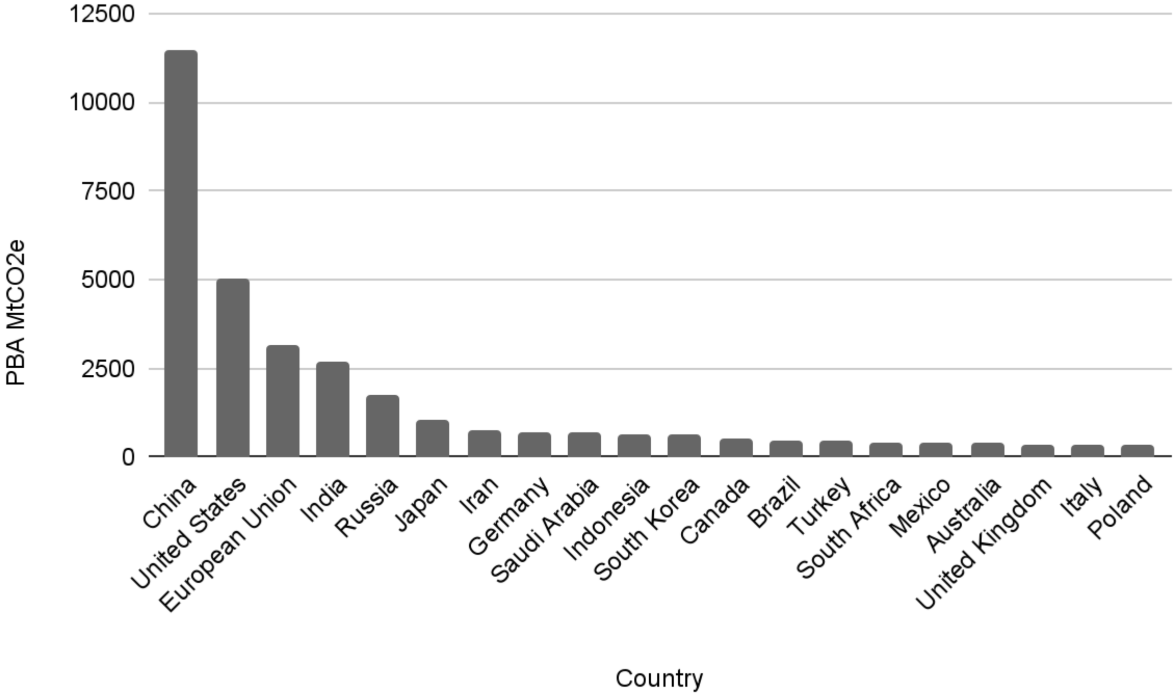


Source: OurWorldinData, Author's calculations.

Figure 1.2 presents production based GHG emissions (including LUCF) in billions kt per country. Compared to the study of 2017, the first six world emitters remain the same but not necessarily in the same order. While China, the US, the EU (27) and India are on the top of the chart, Indonesia has climbed to 5th place and on the other hand Germany is now in 12th place. China's emissions are sky-rocketing compared to other countries, and have increased significantly since 2014. On the other hand, GHG emissions are lower for some countries in the 2017 study. Similarly, all the other countries are below 2000 KtCO2. Thus the first 4 emitters are responsible for the vast majority of CO2 emissions in the world, disproportionately to other countries. Some countries like Indonesia are now placed higher in the ranking of the top emitters. Other countries have exited the top 20 in terms of GHG emissions, namely Italy, the UK and France. On the other hand, the Democratic Republic of Congo, Vietnam, Thailand and Pakistan have entered the top

20. At first glance, it seems that emissions are still strongly linked to output, even though the exit of some countries from the top 20 gives premonition on the state of decoupling for those countries.

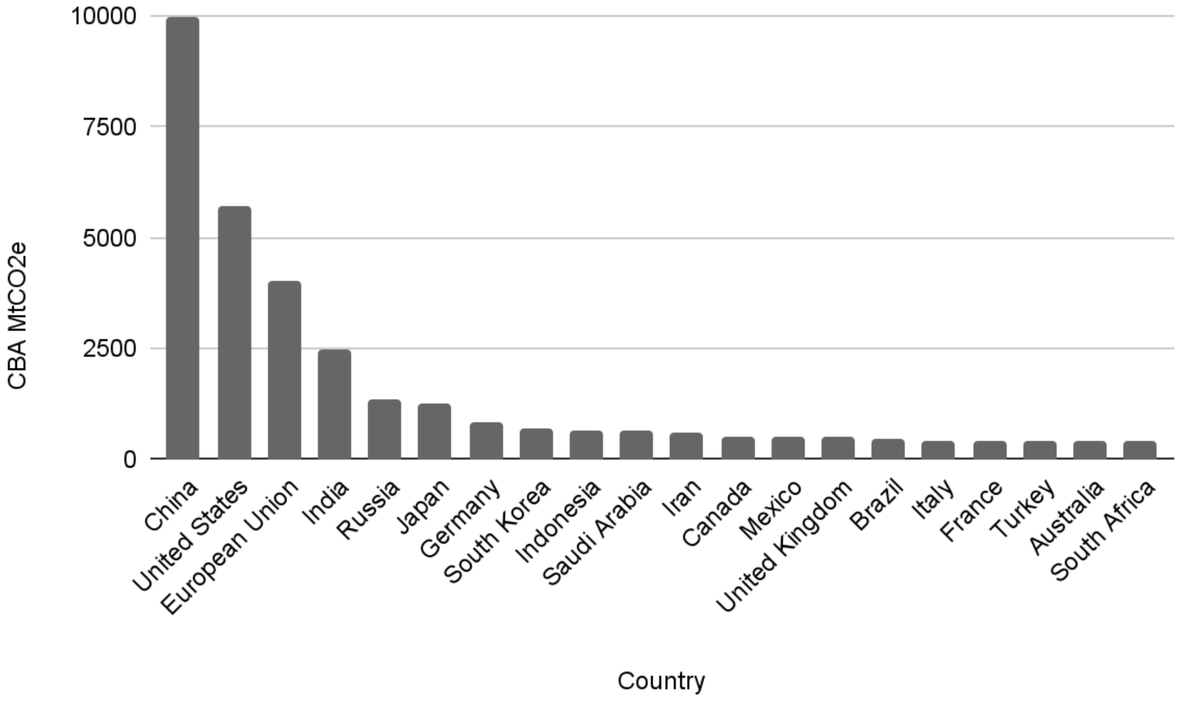
Figure 1.3: Top 20 World emitters - production based CO2 emissions (2021)



Source: OurWorldinData, Author's calculations.

Production based CO2 (PBA) emissions show different results from production based GHG emissions. The top four emitters remain China, the US, the EU (28) and India by far. Once again those countries account for the vast majority of emissions in the world. However, the ranking of countries after the first sixth, changes. Iran is much higher in the ranking while Brazil is lower. The new countries present in Figure 1.2 (namely Thailand, Democratic Republic of Congo and Pakistan) have now exited the ranking, aside from Poland and Vietnam. It is interesting to see that Asian countries are now more present in the world's top emitters compared to 2014. In addition, Poland has entered the top 20 with respect to production based CO2 emissions. Overall, the top 20 emitters for CO2 emissions have not changed much compared to GHG emissions for 2014.

Figure 1.4: Top 20 World emitters - consumption based CO2 emissions (2021)



Source: OurWorldinData, Author's calculations.

Using consumption based CO2 emissions (CBA) metrics, the top three emitters remain the same but the list changes compared to Figure 1.3. All the countries that appeared in Figure 1.2 and 1.3 have now completely disappeared from the top 20, leaving the exact same countries as in 2014. This piece of foreshadowing highlights the importance of considering consumption based emissions when estimating decoupling. It is also noteworthy that the maximum CO2 emissions per country is lower for consumption based emissions than production based emissions. Although countries have remained the same as chosen by Cohen et al. (2018), their place amongst the top emitters changes which can be due to other types of emissions not being accounted for here.

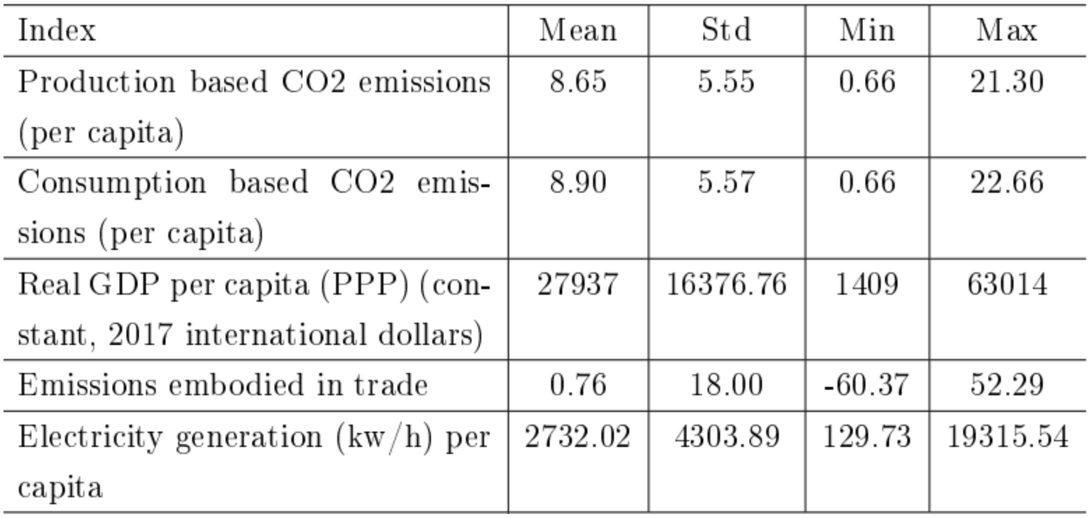
Overall, at first glance, emissions have significantly increased and one could think that no progress has been made towards decoupling, compared to the situation several years ago.

Thus, countries from figures 1.3 and 1.4 are included in this thesis, except for the Democratic Republic of Congo for lack of data. Our final sample contains 23 countries which represent up to three and a half times the world's amount of CO2 emissions per capita for countries like the US in 2021. The rise in emissions in India is also noteworthy, with a relative change of plus 100 000% compared to 1990. In addition, our top three emitters represent up to one third of the world's total population and make up for one third of the world's GDP.

3.3 Summary statistics

Summary statistics for the entirety of the panel are reported in Table 1.1 and statistics for individual countries in Table 1.2.

Table 1.1: Summary statistics for panel data



Index	Mean	Std	Min	Max
Production based CO2 emissions (per capita)	8.65	5.55	0.66	21.30
Consumption based CO2 emissions (per capita)	8.90	5.57	0.66	22.66
Real GDP per capita (PPP) (constant, 2017 international dollars)	27937	16376.76	1409	63014
Emissions embodied in trade	0.76	18.00	-60.37	52.29
Electricity generation (kw/h) per capita	2732.02	4303.89	129.73	19315.54

Table 1.1 shows summary statistics for the whole dataset, taken as panel data. CO2 emissions have a mean around 8 but a standard deviation around 5 (production and consumption based) which is quite high compared to the mean. This shows high heterogeneity between countries in terms of emissions. It is also notable that the maximum value for CO2 emissions is almost 20 times higher than the minimum value. Since this number is taken across countries and across times, it shows not only heterogeneity in the panel but also in the time series. In other words, CO2 emissions have skyrocketed since 1990, seemingly for all countries and as seen in Figures 1.1 to 1.4. The variation in GDP per capita also shows differences between countries but those differences are less pronounced. This can be explained by the fact that most of the dataset comprises high or middle income countries.

Table 1.2: Summary statistics for Australia and Brazil

Australia Index	Mean	Std	Min	Max
Production based CO2 emissions (per capita)	17.52	1.16	15.09	19.21
Consumption based CO2 emissions (per capita)	15.78	1.39	13.81	18.22
Real GDP per capita (PPP) (constant, 2017 international dollars)	42442.16	6544.99	30857.39	51349.48

Brazil Index	Mean	Std	Min	Max
Production based CO2 emissions (per capita)	2.02	0.34	1.45	2.74
Consumption based CO2 emissions (per capita)	2.10	0.38	1.62	3.01
Real GDP per capita (PPP) (constant, 2017 international dollars)	42442.16	6544.99	30857.39	51349.48

Italy Index	Mean	Std	Min	Max
Production based CO2 emissions (per capita)	7.31	1.09	5.08	8.66
Consumption based CO2 emissions (per capita)	9.23	1.29	6.53	10.94
Real GDP per capita (PPP) (constant, 2017 international dollars)	41546.25	2446.85	36952.01	45522.06

Canada Index	Mean	Std	Min	Max
Production based CO2 emissions (per capita)	16.72	1.10	14.11	18.46
Consumption based CO2 emissions (per capita)	16.82	1.65	12.95	18.90
Real GDP per capita (PPP) (constant, 2017 international dollars)	16.82	5244.46	33593.093	49560.84

Table 1.2 confirms the previous comments. Not only do variables differ greatly between countries (eg. Australia has a mean production based CO2 emissions of 17 and Brazil has a mean of 2) but also within time series.

Chapter 4

Methodology

This chapter presents the methodology used to investigate emissions-output decoupling in the world's top 23 emitters from 1990 to 2021. Following the approach developed by Cohen et al. (2017, 2018, 2022) we first extract trend and cycle components from emissions and output to estimate short term and long term elasticities. Then, we test the validity of the Environmental Kuznets Curve for each individual country and for the panel. Finally, we conduct two experiments: one by aggregating data from all countries and creating a "world" time series, and another one by estimating elasticities for the subsample 1990-2015.

4.1 Baseline model

4.1.1 Unit root and cointegration tests

Before any regression using time series data, the stationary properties of the variables need to be investigated, especially as GDP and CO2 emissions are often considered non-stationary variables. To this mean we use the Augmented Dickey-Fuller test and find that both unit roots have variables and are cointegrated of the same order. Since transformation of the variables can make the variables stationary, we also test for each variable after applying the natural logarithm and first differences. Estimation of cointegration relationship is provided as robustness check in later chapters.

4.1.2 Emissions-output elasticity

As a preliminary estimation of emissions-output elasticity we estimate Eq (1), our baseline model, using ordinary least squares (OLS).

$$\Delta C_t = \alpha + \beta \Delta y_t + u_t \tag{1}$$

Where ΔC_t is the change in CO2 emissions per capita, Δy_t the real GDP growth, u_t the error term and finally β the estimate which represents the emissions-output elasticity.

As noted previously, Eq (1) can lead to misleading results as it does not distinguish short term fluctuations from long term structural changes.

4.1.3 Trend-cycle decomposition

Trend and cycle components are extracted from CO2 emissions and real GDP using the Hodrick-Prescott (Hodrick-Prescott,1997) filtering method which minimizes the function:

$$min\{\sum_{t=1}^{T}(x_t - x_t^T)^2 + \lambda \sum_{t=1}^{T}[(x_t - x_{t-1}^T) - (x_{t-1}^T - x_{t-2}^T)]^2\} \tag{2}$$

Where comprises both emissions and gdp variables. λ is the penalty parameter or smoothing parameter for which higher values will result in a smoother trend component with less variability. Different values of are used in the literature: Cohen et al. (2018) set lambda to 100, Ravn and Uhlig (2022) and Jalles and Ge (2019) recommend using 6.25 and finally Rand and Tarp (2002) set it to 12. Although common practice is to set to 100 for annual data, we find that choosing 100 smoothes the variables' trend too much and choose to follow Ravn and Uhlig approach by setting equal to 10. The filter is applied to production based CO2 emissions per capita, consumption based CO2 emissions per capita and real GDP per capita to extract trends and cycles from the variables. The HP filter has been criticized previously (Hamilton, 2017) and other filtering methods have been used. Namely, Cohen et al. (2017) compare their results with the Hamilton filter, the Baxter-King filter and the Christiano-Fitzgerald filter. The Hamilton filter will also be used in Chapter 6 as a robustness check.

OLS is used to estimate the cycle elasticity in Eq (3) and trend elasticity in Eq (4) for each of our time series:

$$C_t^c = \beta^c y_t^c + \epsilon_t^c \tag{3}$$

$$C_t^T = \gamma + \beta^T y_t^T + \epsilon_t^T \tag{4}$$

Where C_t^c and C_t^T are the cycle and trend components of the logarithm of CO2 emissions per capita and y_t^c and y_t^T are the cycle logarithm of real GDP per capita. β^c is the cycle elasticity and β^T the trend elasticity. In both equations ε_t denotes the error term.

Finally, In Eq. (4) an intercept is included to account for countries' preexisting differences in emissions. Eq (3) and (4) show responses of emissions in the short run and in the long run to changes in income. Regressions are conducted for both production based and consumption based emissions to account for possible effects of international trade or carbon leakage.

Adding energy (*ENER)* and trade (*TRADE*) variables to the Kuznet elasticity estimation yields:

$$C_t^T = \gamma + \beta^T y_t^T + \theta ENER_t + \theta TRADE_t + \epsilon_t^T \tag{5}$$

4.2 Environmental Kuznets Curve

To complement this approach, the existence of country specific Environmental Kuznets Curves is examined using the trend component of consumption based emissions and the trend component of real GDP. Using a quadratic function, the form of the EKC is specified as:

$$C_t^T = \beta_0 + \beta_1^T y_t^T + \beta_2^T (y_t^T)^2 + u_t^T \qquad (6)$$

Where C_t^T is the trend component of consumption based CO2 emissions, y_t^T the trend component of real GDP per capita and β_0 , β_1 and β_2 the intercept and estimates of the regression. If the hypothesis is validated, then $\beta_1 > 0$ and $\beta_2 < 0$, creating an inverted U-shaped function with a turning point or peak at $tp = -\beta_1 / 2 . \beta_2$.

4.3 Global scale decoupling

Panel data analysis is used to estimate the trend elasticity for the whole dataset (23 countries, 731 observations). The Hausman test indicates that fixed effects is the most suitable estimator.
The fixed effects regression's equation is as follows:

$$C_{i,t}^T = \gamma + \beta^T y_{i,t}^T + \alpha_{i,t} + \delta_{i,t} + \epsilon_{i,t}^T \qquad (7)$$

Where $\alpha_{(i,t)}$ represent country fixed effects and $\delta_{(i,t)}$ time specific fixed effects to capture unobserved heterogeneity in the panel.

Including additional variables, fixed effects regression of Eq(5) becomes:

$$C_{i,t}^T = \gamma + \beta^T y_{i,t}^T + \theta ENER_{i,t} + \theta TRADE_{i,t}\, \alpha_{i,t} + \delta_{i,t} + \epsilon_{i,t} \qquad (8)$$

Estimating panel data emissions-output elasticity has several disadvantages as it loses cross-sectional information and assumes common slope coefficient across countries over time.

Thus, long term elasticity is also estimated at the global level by aggregating all values of a variable for a single year for all countries to create a new "world" time series from 1990 to 2021. This step is repeated for real GDP and consumption based CO2 emissions. The model is estimated using OLS.

$$C_t^w = \gamma + \beta^w \, y_t^w + \epsilon_t^w \tag{9}$$

Where y_t^w is the sum of trends of real GDP per capita for all countries for a year *t* and C_t^w the sum of trends of consumption based CO2 emissions per capita for all countries for a given year *t.*

This model is also extended to a cubic form to test for the Environmental Kuznets Curve with the Eq (10).

$$C_t^w = \beta_0^w + \beta_1^w \, y_t^w + \beta_2^w \, (y_t^w)^2 + \epsilon_t^w \tag{10}$$

Chapter 5:

Results

In the first part of this chapter the HP filter is used to extract trend and cycle components of real GDP and CO2 emissions. Using OLS, short term and long term elasticities are estimated and compared from production based and consumption based emissions. Table 5.11 presents all estimates. In the second part, further evidence is provided by estimating the Environment Kuznets Curve for each individual country and for panel data using fixed effects. Additional variables are also included to account for the effects of trade and energy. Finally, an exercise is conducted by aggregating country data for a set year *t* to estimate decoupling at the global scale.

5.1 Preliminary regressions: emissions-output elasticity

This subsection presents country specific estimates of the elasticity of CO2 emissions and real GDP for the top 23 emitters. Elasticity coefficients higher than 1 are interpreted as coupling of emissions and output. On the other hand, coefficients close to 0 suggest "relative decoupling" and estimates lower than 0 provide evidence of "absolute decoupling" (Rodriguez et al. 2016). Relative decoupling defined by the OECD as "when the growth rate of the environmentally relevant variable is positive, but less than the growth rate of the economic variable" while absolute decoupling refers to a state "when the environmentally relevant variable is stable or decreasing while the economic driving force is growing" (OECD, 2011). Results can be found in Figure 5.1 and Table 5.1.

Baseline results show that elasticities are positive for all countries and very few countries have elasticities higher than one aside from Mexico, Iran, France and Canada. Italy and Ukraine have the highest coefficient of the sample so much so that Italy can be considered an outlier. However, results for these two countries are not statistically significant. Although most of the estimates are lower than one, 60% of our sample shows elasticity estimates higher than 0.5 which indicates low signs of decoupling. Only Vietnam (0.28) and Japan (0.37) are the closest to relative decoupling.

Figure 5.1: Preliminary regression: emissions-output elasticity

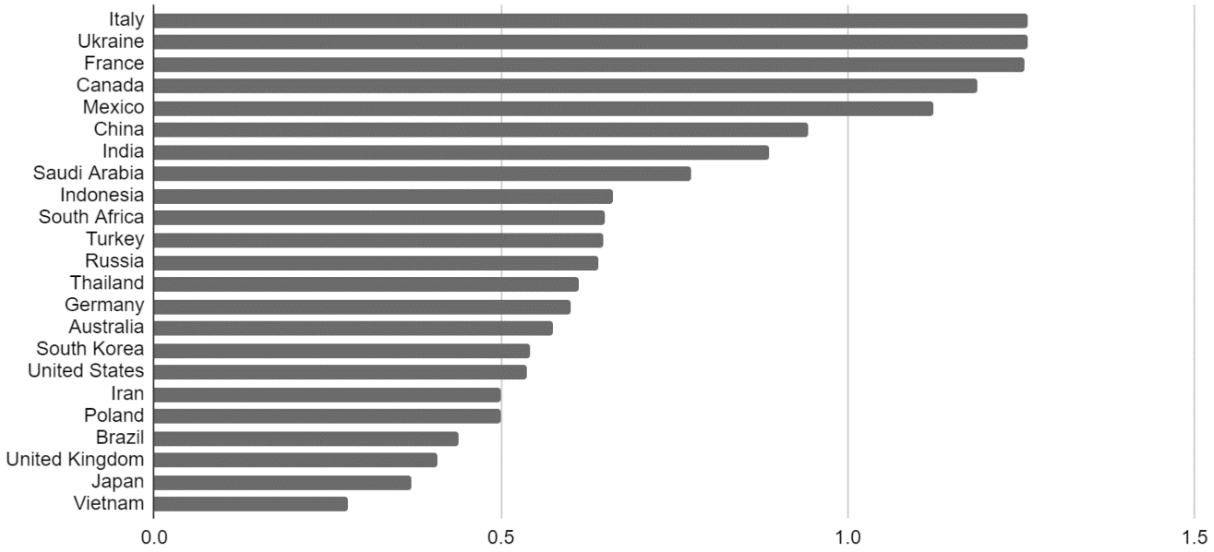


Table 5.1: Preliminary regression: emissions-output elasticity

	β	P. Value
Australia	0.57	**
Brazil	0.43	***
Canada	1.18	***
China	0.94	***
France	1.25	***
Germany	0.60	*
India	0.88	***
Indonesia	0.66	**
Iran	0.50	***
Italy	2.19	
Japan	0.37	*
Mexico	1.12	***
Poland	0.49	***
Russia	0.64	***
Saudi Arabia	0.77	*
South Africa	0.65	*
South Korea	0.54	***
Thailand	0.61	***
Turkey	0.64	**
Ukraine	1.25	
United Kingdom	0.40	*
United States	0.53	*
Vietnam	0.27	**

Note: The table presents country-specific estimates.* , **, *** denote statistical siginificance at the 10, 5 and 1 percent levels respectively.

As argued by Cohen et al., these results do not distinguish between short term changes from cyclical movements and long run structural changes from trends. To investigate further, we decompose emissions and income into their trend and cycle components and estimate their trend elasticity or "Kuznets elasticity" as well as their cycle elasticity or "Okun elasticity" (Cohen et al. 2017).

5.2 Cycle elasticity

5.2.1 Production based emissions

After decomposing emissions and income into their trend and cycle component using the HP filter, we estimate the cyclical elasticity or Okun coefficients for individual time series and for both production and consumption based emissions. Results for the cycle estimates can be found in tables 5.2 and 5.3 and Figure 5.2. Figure 5.3 shows graphical representations of the production based CO2 emissions and real GDP cycles. Finally, estimates for consumption based cyclical elasticities are presented in table 5.3

Figure 5.2: Cycle elasticity estimates (PBA)

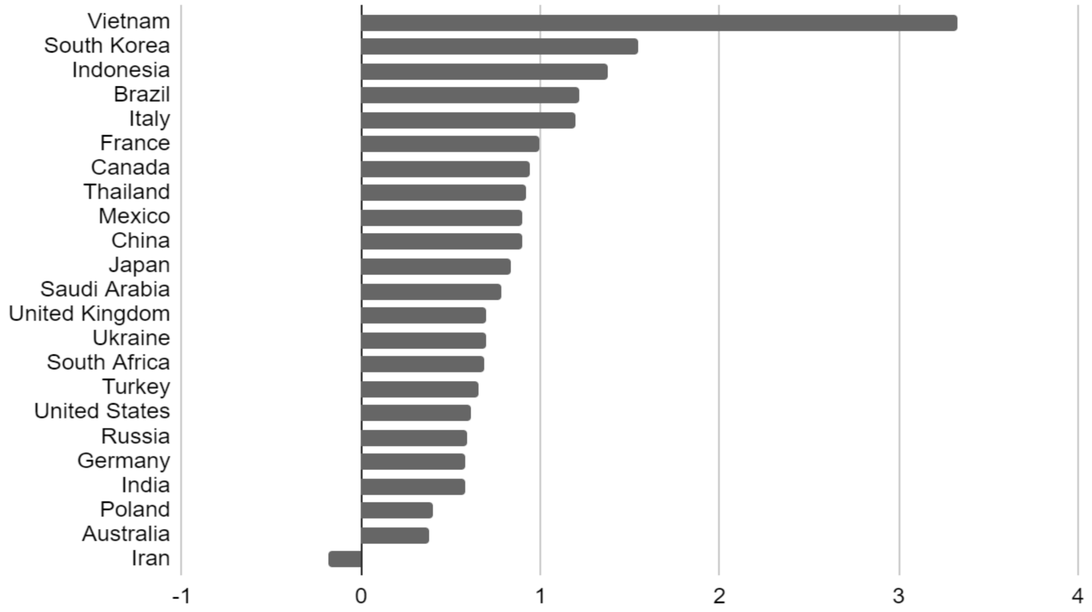


Table 5.2: Cycle elasticity estimates (PBA)

Country	β^C (PBA)	P Value	R Squared
Australia	0.379		0.09
Brazil	1.21	***	0.46
Canada	0.941	***	0.60
China	0.894	*	0.10
France	0.991	***	0.30
Germany	0.581	*	0.13
India	0.579	***	0.35
Indonesia	1.378	***	0.38
Iran	-0.181		0.00
Italy	1.198	***	0.63
Japan	0.836	***	0.29
Mexico	0.899	***	0.58
Poland	0.401		0.07
Russia	0.592	***	0.41
Saudi Arabia	0.783		0.03
South Africa	0.682		0.04
South Korea	1.546	***	0.73
Thailand	0.919	***	0.56
Turkey	0.659	***	0.46
Ukraine	0.696	***	0.53
United Kingdom	0.698	**	0.27
United States	0.6127	***	0.62
Vietnam	3.33	***	0.30

Note: The table presents country-specific estimates for cycle elasticities for production based emissions.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

First, for production based emissions, we find environmental Okun estimates to be between -0.18 for Iran and 3.33 for Vietnam with an average of 0.9 over the sample. CO2 emissions are said to be procyclical when $\beta>1$ and countercyclical if $\beta<0$ Higher value of the estimate (closer to one) means that the country studied is not actually delinking emissions and income and has, on the contrary, quite procyclical emissions. Results are significant for 19 countries out of 23 in our sample for production based emissions and for 17 countries for consumption based emissions.

Iran is the only country to have a negative value, indicating countercyclical CO2 emissions. The rest of the sample shows positive and relatively high estimates: 20 countries out of 23 have an estimate higher than 0.5 and 58% of the countries have an estimate higher than 0.8. Although this result is not in line with the literature it is necessary to note that results for the elasticity are not statistically significant for Iran. On the other side of the spectrum, Vietnam has highly procyclical emissions (with significant results) which can be attributed to different factors including high emissions transportation systems. Most results are significant, except for Australia, Iran, Poland and Saudi Arabia. Brazil, Indonesia and Thailand have the highest elasticity estimates and strongly procyclical emissions. In other words, CO2 emissions tend to decrease during periods of economic growth or expansion, and increase during periods of economic contraction. Therefore, measuring decoupling without decomposing the extracting trend and cycle components could lead to misleading interpretations of decoupling where emissions decrease in times of economic downturn.

Contrary to Cohen et al. (2017), Cohen et al. (2022) and Doda (2014) we do not find that procyclicality increases with GDP. Results are heterogeneous within income groups, such that we cannot determine if emissions are more or less procyclical for developing countries than for developed countries. Moreover, results are aligned with the literature on the cyclicality of emissions (Doda, 2014; Heutel 2012) but are overall higher than in most studies. We report an average estimate of 0.9, higher than Cohen et al. (2017) who found an average cycle elasticity of 0.6. Calculating correlation coefficients of the cyclical component of CO2 emissions and GDP also allows us to compare our results with that of the literature. In this case, a correlation coefficient higher than 0.5 suggests strongly linked emissions, coefficient between 0 and 0.5 denote weak link of emissions and income and finally, a correlation coefficient of 0 or less suggests delinking of the two variables. Doda (2014) found correlation of 0.5 and France, 0.4 for the UK, 0.2 for Germany, -0.14 for India and 0.4 for Brazil, using CO2 emissions and GDP per capita on a 1950-2011 sample. Mindful of the difference in the period studied, we report higher correlation for the mentioned countries with a 0.8 coefficient for France, 0.54 for the UK, 0.39 for Germany, 0.60 for India and 0.70 for Brazil. What's more, Heutel (2012) finds elasticity between 0.5 and 0.9 for the US while we find a cyclical elasticity of 0.6. Finally, Jalles and Ge (2020) who use the same approach on GHG emissions from 1990 to 2014, find for Okun elasticities close to 0 for Iran and close to 1 for Saudi Arabia.

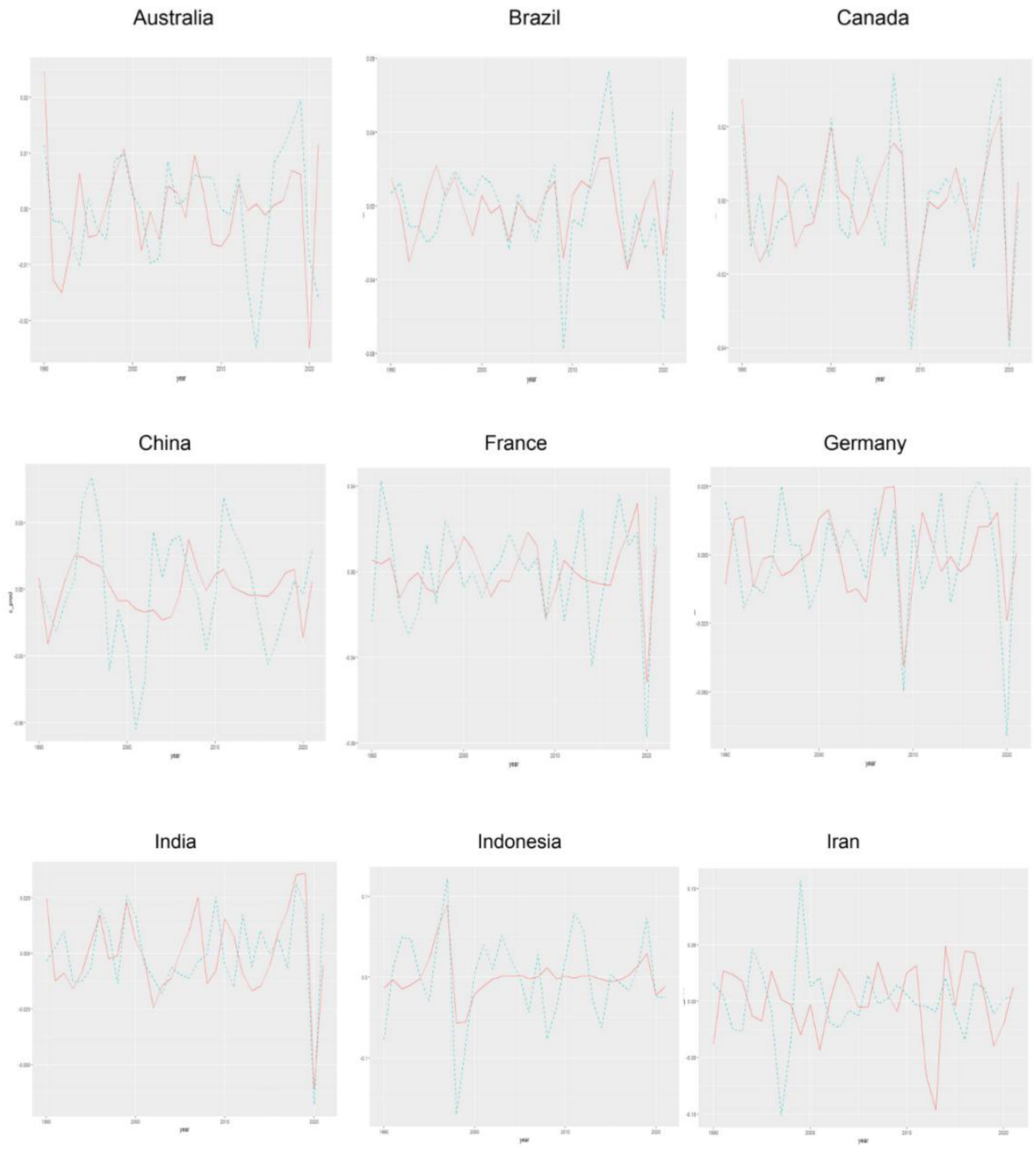
Consumption based emissions and output short term elasticities are reported in Table 5.3, the elasticity coefficients range from -0.10 for Iran to 4.42 for Vietnam. Once again the results are not significant for Iran. Overall results show a slightly higher level of procyclicality for consumption based emissions than production based emissions. All estimates (China and Canada aside) are higher for consumption based emissions than production based emissions but results do not vary greatly, suggesting that they may have similar cyclical patterns due to interconnectedness. This result also aligns with the estimations of Jalles and Ge (2020) reached similar conclusions by comparing consumption and production based cyclical elasticities in their sample.

Table 5.3: Cycle elasticity estimates (CBA)

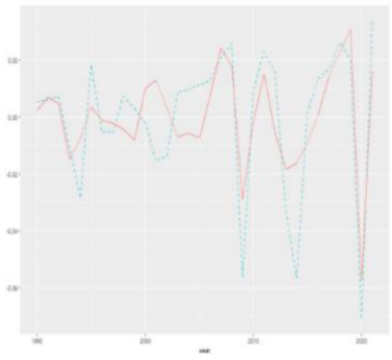
	β^C (CBA)	P Value	R Squared
Australia	0.483		0.04
Brazil	1.816	***	0.62
Canada	0.506	*	0.12
China	0.502		0.03
France	1.00	***	0.37
Germany	0.583	*	0.15
India	0.677	***	0.33
Indonesia	2.299	***	0.43
Iran	-0.105		-0.03
Italy	1.017	***	0.35
Japan	0.755	*	0.13
Mexico	1.224	***	0.73
Poland	0.296		0.02
Russia	0.89		0.01
Saudi Arabia	1.242	*	0.15
South Africa	0.752		0.04
South Korea	2.731	***	0.81
Thailand	1.457	***	0.51
Turkey	1.173	***	0.52
Ukraine	1.109	***	0.31
United Kingdom	0.723	**	0.22
United States	1.282	***	0.67
Vietnam	4.421	***	0.31

Note: The table presents country-specific estimates for cycle elasticities for cpn-sumption based emissions.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively

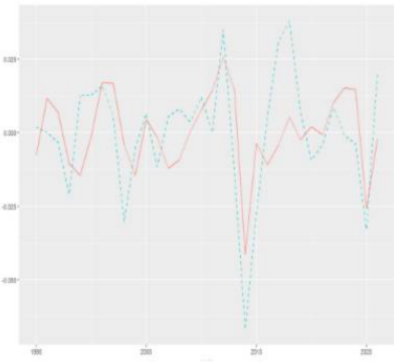
Figure 5.3: Production based CO2 emissions and GDPcycles



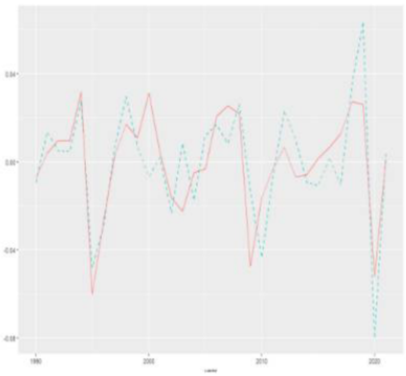
Italy



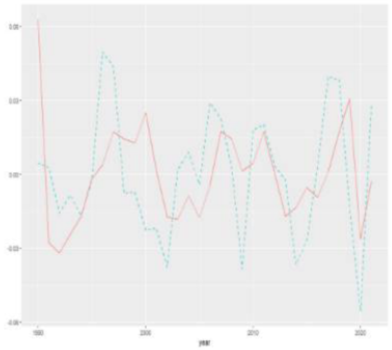
Japan



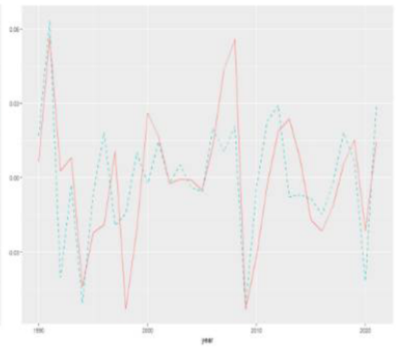
Mexico



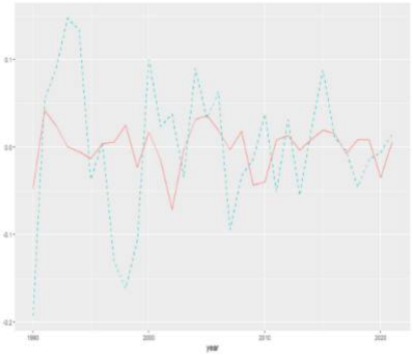
Poland



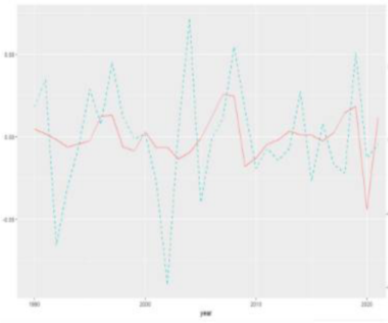
Russia



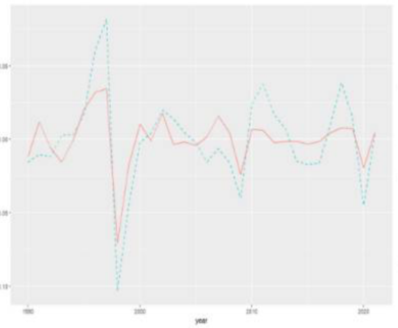
Saudi Arabia



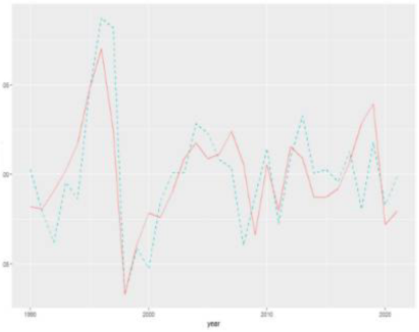
South Africa

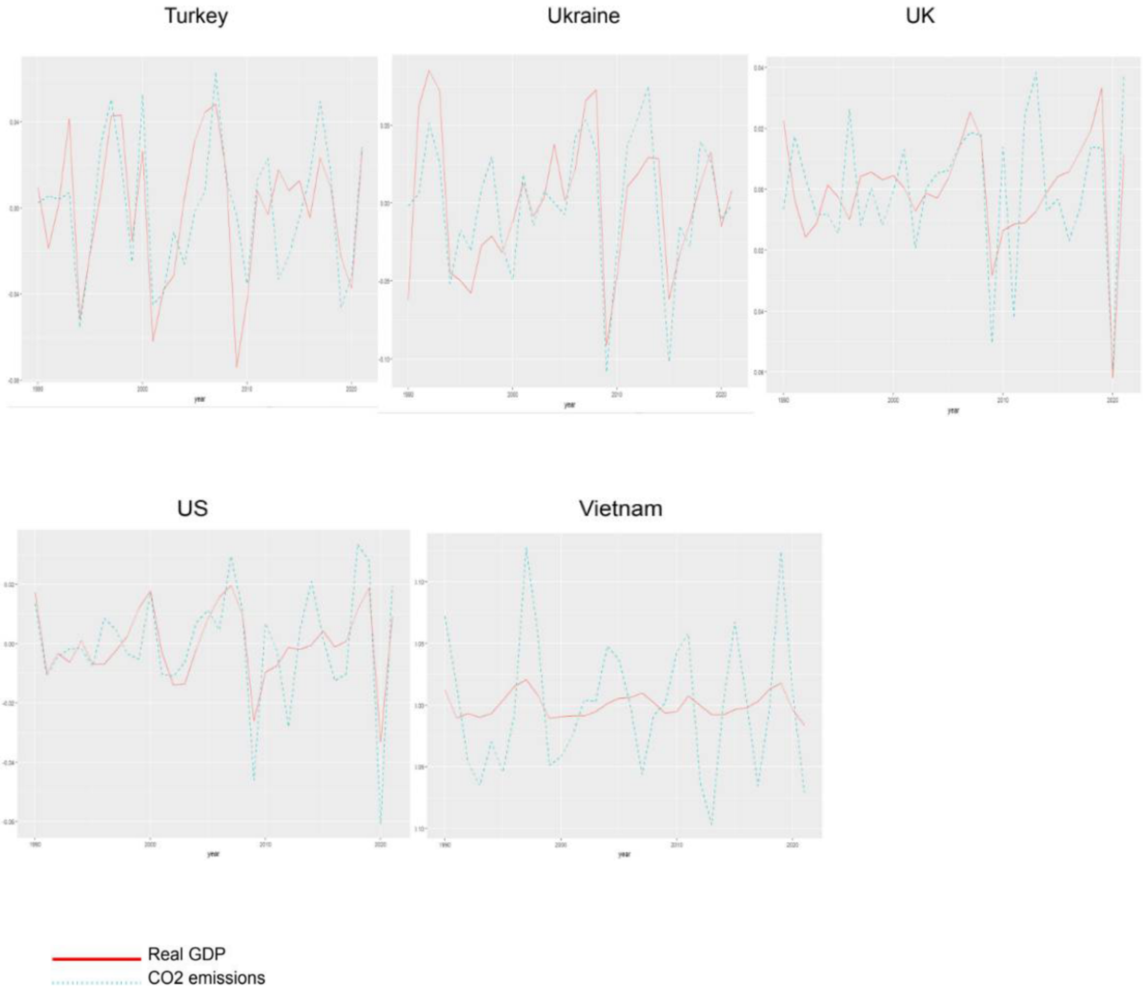


South Korea



Iran





5.3 Trend elasticity

5.3.1 Production based emissions

We estimate long term emissions to output elasticity which results are summarized in Table 5.4 and Figure 5.4. Coefficients for Kuznets elasticity vary between -1.2 for the UK and 2.5 for Saudi Arabia with an average of 0.32. Several developed countries such as France, Canada, the UK, the US or Germany present negative coefficients, suggesting that they have achieved absolute decoupling. Among those, European countries (France, Germany, the UK) have the lowest estimates, followed by the US and Canada and finally Japan and South Korea (which has a positive estimate). This result is not surprising considering European countries are often considered "eco leaders" in terms of environmental policies. On the other hand, other countries such as Russia, China or South Africa have shown signs of relative decoupling with estimates close to 0. Among those, Mexico is the only one to have a negative Kuznets elasticity but it is not statistically significant. Unsurprisingly, Iran and Saudi Arabia have one of the highest estimates of the sample, due to their oil activity. Finally, Brazil, Vietnam, Saudi Arabia and Iran are the only countries which Kuznets elasticity is close to or higher than 1 thus still maintain a strong linkage of their real GDP and CO2 emissions. Compared to Okun coefficients, Kuznets elasticities are lower but also tend to be less statistically significant across the sample. Results are significant for all countries aside from Ukraine, Italy, Russia, Canada, Australia and Mexico. For Italy and Ukraine results were also not significant in previous estimations which suggests the existence of specific underlying forces in those countries that are not captured by the model.

Developing countries have much higher elasticities with an average of 0.84 against -0.37 for developed countries. Similarly to Cohen et al. (2017, 2018, 2022), Jalles and Ge (2019) and Fan et al. (2006) our results for production based emissions suggest that decoupling is achieved in high income countries while developing countries only reach relative decoupling or do not exhibit signs of decoupling at all. However, results presented in this thesis are also more optimistic than previous literature. Cohen et al. (2018, 2022) found absolute decoupling for Germany, France and the UK, which have the lowest (negative) elasticities in our results, showing even more progress towards delinking of emissions and output. What's more, we report nine countries showing evidence of absolute decoupling, against the three previously mentioned for Cohen et al. (2018, 2022). Comparing trend elasticities with other studies is difficult insofar as most of them use different approaches (econometrically or in their model itself). The closest comparison that can be achieved is with Narayan and Narayan (2010) who compare long run and short run elasticities. Similar conclusions are reached for countries like Iran, India or Saudi Arabia whose elasticities are close or higher than 1. We also find evidence of absolute decoupling for Mexico (negative estimate), as do Narayan and Narayan (2010) who find long term elasticity of 0.43 and short term elasticity of 0.60, showing decreased emissions and increased output. South Africa is another salient example: our elasticity estimates (0.2) show evidence of relative decoupling while Narayan and Narayan (2010) find a lower long term elasticity than the short term one, also showing evidence of decoupling.

Figure 5.4: Trend elasticity estimates (PBA)

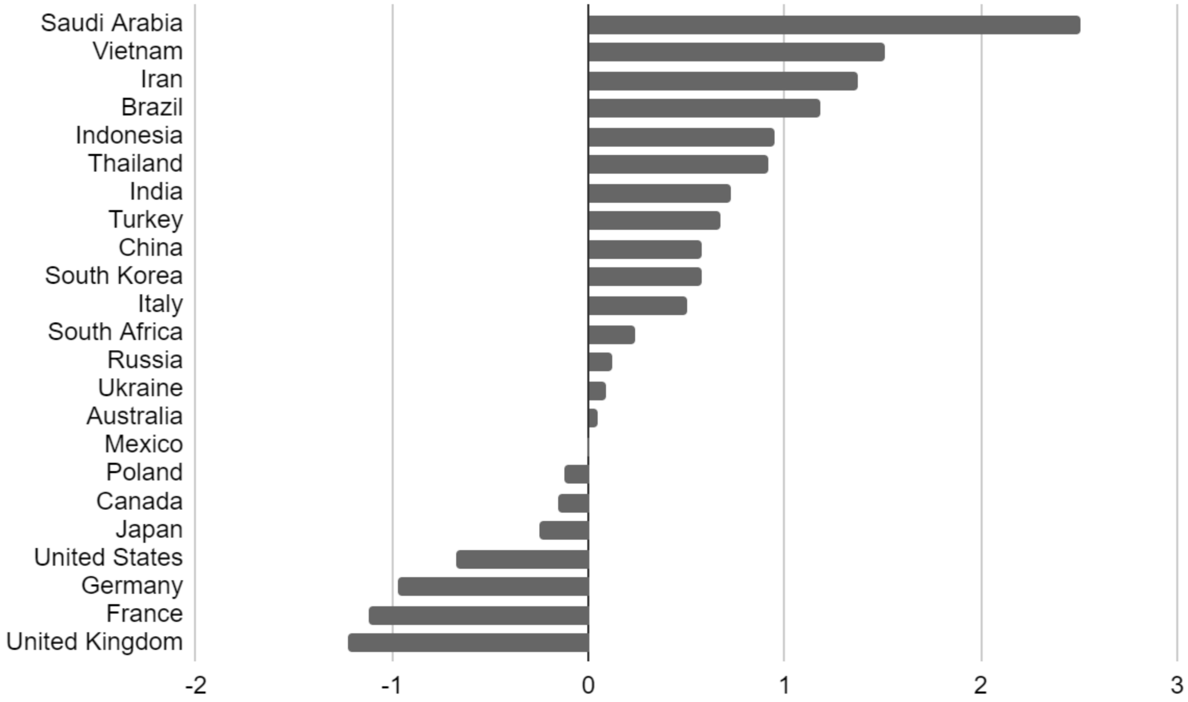


Table 5.4: Trend elasticity estimates (PBA)

	β^T (PBA)	P Value	R Squared
Australia	0.0506		-0.017
Brazil	1.186	***	0.919
Canada	-0.151		0.060
China	0.582	***	0.973
France	-1.123	***	0.564
Germany	-0.967	***	0.882
India	0.730	***	0.995
Indonesia	0.944	***	0.964
Iran	1.367	***	0.902
Italy	0.499		-0.00010
Japan	-0.251	*	0.114
Mexico	-0.0060		-0.033
Poland	-0.127	***	0.652
Russia	0.122		0.059
Saudi Arabia	2.503	***	0.729
South Africa	0.238	*	0.173
South Korea	0.572	***	0.946
Thailand	0.921	***	0.891
Turkey	0.667	***	0.962
Ukraine	0.087		-0.0269
United Kingdom	-1.226	***	0.559
United States	-0.678	***	0.596
Vietnam	1.515	***	0.996

Note: The table presents country-specific estimates for trend elasticities for production based emissions.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

5.3.2 Consumption based emissions

Consumption based estimates are summed up in Table 5.5 and Figure 5.5. The highest coefficient is 3.75 for Saudi Arabia and the lowest -1.02 for Germany with an overall average of 0.42. On average, Kuznets elasticities are higher for consumption based emissions than production based emissions and are also more statistically significant across the sample (except for the usual suspects Ukraine and Italy). Similar to previous results and in accordance with findings from the literature, developed countries show more signs of absolute and relative decoupling with a mean elasticity of -0.29 compared to developing countries which show a mean elasticity of 0.68.

According to the PHH hypothesis, richer countries displace pollution intensive industries thanks to international trade. Expected results should show that production based emissions lead to lower elasticities than consumption based emissions. In other words, when using production based emissions, advanced countries appear to have achieved decoupling but they still consume enough emissions to maintain a clear link between real GDP and CO2 emissions. The presented results show higher elasticities for consumption based emissions than production based emissions which does indicate that international trade makes a difference in measuring emissions-output decoupling. For most of the developing countries, consumption based emissions are lower than production based emissions. Results are consistent with the literature on trade and emissions (Peters et al., 2011; Kozul-Wright and Fortunato, 2012; Lucas et al., 1992; Yeats, 1992) and seem to indicate validity of the PHH hypothesis. This result does not extend to all developed countries of the panel. For Canada, Germany, Japan or South Korea the results are reversed meaning that consumption based emissions are lower than production based emissions. Thus, although our findings point toward the direction of a displacement effect, this conclusion would need further investigation with more information on specific trading partners and exchanges to reach a robust and strong conclusion.

Similar to Cohen et al. (2018), we find delinking between production (and consumption) based emissions and GDP when using the trend component but results for the cycle component seem to point towards a cyclicality of emissions. On the other hand, while the authors conclude higher levels of decoupling for advanced economies than for emerging countries, no clear pattern seems to emerge from our results.

Figure 5.5: Trend elasticity estimates (CBA)

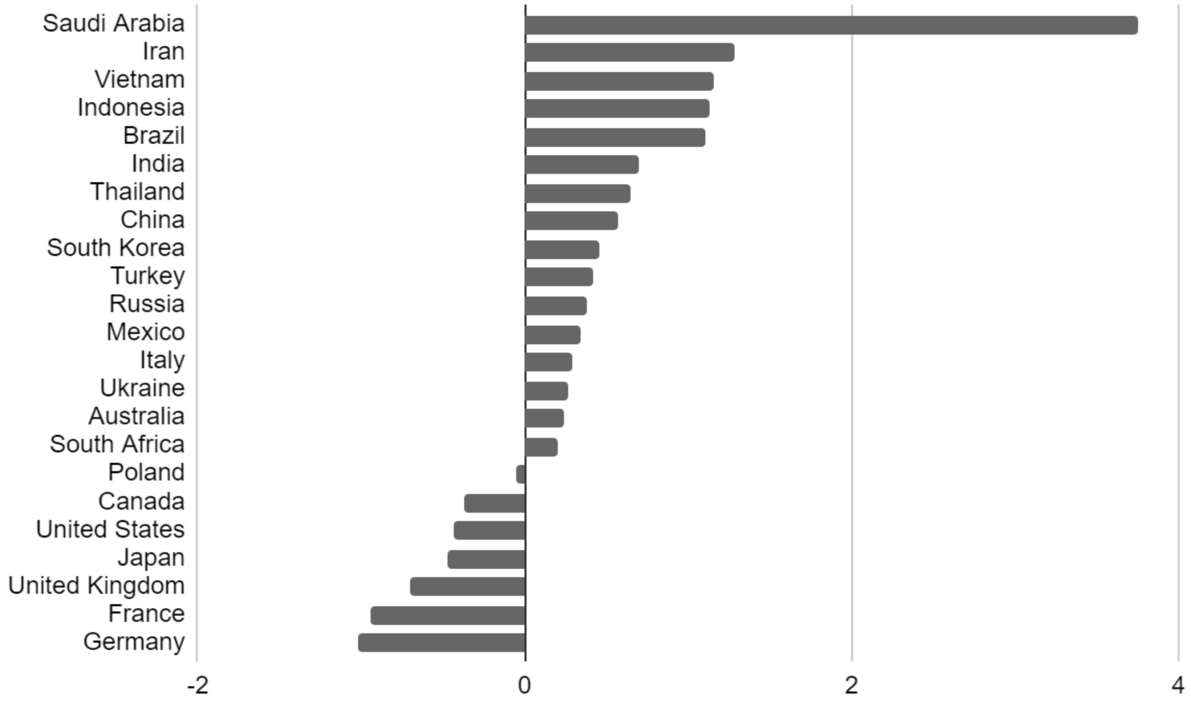


Table 5.5: Trend elasticity estimates (CBA)

	β^T (CBA)	P Value	R Squared
Australia	0.234	*	0.171
Brazil	1.102	***	0.838
Canada	-0.372	**	0.186
China	0.572	***	0.972
France	-0.941	***	0.430
Germany	-1.021	***	0.886
India	0.697	***	0.992
Indonesia	1.134	***	0.962
Iran	1.282	***	0.936
Italy	0.296		-0.020
Japan	-0.473	**	0.194
Mexico	0.346	*	0.098
Poland	-0.056	**	0.186
Russia	0.382	***	0.659
Saudi Arabia	3.752	***	0.813
South Africa	0.205	*	0.1644
South Korea	0.457	***	0.9487
Thailand	1.457	***	0.5121
Turkey	0.419	***	0.7153
Ukraine	0.271		0.073
United Kingdom	-0.702	***	0.299
United States	-0.438	***	0.306
Vietnam	1.150	***	0.996

Note: The table presents country-specific estimates for trend elasticities for consumption based emissions.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

5.3.3 Added variables

Table 5.6 provides results for our model including additional trade and energy variables for each country. As expected the two variables allow to improve the fit of the model, which is in accordance with the conclusion reached by Saqib and Benhmad (2021). For instance, in the case of Australia, the adjusted R square increases from 0.17 to 0.85 by adding energy and trade variables. Results of elasticity estimates also show higher levels of decoupling with a coefficient of -0.08 (instead of 0.2 previously). Finally, trade and energy do not play a significant role compared to GDP (which is also in line with Saqib and Benhmad (2021)) as their estimates are null but significant for Australia. These observations, however, may vary depending on the country. For some countries such as Brazil or Italy, trade enters with a negative sign while the estimate is positive for Canada or France which is more expected. In the same way, the estimate for energy for China is negative but positive for Iran or Japan. Overall, trade and energy improve the model's fit but the estimate is almost always null and results are overall significant for all variables across all countries.

Table 5.6 Estimations with added variables

Country	β^T (CBA)		ENER		TRADE		R-squared
Australia	-8.60E-02		9.86E-05	***	1.13E-02	***	0.849
Brazil	1.53E+00	***	-1.10E-04		5.29E-03	**	0.899
Italy	5.65E+00	***	-7.10E-04	***	7.69E-03		0.328
Canada	1.54E-01		7.44E-05	***	1.28E-02	***	0.830
S Korea	1.51E+00	***	-9.12E-05	***	-1.07E-03		0.564
China	3.38E-01	***	1.11E-04	**	-5.37E-03		0.978
France	-1.68E+00	***	2.08E-04	***	5.86E-03	*	0.781
Germany	-1.349	***	0.0001	***	0.002	*	0.973
India	0.437	**	0.00069	**	0.019	**	0.982
Indonesia	0.919	***	-0.00035		0.00022		0.992
Iran	-1.195		0.00167	***	0.0348	**	0.953
Japan	-3.36E-01	*	7.01E-05	**	9.98E-03	***	0.605
Mexico	2.26E+00	**	-4.62E-04	**	1.71E-03	**	0.265
Russia	-7.592	***	0.00381	***	0.146	***	0.816
S Arabia	6.68E-01	***	-6.22E-05	***	1.78E-03	***	0.88
S Africa	1.15E+00	***	-3.03E-05		-2.61E-03		0.996
Turkey	0.0166		0.00019	*	0.00602	***	
Ukraine	-1.48E-01	**	3.45E-04	***	-1.75E-03		0.926
Ukraine	6.70E-01	***	9.96E-05	***	-1.66E-02	***	0.944
USA	1.00E+00	***	4.15E-21		3.95E-19		1
Thailande	1.121	***	-0.00021		0.0014	*	0.959
Poland	-1.62E-01	*	6.91E-05		6.16E-03	*	0.299
Vietnam	1.14E+00	***	5.23E-05	**	2.04E-03	**	0.998

Note: * , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively

5.3.4 Comparison with preliminary results

Trend elasticities reveal a brighter picture than our preliminary results, for which none of the countries had achieved decoupling. Extracting the trend component from real GDP and CO2 emissions makes a significant difference in the measurement of decoupling. Countries which appeared to have the strongest link between emissions and output such as France, Canada or China now have negative or near zero CO2 emissions-real GDP elasticities. On the contrary, results from preliminary regression were also misleading since Saudi Arabia which was only the 6th highest w estimate is an outlier for both production and consumption based trend elasticity with values that are double, sometimes triple, other countries. This result is especially significant as the literature on emissions-output elasticity does distinguish trend and cyclical components in their estimations of decoupling which could lead to misleading results, showing less progress than there actually is.

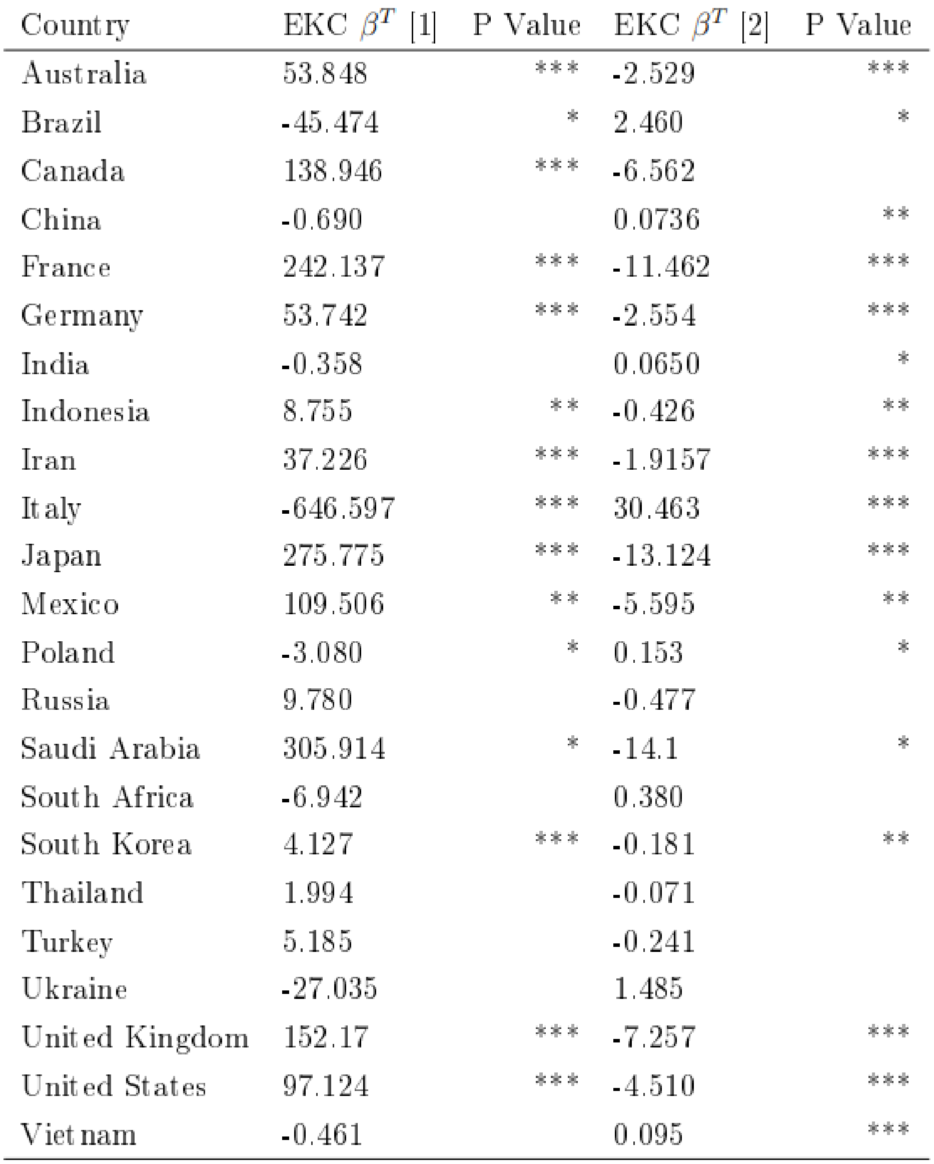
5.4 Environmental Kuznets Curve

To further this research, we test the validity of the Environmental Kuznets Curve for all 23 countries of the sample, using the trend of real GDP per capita and trend of CO2 emissions per capita and a quadratic specification. Results can be found in Table 5.7 and Figure 5.6 and 5.7.

Under quadratic form, the EKC hypothesis is validated when $\beta_1 > 0$ and $\beta_2 < 0$ and when the plot takes the form of an inverted U. After extracting the trend component from consumption based CO2 emissions and real GDP per capita, we find coefficients under such restrictions for 15 out of 23 countries. The EKC is validated for countries such as France, Germany, the UK or the US who's Kuznets estimates also suggested absolute decoupling. The reverse is also true for countries like Indonesia or Iran. For some countries such as Saudi Arabia or Russia the estimates also follow the pattern of the EKC which is not consistent with previous findings of their trend elasticities, however results are not statistically significant. Overall, results are much less significant than for previous estimations and although coefficients match the restriction imposed, graphical representations of the EKC are only valid for a few (developed) countries.

Figure 5.6 shows an inverted U-shape of the income emissions function for Australia, France, Germany and Japan and Figure 5.7 shows a monotonically increasing function for China, India and Vietnam.

Table 5.7: Environmental Kuznets Curve "trend" estimates



Country	EKC β^T [1]	P Value	EKC β^T [2]	P Value
Australia	53.848	***	-2.529	***
Brazil	-45.474	*	2.460	*
Canada	138.946	***	-6.562	
China	-0.690		0.0736	**
France	242.137	***	-11.462	***
Germany	53.742	***	-2.554	***
India	-0.358		0.0650	*
Indonesia	8.755	**	-0.426	**
Iran	37.226	***	-1.9157	***
Italy	-646.597	***	30.463	***
Japan	275.775	***	-13.124	***
Mexico	109.506	**	-5.595	**
Poland	-3.080	*	0.153	*
Russia	9.780		-0.477	
Saudi Arabia	305.914	*	-14.1	*
South Africa	-6.942		0.380	
South Korea	4.127	***	-0.181	**
Thailand	1.994		-0.071	
Turkey	5.185		-0.241	
Ukraine	-27.035		1.485	
United Kingdom	152.17	***	-7.257	***
United States	97.124	***	-4.510	***
Vietnam	-0.461		0.095	***

Note: The table presents country-specific estimates for the EKC using trend components of emissions and output.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

Figure 5.6 EKC for selected countries

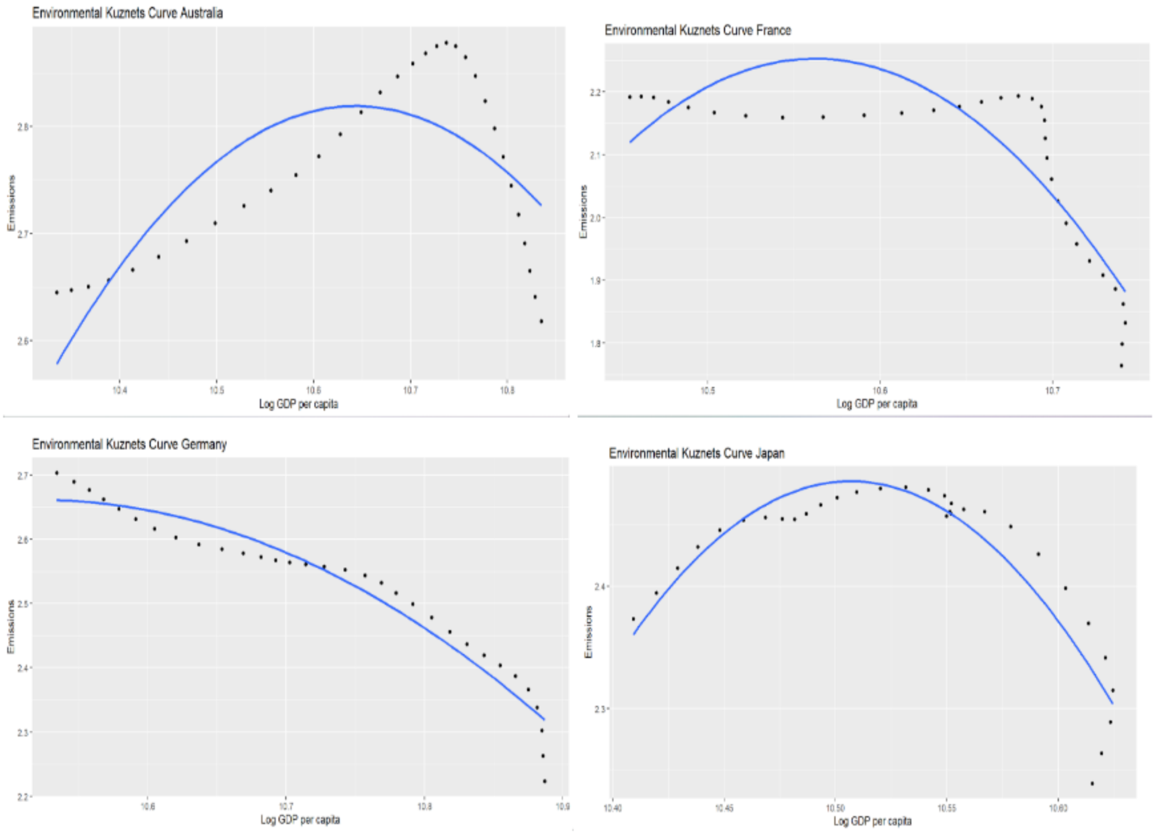
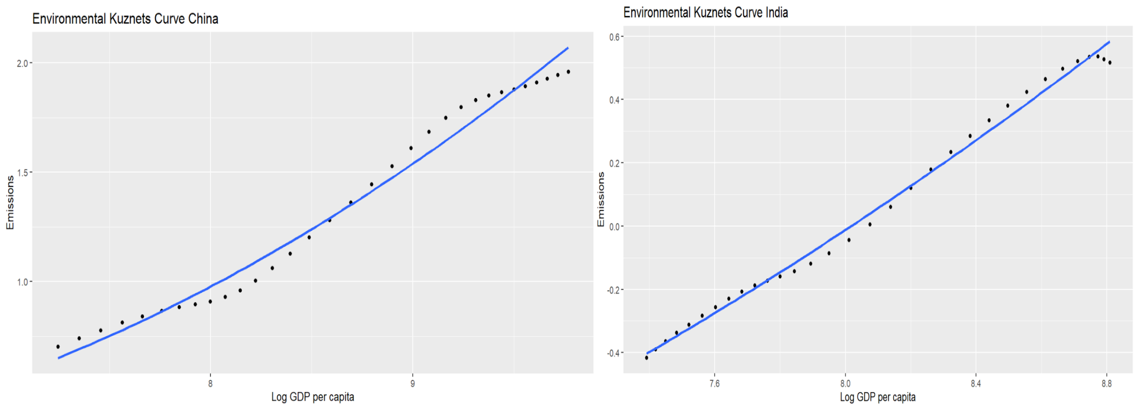
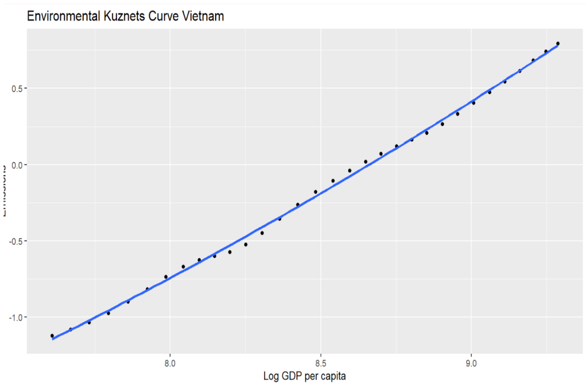


Figure 5.7 Emissions as monotonically increasing function of income for selected countries





From Figure 5.6 and 5.7, it is also noteworthy that monotonically increasing functions better fit results for the selected countries than inverted U fit results for countries that show patterns of the EKC.

For the countries that do validate the EKC hypothesis, it is possible to calculate the turning point, or in other words, the peak in income that needs to be attained before emissions start decreasing. The turning point can be calculated as: $tp = -\beta_1 / 2 * \beta_2$.

However, simply calculating the turning point using the Kuznets elasticities would make it impossible to compare with results from previous studies as the turning point in our model is expressed in trends of logarithm of GDP per capita. Thus we re-estimate the model using only the natural logarithm of GDP and the natural logarithm of CO2 emissions for certain countries of interests that either validated the EKC (Australia, Japan, France, Germany) or on the contrary showed no evidence of EKC (China, India). For instance, results for France are consistent with Ang (2007) and Iwata et al. (2010) whose findings validated the EKC for France, with a turning point of 9.55. Although our estimates are also in favor of the EKC, we find a higher turning point of 10.55 in logarithm of GDP per capita but that is within the sample period. It is also noteworthy that the turning points for the four countries mentioned are all around 10 (eg. 10.99 for Australia, 10.52 for Japan and 10.13 for Germany). For India on the other hand, our results do not coincide with the results from Tiwari et al. (2013). For China we find no evidence of the EKC but a monotonically increasing function which is in contradiction with Pao and Tsai (2010) but in accordance with Liu and Bae (2018) and Yilanci and Pata (2020) for instance.

Literature and evidence on the existence of the EKC in various countries is mixed. It is therefore not surprising to find that our results do not all coincide with the literature on country specific studies. To sum up, results for the Environmental Kuznets Curve specification of our model are less significant than for trend and cycle elasticities and do not always coincide with previous findings. According to our results absolute decoupling has been achieved for Germany and is said to remain this way. The country's path to decoupling is set to continue in the long run. For other countries like Canada or France however, the EKC analysis reveals different results.

5.5 Global scale results

Previous results show signs of decoupling at the individual country level. To estimate whether this conclusion holds at the global scale, elasticities are estimated using panel data and fixed effects. Then an exercise is conducted by estimating elasticity at the "world" level, as an aggregation of all country's GDPs and emissions. Results for panel estimation are presented in Table 5.8 and results for the exercise are presented in Table 5.9.

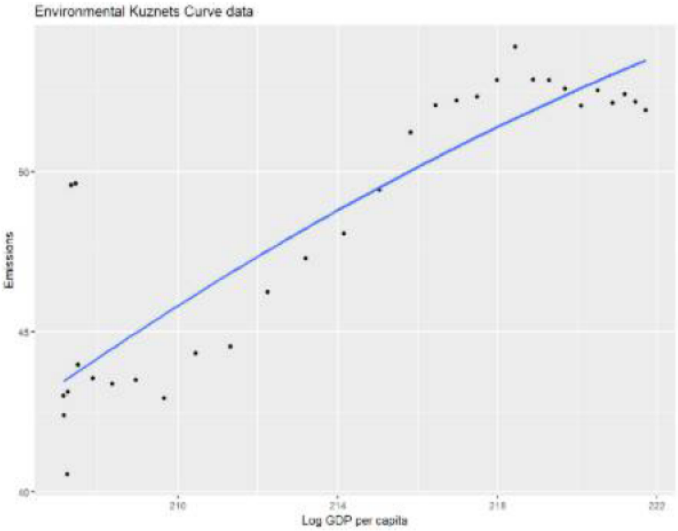
Using Fixed Effects to estimate decoupling on the panel, we find a global trend elasticity of 0.83 which puts the world closer to coupling than decoupling, although this estimate is still lower than one. Although the panel is very heterogeneous, it is necessary to note that, using country and time specific effects, our estimate is statistically significant. We also test for a panel EKC and find the first coefficient for GDP to be 0.76 and the second coefficient for GDP squared to be 0.008, both statistically significant. Those results confirm our long term elasticity results: using panel data estimation, there is no evidence of decoupling. Including additional trade and energy variables does not make a significant difference in our results. Estimates for those variables enter with an expected positive sign but are null. On the contrary, we find that GDP is the most important determinant of CO2 emissions at the global level. This result is in line section 5.3.3.

Table 5.8 Panel data estimations

	FE	
Trebd Exracted		
GDP	0.834	***
EKC		
GDP	0.761	***
GDP^{2}	0.008	*
Added variables		
GDP	0.763	***
ENER	0.004	*
TRADE	0.001	*

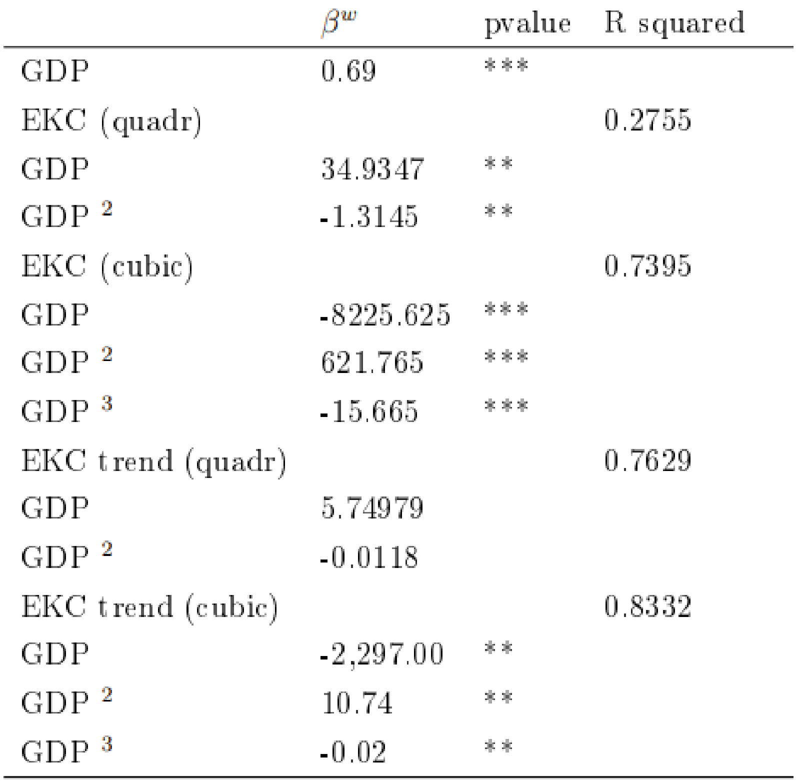
Note: The table presents panel data estimation for trend elasticity, EKC and trend elasticity with added variables using Fixed Effects.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

Figure 5.8: Environmental Kuznets Curve for Panel estimation



We also estimate results using aggregated levels, by adding GDP per capita and CO2 emissions levels of all countries for a single year *t*. We thus create a new time series for the "world". Using variables at level (without extracting trend), we find CO2 emissions-income elasticity very close to 0 and not statistically significant. Aggregated level we find an consumption based CO2 emissions-income elasticity very close to 0 and with no statistically significant results. When aggregating trends of GDP, the trend elasticities for consumption based CO2 emissions is 0.69 and statistically significant at the 0.01% level. This result is quite close to the panel data estimation but still much lower, indicating relative decoupling for world aggregated data.

Table 5.9: World level aggregated emissions-output elasticities and Kuznets curve



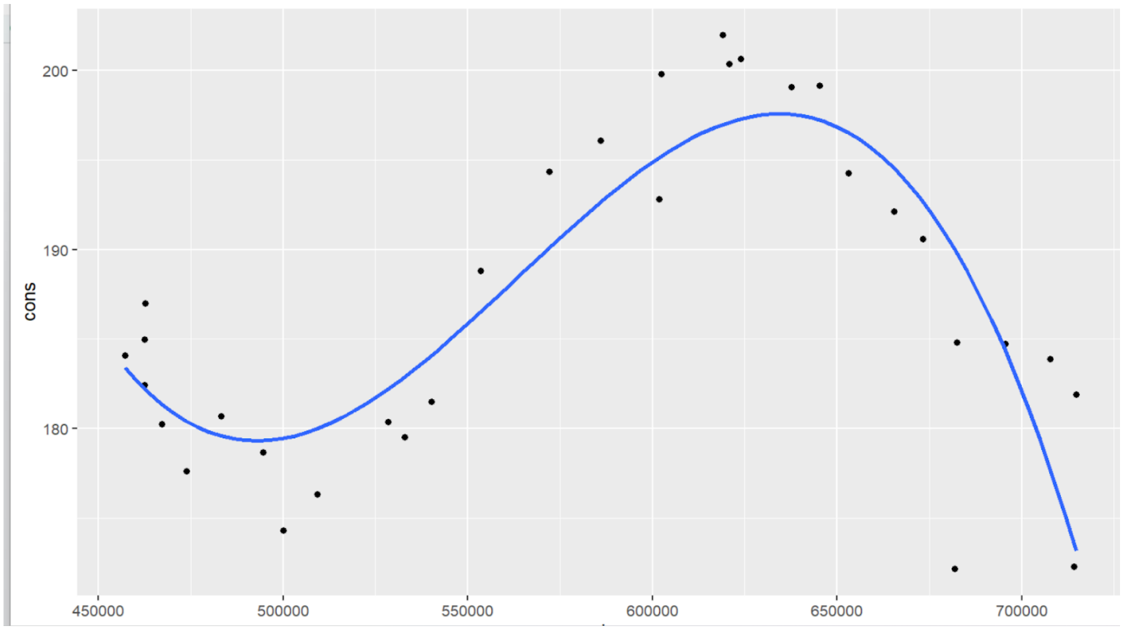
	β^w	pvalue	R squared
GDP	0.69	***	
EKC (quadr)			0.2755
GDP	34.9347	**	
GDP ^{2}	-1.3145	**	
EKC (cubic)			0.7395
GDP	-8225.625	***	
GDP ^{2}	621.765	***	
GDP ^{3}	-15.665	***	
EKC trend (quadr)			0.7629
GDP	5.74979		
GDP ^{2}	-0.0118		
EKC trend (cubic)			0.8332
GDP	-2,297.00	**	
GDP ^{2}	10.74	**	
GDP ^{3}	-0.02	**	

Note: The table presents trend elasticity and EKC specifications for aggregated data at the global level.* , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

We then estimate the EKC for aggregate world time series using both variables at their level and trend extracted variables. First, for level variables we find that a cubic form better fits the model as Adjusted R square increases from 0.27 with quadratic form to 0.73 with cubic form and the statistical significance improves as well. Our results show an inverted N shape where emissions decrease before increasing and then decreasing again with a turning point at around $180 and $195 in logarithm of world GDP per capita. Mentioned results are presented in Figure 5.9 and 5.9 as well as Table 5.9.

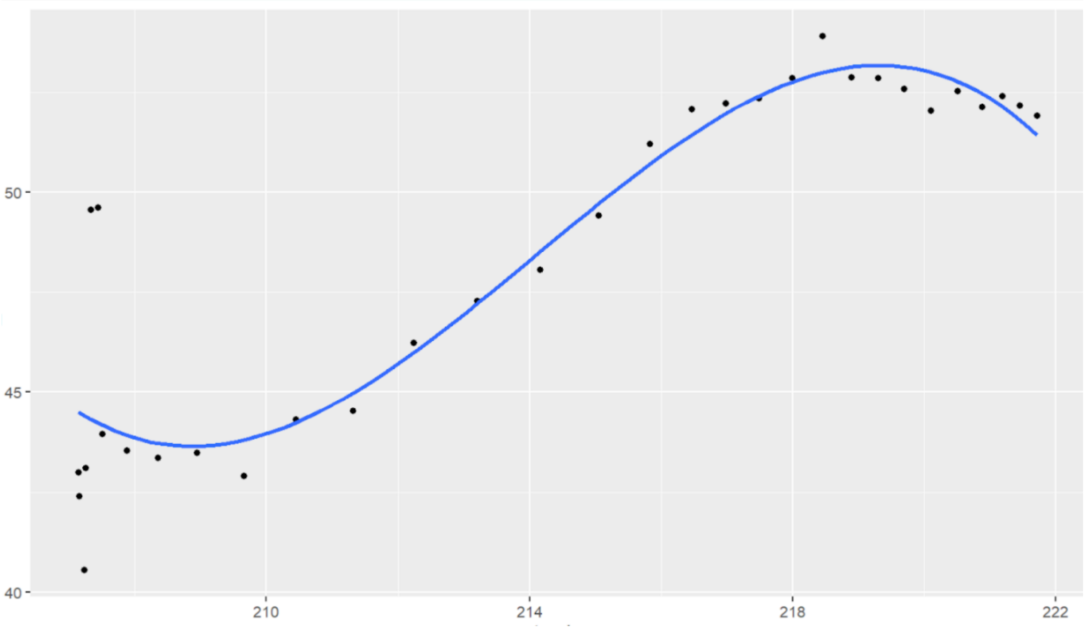
Although the model fits the inverted N-shaped curve quite well, turning point values are very high. In comparison, Martinez-Zarzoso and Bengochea-Morancho (2004) report a turning point between 3.69 and 4.25 in the logarithm of GDP for OECD countries. Panayotou (1993) had previously found a turning point of 3.49 and Stern and Common (2001) found a peak around 5 in logarithm of GDP. Our maximum aggregated world GDP per capita value is also around 5. Thus results for the turning point are unrealistic.

Figure 5.9: Environmental Kuznets curve aggregated data



Then looking at the EKC using our decomposition technique, we also find that a cubic function fits the model better and the curve is highly similar, only with less depth of variation. Mentioned results are reported in Table 5.9 and Figure 5.10.

Figure 5.10: EKC aggregated data - trend elasticities



6. Robustness and sensitivity checks

6.1 Sensitivity check

We conduct an exercise to see by using the model described in Eq (2) and (3) on a subsample for the period 1990 to 2015 and estimate country elasticities. Estimating the model for a different time period will allow us to check for sample sensitivity and assess whether estimated elasticities and conclusions are consistent across different time frames. Results are described in Table 6.1 and figures 6.1 and 6.2

Table 6.1: Sub-sample estimates

	β^c [PBA]	P. Value	β^c [CBA]	P. Value	β^t [PBA]	P. Value	β^t [CBA]	P. Value
Australia	0.390	*	0.435		0.240	***	0.504	***
Brazil	1.067	***	1.872	***	1.220	***	1.245	***
Canada	0.00016	***	0.347		0.044		-0.301	
China	0.018	*	0.081		0.626	***	0.585	***
France	0.412		0.0051	**	-0.722	***	-0.466	**
Germany	0.146		0.15		-0.784	***	-0.821	***
India	0.259		0.087		0.742	***	0.701	***
Indonesia	0.001	***	0.001	***	1.039	***	1.264	***
Iran	0.33		0.893		1.550	***	1.459	***
Italy	0.0001	***	0.0066	**	0.595		0.387	
Japan	0.003	**	0.035	*	0.216	***	0.222	
Mexico	0.0001	***	0.001	***	0.465	***	0.842	***
Poland	0.215		0.859		-0.1730	***	-0.060	*
Russia	0.001	***	0.3		0.155		0.432	***
Saudia Arabia	0.238		0.024	*	2.445	***	3.724	***
South Africa	0.136		0.271		0.409	***	0.364	***
South Korea	0.001	***	0	***	0.633	***	0.508	***
Thailand	0.001	***	0.001	***	1.098	***	0.722	***
Turkey	0.001	***	0.001	***	0.761	***	0.543	
** Ukraine	0.0000136	***	0.0028	**	0.348		0.483	***
United Kingdom	0.128		0.034	*	-0.731	***	-0.240	
United States	0.001	***	0.001	***	-0.402	***	-0.128	
Vietnam	0.003	**	0.001	***	1.509	***	1.122	***

Note: The table presents trend and elasticities for all countries on a subsample from 1990 to 2015.* , **, *** denote statistical significance at the 10, 5 and 1 percent

Results for Okun or cycle elasticities are much less significant than for the whole sample period (1990-2021), however this could be due to the fact that the number of observations is reduced drastically and inference becomes more difficult. The average cycle elasticity for CO2 production based emissions is 0.14 which is lower than the results found in section 5.2. It is important to note that some values are also inconsistent with previous findings. For example, elasticities for South Korea, Thailand and Ukraine are close to zero but results are statistically significant. The maximum is also much lower and peaks at 1.06 for Brazil whereas Vietnam, which had a cycle elasticity of 3.33 for CO2 production based emissions, now has a coefficient close to 0 for the 1990-2015 subsample.

If we look at trend elasticities for production based CO2 emissions, results for the 1990-2015 sample are significant for 19 countries out of 24. We find a maximum elasticity of 2.45 for Saudi Arabia and minimum elasticity of -0.78 for Germany. The average Kuznets elasticity from 1990 to 2015 is 0.49. Compared to the results described in Chapter 5, the coefficients for the sub sample are consistent as Saudi Arabia has once against the strongest link between emissions and output and Germany is amongst the countries that are closest to decoupling. It is notable that the average elasticity is much higher than for the full sample and only 20% of our sample exhibits signs of absolute decoupling. In other words, this does confirm our conclusion that countries are now on the path to low carbon transition Significant progress towards decoupling of CO2 emissions and real GDP has been made since 2015, even if usual estimations that do not account for trend-cycle decomposition often paint a much more pessimistic picture. Finally, comparing with Kuznets elasticities found by Cohen et al. (2018) using production based GHG emissions over the period 1990-2014, we find higher estimates on average (0.49 for our subsample and 0.40 for the 2014 study) but the difference between using GHG emissions and CO2 emissions is not striking. Lastly, we compare trend elasticities for production and consumption based CO2 emissions for the subsample than for the full sample. We reach similar conclusions suggesting that consumption based emissions are higher than production based emissions for developed countries such as Australia, the US, the UK or France. The reverse is true for some developing countries such as

Vietnam, Turkey or Thailand. Overall, when looking at cycle elasticities the sub sample results are not consistent with our findings but Kuznets elasticities are similar to the full sample and also close to Cohen et al. (2018) estimation on the same period.

Figure 6.1 Sub-sample trend estimates (PBA)

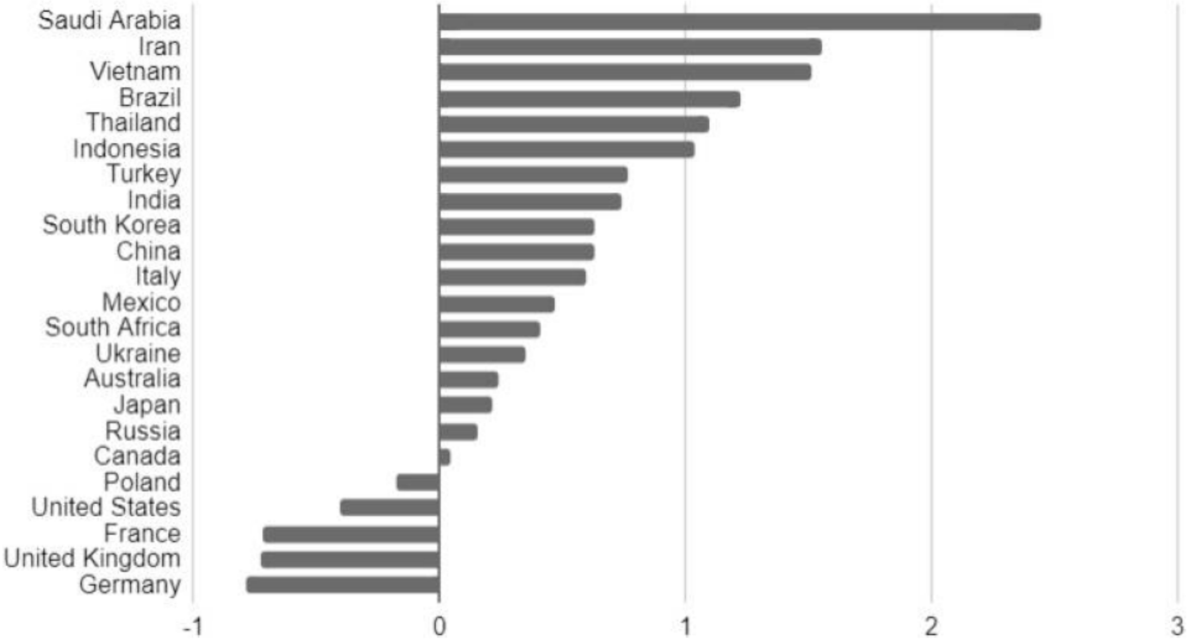
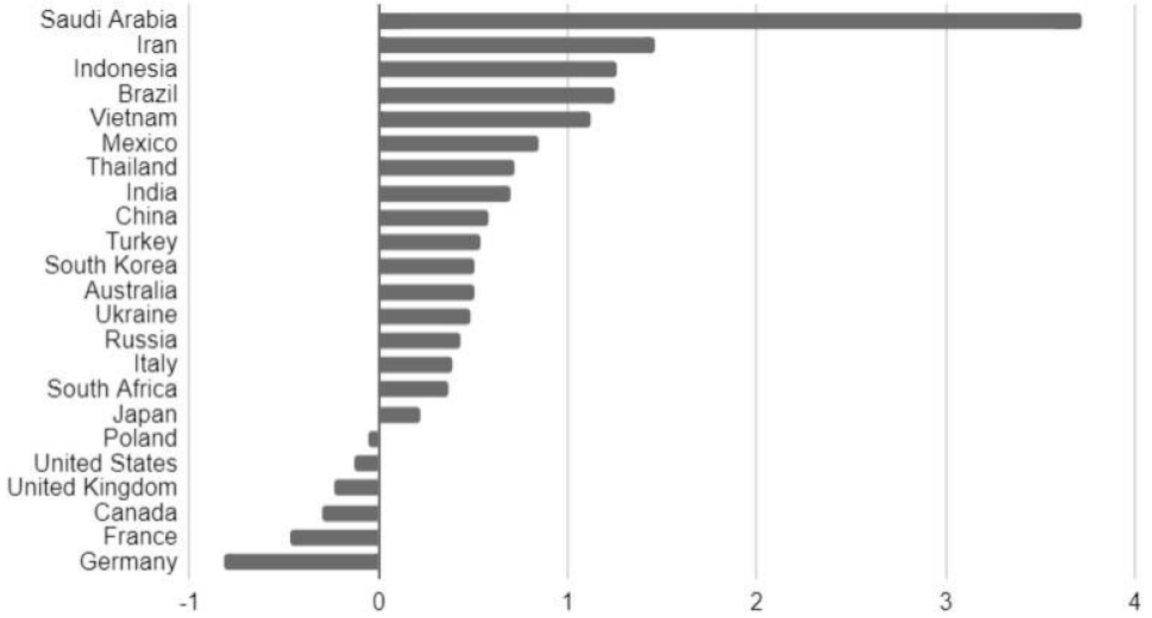


Figure 6.2: Sub sample trend estimates (CBA)



It is important to note that the number of observations for individual country regression is very small (31 for the full sample and 25 for the subsample 1990-2015). To remedy this problem Cohen et al. (2017, 2018) conduct two experiments by estimating their model on longer time series, fetching data as early as 1850 for some countries. In their 2022 interpretation, the authors use data from 1960 to 2018 creating a total of 58 observations. Therefore, results presented in chapter 5 need to be interpreted with caution.

6.2 Non-stationarity

GDP and emissions are variables known for their non-stationary properties, which is why estimations of decoupling often use cointegration analysis in the literature. Cohen et al. (2018, 2022) are not concerned with stationarity properties of the variables before estimating their model, which is why unit root testing is presented in this section. First, we conduct an Augmented Dickey-

Fuller test on the residuals of both cyclical elasticities and trend elasticities. Then, we also perform cointegration tests on the sample as a panel data. Testing for cointegration of the variable is key to avoid spurious regression. Results, per country, are reported in Table 6.2.

Results from the ADF test on residuals show p-values for the test that are higher than the significance level (at the 5% or 1%) for all countries and for all four estimates of elasticities. The null hypothesis of unit root in the time series can be rejected, although the evidence is not very strong for some countries.

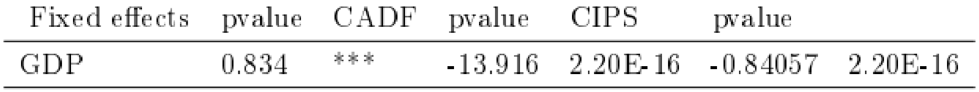
Table 6.2: ADF test results

Country	β^T (PBA)	p value	ADFT	p-value	β^T (CBA)	p value	ADFT p-value
Australia	0.050		0.050		0.234	*	0.252
Brazil	1.186	***	0.01		1.10258	***	0.506
Canada	-0.151		0.5097		-0.372	**	0.342
China	0.582	***	0.01		0.572	***	0.01
France	-1.123	***	0.024		-0.941	***	0.101
Germany	-0.967	***	0.945		-1.021	***	0.99
India	0.730	***	0.01		0.697	***	0.085
Indonesia	0.944	***	0.624		1.134	***	0.923
Iran	1.367	***	0.219		1.28254	***	0.336
Italy	0.499		0.114		0.2963		0.557
Japan	-0.251	*	0.99		-0.473	**	0.99
Mexico	-0.00608		0.864		0.3461	*	0.970
Poland	-0.127	***	0.192		-0.0561	**	0.260
Russia	0.122		0.6386		0.382	***	0.052
Saudi Arabia	2.503	***	0.257		3.752	***	0.047
South Africa	0.238	*	0.969		0.205	*	0.970
South Korea	0.572	***	0.978		0.457	***	0.99
Thailand	0.921	***	0.322		0.643	***	0.404
Turkey	0.667	***	0.99		0.419	***	0.432
Ukraine	0.087		0.01		0.271		0.183
United Kingdom	-1.226	***	0.298		-0.7025	***	0.612
United States	-0.678	***	0.141		-0.438	***	0.226
Vietnam	1.515	***	0.01		1.150	***	0.661

Note: Results from the ADF test for trend elasticities (PBA and CBA). * , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

Regarding panel data, and as pointed out by Dogan and Aslan (2017), many studies fail to account for the possibility of cross sectional dependence and heterogeneity of the panel. To test for cross sectional dependance we use the Pesaran's CD or Breusch–Pagan's LM test. The results for Pesaran's CD and Breusch–Pagan's LM test for cross sectional dependence confirm the presence of cross sectional dependence in the panel. Thus we perform a second generation unit root test that accounts for cross sectional dependence by following the same approach as previously and testing residuals from the panel estimation. The cross-sectionally augmented ADF (CADF) and cross-sectionally augmented IPS (CIPS) unit root tests are performed on the residuals. The p-value for both tests is lower than the significance level, which suggests strong evidence against the null hypothesis of no cointegration between the variables. In other words, variables are cointegrated and have a long term relationship when considering panel data. Results are presented in Table 6.3.

Table 6.3: CADF and CIPS tests results



Fixed effects	pvalue	CADF	pvalue	CIPS	pvalue	
GDP	0.834	***	-13.916	2.20E-16	-0.84057	2.20E-16

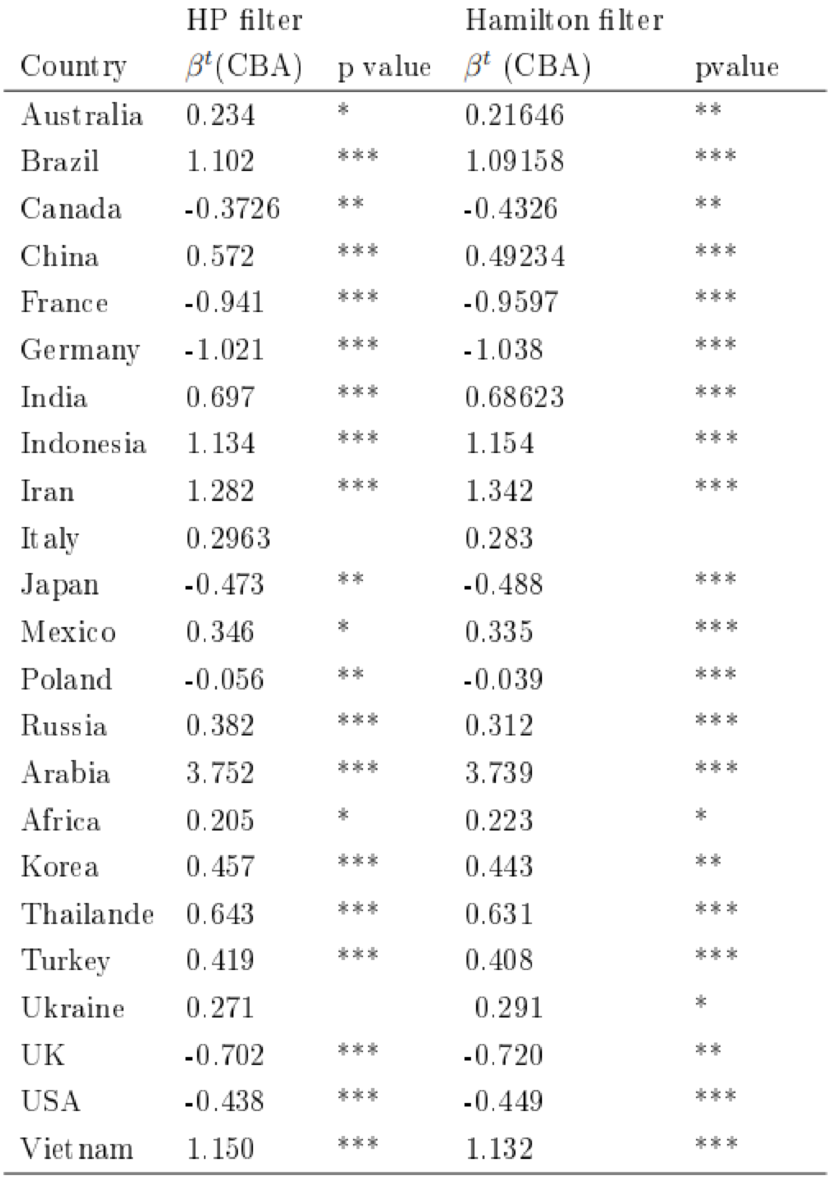
Note: Table presents results of trend elasticitiy (CBA), CADF and CIPS tests on residuals. * , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

6.3 Filtering methods

In the analysis presented in Chapter 5, the HP filter is used to extract trend and cycle components from variables of interest. However, the HP filter has been criticized for "introducing spurious dynamics relations" and " smoothing parameters vastly at odds with common practice" (Hamilton, 2017). Thus it is common practice in the literature focusing on cyclicality of emissions, or simply using the HP filter to detrend data, to use an alternative filtering method as a robustness check (Doda, 2014; Cohen et al. 2014; Papiez et al. 2020; Hetuel, 2012; Alege et al. 2017; Sarwar et al.

2021). Arguably, this does not make a significant difference as has shown (Papiez et al. 2022; Cohen et al. 2018; Delgado Rodriguez et al. 2018). Nevertheless, results from using the Hamilton filter are presented in Table 6.4 for consumption based trend elasticities.

Table 6.4: Trend elasticities from Hamilton filtering method



	HP filter		Hamilton filter	
Country	β^t(CBA)	p value	β^t (CBA)	pvalue
Australia	0.234	*	0.21646	**
Brazil	1.102	***	1.09158	***
Canada	-0.3726	**	-0.4326	**
China	0.572	***	0.49234	***
France	-0.941	***	-0.9597	***
Germany	-1.021	***	-1.038	***
India	0.697	***	0.68623	***
Indonesia	1.134	***	1.154	***
Iran	1.282	***	1.342	***
Italy	0.2963		0.283	
Japan	-0.473	**	-0.488	***
Mexico	0.346	*	0.335	***
Poland	-0.056	**	-0.039	***
Russia	0.382	***	0.312	***
Arabia	3.752	***	3.739	***
Africa	0.205	*	0.223	*
Korea	0.457	***	0.443	**
Thailande	0.643	***	0.631	***
Turkey	0.419	***	0.408	***
Ukraine	0.271		0.291	*
UK	-0.702	***	-0.720	**
USA	-0.438	***	-0.449	***
Vietnam	1.150	***	1.132	***

Note: Table presents results of trend elasticities from using the HP filter and the Hamilton on filter. * , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

Results from the Hamilton filtering are very similar to using the HP filter and there is no difference in statistical significance. This conclusion aligns with previous robustness checks from the literature.

6.4 Additional robustness tests

Elasticity coefficients are estimated using OLS, which requires strong assumptions. At first glance, results presented in Chapter 5 may suffer from several issues due to the small sample size (31 observations for individual country analysis) and possible endogeneity from committed variables. Thus, we check the robustness of the main results by conducting a series of tests on the model for trend elasticities for each country.

First, we test for heteroskedasticity using the Studentized Breusch-Pagan test. Although results are heterogenous, we find p_value higher than the conventional level of significance set at 0.05 for all countries. Results suggest that the variance of the error terms in the regression model is constant across observations and that the assumption of homoscedasticity is not violated. Then the Durbin-Watson test is used to detect the presence of autocorrelation in the residuals. The p-value for the test is lower than the usual significance level for all countries. The null hypothesis is rejected in favor of the alternative hypothesis of autocorrelation. In addition, the Shapiro-Wilk test assesses the normality of distribution of residuals. In the case of our regressions for trend elasticities, the p-value is higher than 0.05 in all cases. Therefore, the distribution of residuals is considered normal. Finally, omitted variable bias is a common concern in the literature. We use the RESET (Regression Specification Error TEST) to assess the possibility that the linear regression has omitted variables or that the form is misspecified. Results for this test are lower than the conventional level of significance which suggests there may be omitted variables in the model. For the "world" (aggregated) time series, results show the same specifications as mentioned above, with concerns of endogeneity and autocorrelation. Results of the tests conducted are presented in Table 6.5. In addition, and although this will not be tested, regressions using additional variables may suffer from multicollinearity since electricity consumption (energy) and trade are often correlated with GDP.

Table 6.5: Results from Robustness tests

Country	Durbin-Watson	P Value	Breusch-Pagan	P Value	Shapiro-Wilk	P Value	Reset	P Value
Australia	0.0485530	2.2E-16	0.048553	2.20E-16	0.94034	0.07654	105.24	9.46E-14
Brazil	3.7	0.05441	0.15342	2.20E-16	0.95479	0.1968	32.463	5.09E-08
Italy	0.030198	0.862	0.026714	2.20E-16	0.80491	5.05E-05	14.929	3.87E-05
Canada	6.1698	0.01299	0.044041	2.20E-16	0.92642	0.03116	86.036	1.11E-12
S Korea	6.1698	0.01299	0.044041	2.20E-16	0.92642	0.03116	86.036	1.11E-12
China	8.0854	0.004462	0.081695	2.20E-16	0.96283	0.3276	59.025	9.06E-11
France	8.8097	0.002996	0.044664	2.20E-16	0.9614	0.2999	94.014	3.78E-13
Germany	5.3554	0.02066	0.10382	2.20E-16	0.90545	0.00855	66.675	2.25E-11
India	1.2362	0.2662	0.38669	4.21E-10	0.95966	0.2689	19.906	4.19E-06
Indonesia	1.414	0.2344	0.13199	2.20E-16	0.89325	0.004188	9.1339	0.0008837
Iran	0.17542	0.6753	0.99413	0.000488	0.94679	0.1168	2.1487	0.1355
Japan	1.83	0.1761	0.071559	2.20E-16	0.8742	0.001453	76.317	4.62E-12
Mexico	3.6739	0.05527	0.079884	2.20E-16	0.84207	0.0002806	6.0757	0.006433
Russia	0.035599	0.8503	1.2258	0.006195	0.64657	1.51E-07	2.1158	0.1394
S Arabia	0.51223	0.4742	0.2344	8.63E-14	0.97688	0.7051	11.443	0.0002332
S Africa	0.022901	0.8797	0.19804	5.30E-15	0.64358	1.38E-07	3.2278	0.05477
Turkey	0.41703	0.5184	0.096151	2.20E-16	0.91044	0.01154	68.895	1.54E-11
Ukraine	9.0391	0.002643	0.051192	2.20E-16	0.90147	0.006751	6.6187	0.004427
UK	9.0391	0.002643	0.051192	2.20E-16	0.90147	0.006751	6.6187	0.004427
USA	9.7115	0.001831	2.7662	0.9816	0.6517	1.78E-07	44.188	2.18E-09
Thailande	0.033575	0.8546	0.14113	2.20E-16	0.95117	0.1556	8.5657	0.001252
Poland	1.8753	0.1709	0.10855	2.20E-16	0.87357	0.001405	31.596	6.62E-08
Vietnam	0.51223	0.4742	0.2344	8.63E-14	0.97688	0.7051	11.443	0.0002332

Note: Table presents results and values of robustness tests. * , **, *** denote

Overall robustness tests show possible issues of endogeneity (omitted variable bias), small sample bias and autocorrelation of residuals. Cohen et al. (2018, 2022) address endogeneity by using Instrumental Variables approach with lagged GDP and lagged growth rate of the main trading partners as instruments and find close enough estimates to OLS. However, this exercise does not answer concerns on the small sample and autocorrelation is not addressed in the original study. As an additional robustness check, Dynamic Ordinary Least Squares (DOLS) are used to re-estimate the main results from this paper. DOLS has been used commonly in the literature (Dogan and Seker, 2016; Zhang et al., 2017) and has several advantages in that it accounts for possible issues of endogeneity, small sample size and potential non-stationarity of the variables. To account for autocorrelation, the Newey-West HAC standard errors for the estimated DOLS coefficients are computed. Results for trend elasticity estimation are presented in Table 6.6.

Table 6.6: Trend elasticities using DOLS estimation

Robustness Country	β^T	P Value
Australia	0.258	***
Brazil	0.789	***
Canada	0.257	***
China	0.307	***
France	0.187	***
Germany	0.207	***
India	0.808	***
Indonesia	-0.078	***
Iran	0.589	***
Italy	0.206	***
Japan	0.226	***
Mexico	0.148	***
Poland	0.176	***
Russia	0.791	***
S Arabia	0.467	***
S Africa	0.219	***
S Korea	0.257	***
Thailande	0.321	***
Turkey	0.103	***
Ukraine	0.181	***
UK	0.181	***
USA	0.12	***
Vietnam	0.467	***
World	0.23	***

Note: Table presents results of trend elasticities (CBA) using DOLS. * , **, *** denote statistical significance at the 10, 5 and 1 percent levels respectively.

Table 6.6 shows results of trend elasticities coefficients using DOLS estimator and consumption based CO2 emissions. First it is noteworthy that all countries' coefficients are statistically significant using DOLS, which was not the case for Italy and Ukraine in all previous estimations. Then, some countries' estimates remain close to the OLS coefficients. For example, Australia's trend elasticity is 0.23 using OLS and 0.25 using DOLS but more significant. The same goes for South Africa for which the OSL and DOLS coefficients are identical (0.20-0.21). Similar conclusions can be drawn for China, Poland, African and Ukraine, for which the coefficient variation is less than 0.2 from using DOLS. On the other hand, results are drastically different for some countries. Results for Brazil, France, Germany, Indonesia and the UK show coefficients higher than 1 for countries which showed signs of absolute decoupling in previous estimations. This is even extended to Saudi Arabia which, according to the DOLS estimate, shows signs of relative decoupling. However, those results are not contradicting with the conclusions reached in Chapter 5. In other words, although the results are not robust to the estimation method employed, the conclusions drawn in Chapter 5 still show weak evidence of decoupling. For instance, France's trend elasticity is -0.9 using OLS and 0.18 using DOLS. Although coefficients have a 1 point difference, the country still shows evidence of relative decoupling using the DOLS estimation method. In the same way the US has a -0.4 estimate using OLS but a 0.12 elasticity using DOLS. Although results are significantly different, the country still approaches dumpling. This conclusion can be extended to other countries as well and overall, results show weaker signs of decoupling than concluded in Chapter 5 with no countries having negative coefficients. At the world level, results from DOLS estimation show a very different coefficient, as for the individual countries. The estimated elasticity is 0.23 using DOLS and 0.69 using OLS. Both results are statistically significant. The DOLS elasticity coefficient suggests signs of relative decoupling compared to the OLS one. This also aligns with the inverted N-shaped found for the Environmental Kuznets Curve of the aggregated time series. Results are also presented in Table 6.6.

Conclusion

This thesis studies the long run decoupling of CO2 emissions per capita and real GDP per capita on a panel of 23 countries which are the top emitters in the world as of 2021. We base our work off of the approach developed by Cohen et al. (2017, 2018, 2022) which consists in decomposing variables into their trend and cycle component using the HP filter to estimate long run Kuznets elasticities and short run Okun elasticities.

In the first part of this thesis we estimate elasticities in three different ways. First, the emissions-output elasticity is estimated, as is usually done in the literature and without decomposing the variables. Then, the Hodrick-Prescott filter is applied to decompose GDP and CO2 emissions into their trend and cycle components. From there cycle and trend elasticities are estimated using OLS. A strong linking of CO2 cycles and GDP cycles is found, showing procyclicality of emissions. In accordance with previous studies, results show a cyclical elasticity of 0.9 for cycle elasticities on average. On the other hand, Kuznets elasticities are very heterogeneous and paint a different picture. Average trend elasticity using production based emissions is 0.32 and 0.42 for trend elasticity using consumption based emission. According to long term elasticities some countries have achieved relative decoupling and others absolute decoupling. Results differed greatly compared to the preliminary regression using variables without extracting their trend and cycle component, suggesting the relevance of accounting for short term variations in emissions due to changes in the business cycle. Those results are also more encouraging than that of Cohen et al. (2018, 2022), suggesting further progress towards delinking of economic growth and emissions. Comparing the trend elasticities between production and consumption based emissions, this thesis also sheds contradicting light on the Pollution Haven Hypothesis. Consumption based emissions elasticities are higher than production based elasticities for some developed countries, showing the role of international trade and displacement effect of pollution intensive industries to lower income countries. However, this result is not confirmed for all countries and would need further investigation.

In the second part of this thesis, we extended our work by examining the Environmental Kuznets curve model and global level models. The Environmental Kuznets Curve presented mixed findings, sometimes in accordance with previous results, sometimes in contradiction with mentioned elasticities. However, all countries which validated the Environmental Kuznets Curve hypothesis also had negative trend elasticities and showed evidence of absolute decoupling in the previous estimations. For those countries specifically, there is strong evidence of emissions-output decoupling and even robustness to the specification of the function. The literature on the Environmental Kuznets Curve shows mixed results. Thus our results were in accordance with some studies (especially close to Ang (2007) for instance) but not with others. The turning points found for the countries which validated the EKC were also realistic and within the maximum GDP of the sample. Lastly, including additional variables had little impact on the elasticity estimates but improved the model's fit. Finally, decoupling was estimated at the global scale using panel data analysis and global aggregated data. Results for panel data estimations showed very little evidence of decoupling, including when specifying the Environmental Kuznets Curve. On the other hand, aggregated time series showed an inverted N-shape of emissions as a function of income and an elasticity coefficient of 0.69, much closer to decoupling.

However, this thesis is still exposed to limitations. After accounting for sample sensitivity by estimating elasticities on a subsample from 1990 to 2015, results confirmed that countries are on the path to low carbon transition and suggested an increase in decoupling between 2015 and 2021. Robustness tests on the estimation of trend consumption based elasticities showed issues of possible endogeneity and omitted variable bias and autocorrelation of the residuals, in addition to small sample size. Estimations using Dynamic Ordinary Least Squares with HAC correction showed different results than from the OLS regressions. Differences in coefficients range from 0.2 to almost 1 but using the DOLS estimator improved the significance of the results. Although the coefficients estimated using the robust method are significantly different from OLS, the same conclusion on decoupling can still be reached. Thus, the results presented in Chapter 5 are robust but weak.

Overall, this thesis estimated long term and short term emission-output elasticity for the world's top 23 emitters and showed that decoupling (absolute and relative) is possible and has been achieved in some countries. This result is especially relevant in a context of debate on the scope and the extent of environmental policies but also on whether infinite growth can be sustained within the context of the efforts made. Finally, this thesis does not mean policy implications. On the contrary the EKC is very criticized and decoupling is a complex topic which is not robust to estimation methods and parameters of the model. This is especially relevant as environmental agencies, governments and international organizations are still raising the alarm around the next climate target and whether the world will manage to reach it in time. In other words, while those results are quite encouraging, another question remains unanswered as to whether the decoupling achieved is fast enough to avoid extreme case scenarios. As mentioned in the theory of Green Growth, decoupling can be recoupled and rebound effects, which are the object of another literature, do exist. Rebound effects could explain for example why decoupling is not observed at the global scale using panel data, meaning that although decoupling exists in some countries, there are other driving forces that balance out the decoupling achieved in countries. Such conclusions are worth investigating and suggest that further research look more in depth into the impact of country specific variables.

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