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Exploring Renewable Energy Adoption in the OECD: An Observational Panel Data Analysis of the Energy Mix Dynamics

Sindre Finstad Næss

Renan França Fernandes Sa

Submitted in partial fulfillment of the requirements for Master of Science in Sustainable Finance

Supervisor: Assistant Professor Tatyana Marchuk

Department of Finance

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Contents

Abstract

This thesis aims to develop understanding of the determinants of the energy transition by employing panel data analysis of 37 OECD countries over the time period 1990 to 2020. To control for unobserved heterogeneity, we utilize a fixed effects model in analysis of this dataset. To provide a robust analysis, we correct for identified violations of the OLS assumptions. Furthermore, we provide a critical review of how a difference-in-differences study design would be useful in our context, and how it would be infeasible with our data given the underlying assumptions. We challenge the existing literature by applying the renewable energy share of the total energy supply as our dependent variable. Unlike in the existing literature, which tend to deploy renewable consumption in isolation from the total energy mix, we do not find a link between GDP per capita and the energy mix development. As a step to achieve stationary variables, we perform growth transformation of all continuous, non-dummy variables. We find the share of renewable energy to have a significant and positive relationship to EU Emissions Trading System membership, Brent Crude oil price, population, and renewable energy per capita. The EU Emissions Trading System sees the greatest magnitude in our model, and aligns with presented theory about international climate agreements. The Brent Crude oil price's positive and significant relationship with the dependent variable also suggest that the substitution theory holds true for the energy markets in our sample. A negative and significant relationship is found between the dependent variable and the total energy supply, as well as industrial activity levels. No significance is found in the volatility of the Brent Crude oil price.

Acknowledgements

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Acronyms

DiD Difference-In-Differences

EKC The Environmental Kuznets Curve

EU ETS European Union’s Emissions Trading System

FE Fixed Effects

IPCC Intergovernmental Panel on Climate Change

OECD Organisation for Economic Co-operation and Development

OLS Ordinary Least Square

OPEC Organisation of the Petroleum Exporting Countries

RE Renewable Energy

NGO Non-Governmental Organization

1 Introduction

An inaugural part of human development is the consumption energy. Whether it is thermal energy from a bonfire, combustion from driving your car to a destination, or electricity running the lights in your office, some form of energy is being used. While human activity was sustainable for centuries, the industrial revolution was a turning point. Starting late 18th century in Britain, this marked the beginning of human activity that shifted the trajectory towards energy use that could not be sustained over time without depleting our natural resources. Fuelled by coal and eventually oil, the steam engine was a significant catalyst for human economic progress. The industries of metallurgy, textiles, chemicals, and transportation reaped substantial advantages from the utilization of coal as an energy source. The revolution quickly spread throughout Europe and the US and later throughout all the world. While this turning point indisputably advanced global progress, it also subtly introduced a perilous by-product - global warming - attributed to the substantial carbon dioxide (CO2) emissions released into the atmosphere by the use of fossil fuels to generate power.

The problem of global warming continues to this day, but to a far greater extent and with more severe consequences than previously thought. The 2022 report from the Intergovernmental Panel on Climate Change (IPCC, 2022) indicates that global warming will cause significant biodiversity loss, infrastructure damage, climate-induced migrations, and food production deficits, among other repercussions. Consequently, a broad array of stakeholders - governments, corporations, institutions, and NGOs - are endeavoring to mitigate global warming, with the aim to prevent it from reaching a point of no return.

The challenges posed by fossil fuel consumption extend beyond atmospheric degradation; resource scarcity is also a significant concern. Global stocks of coal and petroleum, while seemingly abundant, are not inexhaustible. In fact, according to a report from the United Nations (2022), our rate of fossil fuel usage significantly surpasses their natural replenishment. This unsustainable dynamic underscores the need for a shift towards renewable energy resources.

Equinor, the energy company with which we are collaboratively conducting a thesis internship, is deeply invested in this field. They have set a goal of directing 50% of their gross capital expenditure towards renewable energy and low-carbon solutions, aspiring to achieve net-zero carbon emissions by 2050 (Equinor, 2023). Given these shared interests, we have initiated this thesis paper to identify the factors propelling the shift from high-carbon to low-carbon energy sources, gauge their impacts, and pinpoint any factors that are not significant. The centerpiece of our research is the renewable energy consumption as a percentage share of the total energy supply of OECD member countries.

To understand the energy transition, we review relevant existing literature and relevant economic theories, informing our research direction and building upon previous discoveries. Furthermore, we use panel data to estimate fixed effects models, enabling us to statistically analyze the interactions between independent variables and the renewable energy share. We explore the impact of lagged variables in the regression. Notably, we also incorporated other novel elements into our analysis such as the industrial production index, total energy supply, oil price volatility, and the EU Emissions Trading System (EU ETS).

This thesis finds significant relationships between the renewable energy share of the total energy supply and several factors. Most notably, membership in the EU ETS significantly and positively impacts the share of renewable energy. This result aligns with theoretical expectations about international climate agreements. Furthermore, we find that the Brent Crude oil price, population size, and renewable energy per capita have positive relationships with the share of renewable energy. On the contrary, total energy supply and industrial activity levels are found to have a negative relationship with the share of renewable energy. We do not find any significant link between the GDP per capita and the share of renewable energy, contrary to common results the existing literature. The volatility of the Brent Crude oil price does not show significant impacts on the renewable energy share in our analysis.

This thesis is organised in the following structure. Chapter 2 reviews the relevant academic literature on renewable energy. Chapter 3 presents the theory used to better understand our research context and variable selection. Chapter 4 presents and discusses all variables used in the analysis. Chapter 5 presents the methodology of the thesis. Chapter 6 contains our results, a discussion of the results, and also a comparison to the existing literature. Finally, Chapter 7 concludes the thesis with a brief summary and some reflections.

2 Literature Review

While other research fields in finance and economics such as labor economics and financial economics have a well-established history of research going back many decades, if not centuries, the concept of sustainability in economics have gained prominence over the recent couple of decades. In this section, we present a selection of relevant papers about renewable energy that are relevant to- and guide our research, focusing on variables and results.

2.1 Sadorsky (2009a)

In a paper by Sadorsky (2009a), he examines the relationship between income growth and renewable energy use in emerging economies. The paper uses annual data on 18 emerging economies in the period from 1994 to 2003. He applies two empirical models and finds that as real per capita income grows, per capita consumption of renewable energy also increases. Sadorsky's models reveal that a 1% increase in real income per capita can result in a roughly 3.5% increase in renewable energy consumption. He also finds the long-term renewable energy consumption price elasticity to be around 0.70, indicating that the demand for renewable energy is elastic in the long run. These findings indicate a positive link between economic development and renewable energy adoption in emerging markets.

The paper is noteworthy because it shows how economic growth in developing economies can potentially promote renewable energy use. While this is a significant finding, it is also important to mention that Sadorsky's study mainly focuses on income, overlooking other influential factors like policy incentives, socio-cultural aspects, and technology advancements that might also affect renewable energy consumption. However, Sadorsky's evidence brought us to the conclusion that a per capita GDP variable would pose as a variable with great insight if found significant in our model.

Contrary to the panel cointegration methods used in Sadorsky's paper, we estimate a fixed effects model in this thesis. Despite these methodological differences, Sadorsky's work remains a valuable reference. However, given our focus on OECD countries and a different time span, we should remain open to the possibility that our results might reveal different relationships between income growth and renewable energy consumption.

2.2 Sadorsky (2009b)

In another paper published earlier the same year by Sadorsky (2009b), he explores the dynamics of renewable energy consumption, but in a different way than the former paper introduced. More specifically, this paper examines the relationship between renewable energy consumption, CO2 emissions, and oil prices within the context of the G7 countries.

In his analysis, Sadorsky reveals a mostly positive and significant relationship between CO2 emissions and renewable energy consumption. The oil price's relationship with the renewable energy consumption is inconclusive in this paper, having mixed results with positive and negative relationships and varying significance, depending on the country.

Sadorsky's focus on CO2 emissions and oil prices provides valuable insights about potential factors in our own model. His work motivates our decision to include a variable for oil prices in our model, as we hypothesize that these could be influential in OECD countries' renewable energy share due to substitution effects. Sadorsky had a similar hypothesis about the oil price's relationship with the dependent variable, and despite the lack of general significance in the paper, the different sample of countries in our thesis might yield different results.

Despite Sadorsky's clear results on the relationship between CO2 emissions and renewable energy consumption, we decide against including CO2 emissions in our model. Our rationale for this exclusion is based on our assumption that CO2 emissions, rather than being a driving factor, are more likely a consequence of a country's energy mix.

Moreover, including CO2 emissions in our model might also overlap with other variables that indirectly account for emissions, such as the total energy supply and oil prices. This could potentially lead to multicollinearity, potentially complicating the interpretation of our model's results.

To conclude, while this paper by Sadorsky contributes valuable insights about the G7 countries, we are cautiously inspired by the variable selection and opt to only include an oil price variable, while excluding CO2 emissions.

2.3 Apergis & Payne (2014)

A paper by Apergis & Payne (2014) further explores the dynamics between renewable energy consumption, economic growth, carbon emissions, and oil prices. Their study, employing a dataset on 25 OECD countries from 1980 to 2011, further highlights the relationship between these variables.

Through the use of second-generation panel unit root tests, panel cointegration and error correction modelling, the authors find that a long-run relationship exists between per capita renewable energy consumption, real GDP per capita, carbon dioxide emissions per capita, and real oil prices. They find that a 1% increase in real GDP per capita, carbon dioxide emissions per capita, and real oil prices each result in respective increases in renewable energy consumption per capita by 0.345%, 0.352%, and 0.450%. In this particular paper, renewable energy consumption is represented by renewable electricity consumption, thereby excluding certain forms of energy consumption, perhaps most notably consumption in the transport sector.

These findings suggest that economic growth, CO2 emissions, and fluctuations in oil prices collectively influence the renewable energy consumption. Notably, the study also discovers a feedback relationship, where an increase in renewable energy consumption per capita tends to reduce carbon dioxide emissions and real oil prices in the short-run. It is particularly interesting that increases in renewable energy consumption conversely has a negative effect on oil prices, displaying strong evidence about price based substitution effects in energy consumption.

Apergis and Payne's research provides valuable insights for our study, especially when considering that our work also focuses on OECD countries. Their examination of the relationships between real GDP, CO2 emissions, and oil prices aligns with our variable selection. As previously mentioned, we have chosen not to include CO2 emissions in our model, assuming it to be a consequence, not a driver, of a country's energy mix.

2.4 Nguyen & Kakinaka (2019)

In a study by Nguyen & Kakinaka (2019), the authors examine the association between renewable energy consumption, carbon emissions, and a country's stage of development. The authors apply a panel cointegration analysis to a data set comprising 107 countries from 1990 to 2013. Their research pinpoints distinct relationships among the variables, demonstrating that these relationships differ significantly between low- and high-income countries.

The design of their study makes use of the Environmental Kuznets Curve (EKC) hypothesis. The EKC postulates an inverted U-shape between environmental degredation and economic development (Grossman & Krueger 1995). Nguyen and Kakinaka's investigation of the relationships between renewable energy consumption, carbon emissions, and output across different income groups aligns with the EKC hypothesis and has inspired our adoption of the EKC in our own research. The authors decision of dividing the countries into low-, middle- and high-income countries makes use of different samples that fit the different stages of the EKC.

For low-income countries, the authors found that renewable energy consumption is positively associated with carbon emissions and negatively associated with economic output. In contrast, for high-income countries, which our study focuses on (OECD countries specifically), renewable energy consumption is negatively associated with carbon emissions and positively associated with economic output. These results support the EKC hypothesis and underscore the differing priorities at various development stages.

Furthermore, Nguyen and Kakinaka's policy implications informed our decision to include the EU ETS in our study. They suggested that less developed countries should adopt effective and timely energy policies to shift from non-renewable to renewable energy sources. For high-income countries, they advocate the use of regulatory measures related to renewable energy production and consumption, such as quota policies, feed-in-tariff policies, and subsidies policies.

In conclusion, Nguyen and Kakinaka's research provides significant insights into the dynamics between renewable energy consumption, carbon emissions, and economic development. Their research is particularly useful in utilizing the EKC hypothesis, one which they are able to confirm with their empirical approach and sample split in three development stage categories. Their findings, especially regarding high-income countries, are directly applicable to our study. The fact that the sample countries comprising the high-income countries in this study reflect our own sample to a high degree, we are ultimately inspired to use wealth levels in our model and examine whether we can confirm that the EKC holds true in conjunction with other predictors.

2.5 Concluding Remarks

The studies discussed are part of the growing literature on renewable energy consumption. Together, they provide valuable insights into the factors that influence renewable energy use, including economic development, oil prices, and policy measures. However, we refrain from using carbon dioxide emissions as a determinant of renewable energy consumption. In our view, as a country's overall energy supply expands, CO2 emissions should be seen more as a by-product rather than a determinant, which guides our model's variable selection. In addition to this, the authors applying CO2 as a predictor use advanced models, and we cannot reliably incorporate- and argue in favor of a CO2 variable in our fixed effects model setup. We also diverge from the existing literature by the use of the renewable energy share as the dependent variable. This is in part to differentiate our thesis from the existing literature, since renewable energy consumption at levels form is already applied across many articles.

In conclusion, the literature has provided us with a foundation for our research. It has not only informed our selection of variables, but also helped us to shape the theoretical concepts and frameworks in our own study, such as the substitution effect, the EKC, and policy implications.

3 Theory

This chapter outlines the main theories that lay the foundation for our research question, model selection, and variables of interest.

3.1 The Free Rider Problem

The free rider problem, first detailed by Mancur (1965), highlights the problems in international climate agreements such as the Paris Agreement and the European Union's Emission Trading System (EU ETS). This economic concept highlights situations where individuals exploit resources or goods without contributing to their production or upkeep. In the context of climate change, Nordhaus (2015) further elaborates on this issue, suggesting that ”climate clubs” could alleviate the challenges posed by free riding. Nordhaus' concept of ”climate clubs” base itself on the principle of mutually beneficial cooperation with disincentives for non-compliance.

This collective action aims to reduce the free rider problem by making participation in emission reduction efforts more attractive and non-participation economically unattractive. Under such an arrangement, countries that fail to meet their emission reduction commitments or opt not to participate in the climate club will face trade sanctions or tariffs, thus providing a compelling economic incentive to actively mitigate climate change.

Examining the perspectives of Mancur and Nordhaus, we can hypothesize that the EU ETS, integrated within each member country's legislation and overseen by a governmental body with legislative power, could potentially exert a significantly stronger influence compared to other international agreements. The Kyoto Protocol, though ”legally binding,” falls short when considering the concept of sovereignty and the fact that nations can withdraw at any moment without immediate penalties.

Hence, the EU ETS can be perceived as a response to the slow pace of global climate action. Its creation indicates a realization that environmental altruism among countries might not be as robust as initially anticipated. Thus, in an era where ”legally binding” climate agreements may seem to contradict the principle of sovereignty, the EU ETS stands as an attempt to steer through these challenges, seeking a balance between the sovereignty of nations and the collective responsibility towards climate action. By doing so, the EU ETS aims to ensure that international efforts to combat climate change are not merely symbolic but effective and substantial.

3.2 Externalities

Externalities, a key concept in economics, refers to the unintentional side effects of an activity that impact third parties who are not directly involved in that activity. This concept was initially articulated by in Arthur C. Pigou in his work Pigou (1920). Externalities can be either positive, where the third party gains a benefit, or negative, where the third party incurs a cost.

In the context of our research, environmental externalities, especially negative ones, bear particular relevance. Negative externalities occur when the social or economic activities of one group have an adverse impact on another group. The classic example is pollution, where the actions of a polluter impose costs on others in society, such as health problems and degradation of natural resources.

Climate change is arguably the most significant negative externality facing the world today. Activities that contribute to greenhouse gas emissions impose severe costs on society, yet these costs are not necessarily carried by the polluters themselves. For both countries and companies, pollution is often linked to increases in wealth or revenue through the use of cheaper input factors, despite of them emitting greenhouse gases. As the collective emissions of all market participants grow, the marginal benefit of pollution (e.g., wealth increase) will eventually be outweighed by the marginal cost incurred through negative externalities. In essence, emitters are not bearing the full societal cost of their actions, contributing to excess emissions.

However, while the literature commonly uses carbon dioxide emissions as a predictor variable for renewable energy consumption, we take a more critical stance. CO2 emissions are intimately tied to energy consumption, yet they represent a consequence rather than a driving factor in the dynamics of the outcome. It is not necessarily the case that high CO2 emissions would directly spur renewable energy consumption. Instead, such emissions could merely reflect the energy landscape and regulatory frameworks of a particular region or period.

For these reasons, we do not to include CO2 emissions in our study. Our focus instead is on investigating the policy instruments and other factors that more directly influence renewable energy consumption. This approach provides a clearer picture of the underlying mechanisms and helps to avoid the potential misinterpretations that might arise when CO2 emissions are used as a predictor variable.

3.3 Theory of Comparative Advantage

The theory of comparative advantage, developed by Ricardo (1817), is another key concept in economics. It proposes that nations should specialize in producing and exporting goods or services where they have a lower opportunity cost compared to other countries. Through this specialization, overall efficiency increases and nations mutually benefit from trade, even if one country has an absolute advantage.

With regards to climate change and renewable energy, the theory of comparative advantage suggests nations should concentrate on developing and implementing renewable energy technologies where they have a natural or technological advantage. These advantages could stem from various sources, such as geographical features favorable for certain types of renewable energy (e.g., solar power in regions with high sunlight exposure or wind power in windy areas), or advanced technological capabilities that enable efficient production of renewable energy technologies.

Conversely, countries with abundant fossil fuel resources may find their comparative advantage lies in the continued extraction and use of these fuels. The established infrastructure, employment, and immediate economic benefits offered by these resources could potentially outbalance the perceived benefits of renewable energy development in the short term. Such countries may be slower to transition to renewable sources of energy, given the higher opportunity cost compared to countries less endowed with fossil fuels.

However, Gosens (2017) challenges this perspective, arguing that natural resource endowment may not be a strong driver of renewable energy development, particularly for power generation from wind and solar photovoltaic. His findings suggest that other factors, including policy incentives and technological innovations, might be more significant in influencing renewable energy development.

In our research, we take these complexities into account. While renewable energy potential could explain some variations in renewable energy consumption, policy variables like participation in the EU ETS reflect the non-market mechanisms crucial for renewable energy development.

3.4 The Substitution Effect

The concept of the substitution effect, originally formalized by Hicks (1939), stems from consumer choice theory in economics. It describes how the consumption patterns of individuals or firms changes in response to relative price fluctuations of goods or services. The substitution effect says that consumers will buy more of a good that has become cheaper compared to a comparable good, replacing the goods that have become relatively more expensive. The theory states that the aim is to maintain the same level of utility while minimizing costs (Hicks, 1939; Varian, 2014, p.164).

The substitution effect might be able to explain potential changes in energy use patterns. As the relative prices of various energy sources fluctuate, the substitution effect would predict that countries, industries, or households will adjust their energy consumption patterns accordingly, favouring the cheaper energy source. This would suggest a shift in energy mix towards a relatively cheaper source.

Applying this concept to renewable energy adoption is straightforward. As the costs of renewable energy technologies decrease, these forms of energy become more economically attractive. The same holds true for price increases in traditional fossil fuel based energy. This can stimulate a substitution away from carbon-intensive energy sources towards renewable sources. The substitution effect gives us a general idea of how me might predict the relationship between renewable energy and the pricing of fossil fuels, such as oil.

3.5 The Environmental Kuznets Curve

In the 1950's, economist Kuznets hypothesised an inverted "U" shape relation between economic inequality and income per capita, called Kuznets Curve (Kuznets, 1955). Kuznets's work states that countries with an increasing migration from rural areas to cities tend to have an increasing economic inequality due to the social mobility and competition for wages. However, as an economy turns modern and industrialised, a welfare state is reached and further development leads to decreasing inequality Nielsen (1997).

Grossman & Krueger (1995) reconfigured the Kuznets Curve to form the Environmental Kuznets Curve (EKC). Unlike the original Kuznets Curve, which plots economic inequality against income per capita, the EKC measures Environmental Degradation on the vertical axis. Figure 1 illustrates how Grossman & Krueger described the EKC.

The reason for this change, as explained by Grossman & Krueger, is to investigate the relationship between a country's economic development and the environmental impact it causes. The hypothesis behind the EKC is that as a nation's per capita income increases, environmental degradation first increases but then eventually decreases. The curve illustrates the notion that economic development initially leads to degradation of the environment, but further growth results in increased resources, which can be used towards environmental improvements and more efficient technologies, thus decreasing environmental degradation.

It is important to mention that both KC and EKC have always been under criticism as both hypotheses fail to be an absolute truth among every country in the world, and the EKC's lack of statistical strength in existing literature and is regarded as a theoretical phenomenon (Stern, 2004). However, Nguyen & Kakinaka (2019) was able to confirm the EKC hypothesis as previously discussed.

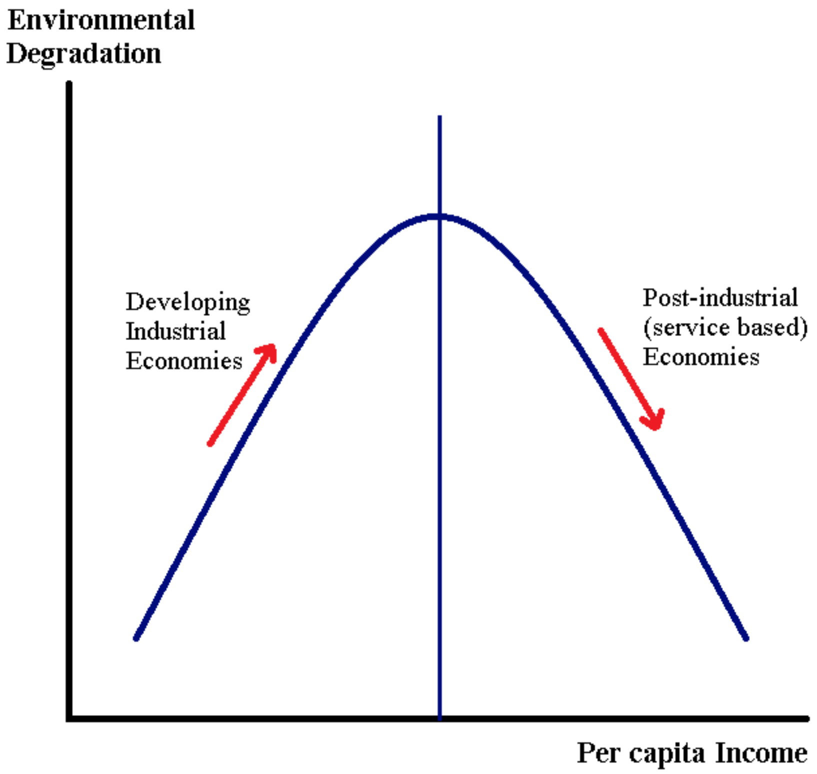

Figure 1: Environmental Kuznets Curve

For this paper, we do know if we will see the full effect of the EKC since our sample period span 30 years and the OECD members might have moved from one development stage to another during this period. However, the EKC is still important since it guides variable selection in the existing literature, and provides an interesting theoretical overview of the relation between wealth and environmental degradations.

4 Data and Variables

4.1 Countries and Periods

This paper deploys country-level data with annual frequency from 1990 to 2020. Our selection consists of OECD-member countries as per 2020, regardless of when the membership was ratified. In total there are 37 OECD countries in our selection, with only Costa Rica being omitted due to severe lack of available data on our parameters. 1990 to 2020 is chosen to capture the long-term dynamics of the energy transition, and also include a number of years prior to- and after major international climate action.

4.2 Variables

4.2.1 Renewable Energy as a Percentage of the Total Primary Energy Supply

This is the main variable of interest and will act as the dependent in our panel regression model. Several authors tend to apply renewable consumption measured in total per country or on a per capita level. We intend to rather use a ratio as our dependent variable. The justification for this is that we believe that this is a more ”true” measure of the energy transition. What is expected, as per the current literature, is a positive relationship with GDP per capita and renewable energy consumption, but we hypothesize that as overall demand for energy increases, renewables will naturally be a part of the expansion of the energy capacity in most countries. This is due to technological advancements, reduction in levelized cost of electricity (LCOE), and countries being relieved of the burden of fossil fuel extraction and imports which is subjected to market speculation. By taking the ratio to the total energy supply, we can get a true picture of how the energy transition has developed and the influencing factors. An increase in renewable sources as a share of the total energy supply would simply indicate that the energy mix has shifted in favor of green energy. The variable is retrieved from OECD’s data website (OECD, 2023a).

4.2.2 Total Primary Energy Supply

When considering our dependent variable, we wanted to find a variable that captures the increase in overall energy consumption in a country. By selecting this variable, we can study how relative changes in the total energy supply can influence the energy mix in a positive or negative way. If we find a significant relationship between the dependent and the total energy supply, the sign of the coefficient will tell us whether increases in the energy supply is are mainly attributed renewables or non-renewables, and thus if countries in OECD grow their economies using a larger or smaller proportion of green energy. Total primary energy supply is measured in million tonnes of oil equivalents and is calculated by OECD using the following formula:

$$TPES = Production + Imports - Exports - InternationalBunkers \pm StockChanges$$

The variable is retrieved from OECD’s data website (OECD, 2023b).

4.2.3 Renewables per Capita (kWh)

Renewable energy per capita measured in kilowatt hours (kWh) is one of the independent variables. We anticipate that the growth of renewable energy measured in kWh to have a positive and significant relationship with the ratio of renewables to the total energy supply, since increased renewables capacity indeed is important for transitioning to a greener energy mix. The variable is retrieved from British Petroleum's (BP) Statistical Review of World Energy in 2021 (British Petroleum, 2021).

4.2.4 Industrial Production Index

The industrial production index is a measure of industrial activity. Manufacturing, construction and transport are sectors that demand huge amounts of energy. By taking the industrial production as an index number with base year 2015 = 100, we can use industrial activity levels to proxy energy demand from each country's industrial sectors and examine how their demand can swing the energy mix in either direction. Assuming industrial agents are rational and competing for profits, we hypothesize that the industry prioritizes availability of energy, in tandem with utilization of existing energy infrastructure, instead of the carbon footprint of the source. We include this in addition to GDP per capita due to the industrial production index proxying energy demand as per economic activity, while GDP per capita would capture wealth-to-abatement as hypothesized by the EKC. The industrial production index variable is retrieved from OECD's statistical website (OECD, 2023c).

4.2.5 GDP per Capita

As mentioned previously, the literature is adamant about the effect that GDP levels have on the consumption of renewable energy. In our context, using a different dependent variable, we are less certain about the effect that GDP per capita will have. Nevertheless, GDP per capita is a strong indication of wealth and we hypothesize a positive and significant relationship with our dependent variable since we believe that wealthier countries are more likely to afford climate-action and abatement measures when expanding their energy capacity. This also ties to the EKC, and our country selection mainly belongs to the middle and right hand section of the curve due to their economic homogeneity. We apply the per capita variable rather than overall GDP of each country since we expect wealth levels to be a significant determinant of the energy mix. GDP per capita, rather than total GDP, would be the best choice in our context if we consider theory about rationality and consequently abatement being a ”luxury” rather than a necessity.

Upon initial inspection of the variable, we could not find any clear patterns between GDP per capita and renewable energy as a percentage of total energy supply. Figure 2 illustrates the relationship between the two variables for the last-year observation only.

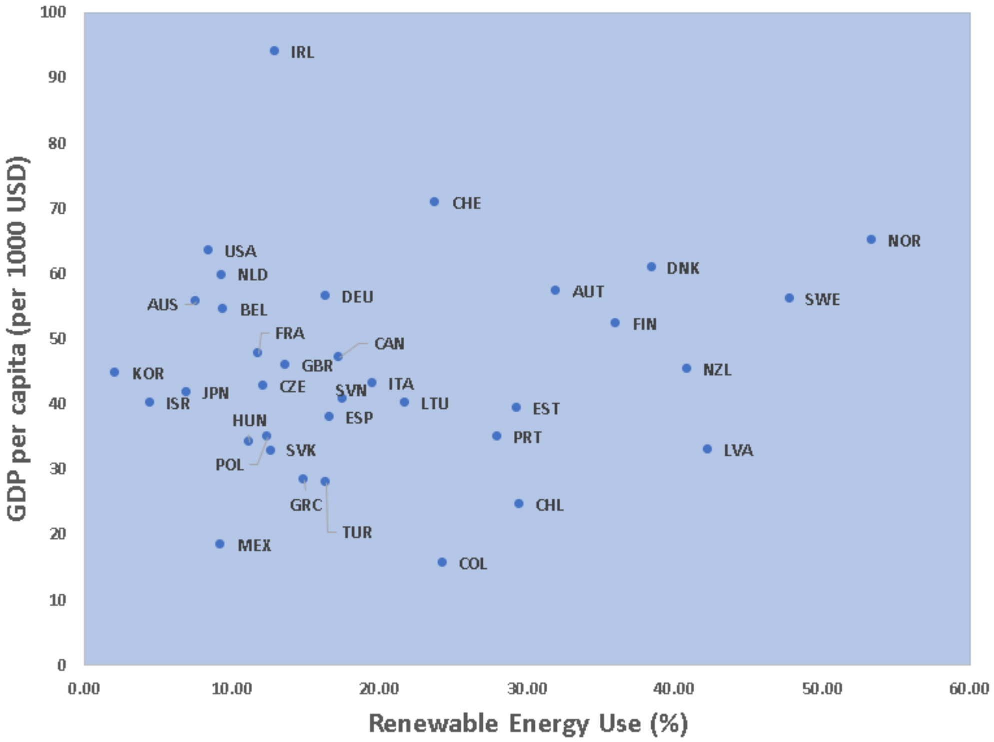

Figure 2: Scatter Plot Showing the Relation Between GDP per Capita and Renewable Energy Use in 2020

The GDP per capita variable is measured in USD using current prices and current PPPs, and is retrieved from OECD’s statistical website (OECD, 2023d).

4.2.6 Population

Population serves as another independent variable in our analysis. This demographic variable is selected because of its natural connection to overall energy demand. While GDP per capita serves as a proxy for wealth and industrial production serves as a proxy for industrial activity, population is intended to capture the overall household energy demand. Ever since the industrial revolution began, energy needs have increased at speeds proportional to the population growth. Before the era of renewables, the growing energy demands would mostly be met using fossil fuels. However, technological advancements have made it so that population growth may be associated with an increase in the ratio of renewable energy to fossil fuels, if countries are able to deploy green energy at a faster rate than fossil fuels to meet the growing population's energy needs.

We anticipate that in the space of 1990 to 2020, population growth will have a significant effect on our dependent variable, but we are uncertain of what sign and magnitue this variable will have, as it is rarely deployed as a control variable in the existing literature. The population variable is denoted in millions of people, and is retrieved from OECD's statistical website (OECD, 2023e).

4.2.7 Brent Crude Oil Price

A key independent variable in our analysis is the price of Brent Crude. Oil Price variables are complex in general due to their importance in global trade. Oil is an energy commodity which can be converted to electrical energy, used for combustion, and is also a method of energy storage. However, oil prices are volatile as the commodity is not only highly useful, but is also subject to the market forces. Speculation in production and demand, geopolitical events, economic recessions, and OPEC+ control are some important determinants of oil price fluctuations.

In the context of our analysis, we believe oil prices to have a significant relationship with the energy mix. As oil prices increase, we believe that countries will shift their energy mix in favor of renewables, essentially acting as a price substitute for oil based energy, such as described by the substitution effect. However, due to unique properties of oil, such as the ability to store it, renewables are not a perfect substitute. This also holds true for the conversion of oil to thermal energy and combustion power, which renewables can not completely substitute for with today's technology and energy infrastructure. We also hypothesize that the relationship between oil and the energy mix may vary across countries due to differences in energy policy, renewable energy technology adoption, and fossil fuel endowment.

The theory of comparative advantage could also contribute to shaping countries' energy portfolios, in addition to potential substitution effects. For instance, as the price of oil increases, countries that export oil stand to benefit and may re-evaluate their strategies for developing renewable energy. This situation closely parallels a recent event in which British Petroleum (BP) announced plans to amplify its oil and gas exports, while simultaneously curbing its expansion into renewables (NY Times, 2023). The rise in oil price augments the comparative advantage for British exports. In contrast, oil-importing countries might respond to this situation by escalating their expansion of renewable capacity. Consequently, an increase in the oil price may not significantly impact the overall energy mix if the actions of exporters and importers balance each other out.

We select only this one fossil fuel variable for several reasons. First, we know that not all OECD countries use Brent Crude, as there are several global oil benchmarks that differs on location and physical properties. Despite this, oil price benchmarks have a long-run price equilibrium, suggesting that any benchmark would reflect the global oil price to a large degree (Hammoudeh, Ewing, Thompson, 2008). Secondly, there is evidence of cointegration between oil and gas prices, as shown through the work of Villar (2006).

Thus, we argue that the Brent Crude price alone will capture a significant portion of the information contained in both global oil benchmarks and natural gas prices. In addition to the above, IEA (2020) reports that oil and gas together accounted for approximately 64.6% of the total energy supply in OECD in 2020. Therefore, we believe that Brent Crude is a valuable variable that can contribute to a better understanding of how the broader fossil fuel pricing influences OECD countries' choices of switching to a greener energy mix.

Our specific variable is in nominal terms, USD, and Free-on-Board (FOB). FOB is simply the price after the production costs have been adjusted for costs related to preparing the oil for shipping or freighting. We use the last trading day closing price for each year, which should further help alleviate of price seasonality. The data is provided by the US Energy Information Administration (2023).

4.2.8 Brent Crude Oil Price Volatility

In relation to the pricing of oil, we examine how the volatility of said price also might have a significant relationship with the long term energy mix development in OECD. More specifically, we hypothesize that increases in the volatility of the oil price in previous periods is an element of uncertainty. Uncertainty in pricing can lead to unpredictability in energy supply, and we believe that countries will expand their renewable energy capacity to mitigate uncertainty if it has persisted over some time. There is no previous attempt in the literature to examine the relationship between fossil fuel price volatility and renewable energy production, or the energy mix for that matter.

Oil volatility is computed by finding the annualized standard deviation from daily observations of the Brent Crude oil price. The formula is as follows:

$$Vol_1y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{n}$$

where:

- n is the number of trading days in the year.
- x_i are the individual daily observations of price.
- $\bar{x}$ denotes the sample mean.

4.2.9 EU Emissions Trading System

In our study, we recognize the influence of market-based policies and interventions in shaping a country's energy mix. Building upon the theory of the free-rider problem and climate clubs in the context of climate abatement, we point to the relevance of policy instruments such as the European Union's Emissions Trading System (EU ETS). The EU ETS, operating as a compulsory ”climate club” with penalties for non-compliance, could significantly affect a country's renewable energy share. This system, based on a ”cap and trade” principle, limits emissions while allowing trade in emission allowances. Since the system's inception in 2005, the total cap allocation has been reduced yearly - another mechanism that is meant to facilitate the energy transition through predictable supply restrictions (European Commission).

To capture this policy variation across countries, we introduce a binary variable indicating EU ETS membership into our model. Specifically, this dummy variable takes on the value 1 for a given country-year if the country is a member of the EU ETS that year, and 0 otherwise. This inclusion allows us to discern differences between OECD countries that participate in the EU ETS and those that do not, thus enabling an evaluation of the system's potential influence on renewable energy share. Furthermore, our model accommodates variations in the timing of EU ETS membership, such as Iceland and Norway participating since 2008.

4.3 Frequency and Seasonality

One important factor that affected the decision of how to handle data was the frequency that each variable was available. Some variables of interest have daily frequency available, such as Brent oil price, and other variables have quarterly data, such as GDP per capita. However, in order to construct a panel data set, all data variables should be in the same frequency, thus the lowest frequency should be used in all variables. Since our dependent variable, renewable energy as a percentage of the total primary energy supply, is only available annually, alongside some of independent variables, we decided to use all variables in their annual frequency. Apart from this, applying annual observations is the norm in the existing literature.

Apart from this, having the variables in annual observations can eliminate seasonality in the data. Seasonality can often occur because of trade cycles trough the year, and we can often see patterns in the data that persists within each year. This is especially true for oil prices. Seasonality can lead to problems in the data, such as residual autocorrelation (Brooks, 2019, p. 577), so the availability being limited to annual is a compromise. On one hand, we get reduced seasonality, but on the other hand, we could potentially lose some information that is only visible having quarterly, monthly, or weekly observations.

4.4 Unit Root Tests

Unit root testing is an inaugural part of econometrics and time series analysis. A unit root in the context of time series implies that the series has some form of stochastic or random trend. In turn, this could mean that the series may drift away from its mean in upwards or downwards direction for prolonged periods of time. Thus, non-stationary time series, i.e. series with a unit root, is a problem in econometric analysis since it can give us unreliable estimations and spurious- results and relationships (Baltagi, 2013, p. 291).

Panel data contains both a cross-sectional and time series component, and will naturally be prone to problems related to both dimensions. A unit root in panel data could give us biased estimators in a regression model, since a core assumption of regression is that the error terms do not suffer from autocorrelation. The presence of a unit root indicates violation of this assumption, leading to spurious regression results (Brooks, 2008, p. 318-319). Our panel has a time series dimension of T = 31, and it is therefore important to test- and correct for unit roots in the data to ensure that the analysis of our results are valid and reliable.

Moreover, by taking the growth terms of our presented variables, we achieve stationarity in our data. In essence, we are differencing the time series component and taking the difference as percentage growth, represented by an integer. Differencing is a conventional way to remove the unit root and consequently detrend the series.

We use the Im-Pesaran-Shin (IPS) test (Im, Pesaran, Shin, 2003) and the Augmented Dickey-Fuller (ADF) test to respectively test for unit roots in panel data and individual time series. More specifically, we apply the IPS test to all variables where observations vary between the cross-sections, and apply the ADF test where the time series is independent of the cross-sectional unit, such as Brent Crude price and volatility.

Failure to reject the null hypothesis would suggest the presence of a unit root and hence a non-stationary process. The null and alternative hypothesis are equal for both IPS and ADF tests. We choose to apply equal differencing to all variables since intepretation is more straight forward if all variables are equal in their form. The results are displayed in Table 1, where ”T-statistic” refers to the achieved test statistic of respective tests and k represents the number of lags used for the particular test result.

Table 1 displays the IPS and ADF test results of all variables in their growth form. As we see, taking the variables in growth terms has detrended all variables, since we are well within the conventional significance values of 1% and 5% according to the obtained p-values.

Table 1: Unit Root Tests

	IPS			ADF		
Variables	T-statistic	P-value	k	T-statistic	P-value	k
Renewable %	-18.075	$< 2.2e-16$	0	–	–	–
Energy Supply	-26.299	$< 2.2e-16$	0	–	–	–
Renewable per Capita	-33.392	$< 2.2e-16$	0	–	–	–
Industrial	-21.624	$< 2.2e-16$	0	–	–	–
GDP per Capita	-20.275	$< 2.2e-16$	0	–	–	–
Population	-9.081	$< 2.2e-16$	0	–	–	–
Brent Crude Price	–	–	–	-4.147	0.0003	0
Brent Volatility	–	–	–	-5.993	$1.87E-06$	0

4.5 Summary statistics

The table 2 provides a summary of the variables used in our model, each of which has been transformed into growth rates, causing a shift in our panel from 1990-2020 to 1991-2020. The statistics show a substantial range in values, indicating a high degree of variability across our variables.

Our panel comprises 37 countries (N=37) observed over a period of 30 years (T=30) after differencing, resulting in a total of 1110 observations (n=1110). The panel is unbalanced due to missing observations, particularly for the early years of some countries. This is more pronounced for the less affluent countries in our sample, such as the Baltic states during the early 90s.

Nevertheless, missing data is a common issue in panel data studies and can be accommodated assuming these missing data points are not systematic in nature, as this could introduce bias. In our case, we have some level of systematic missing data; however, this potential issue is somewhat mitigated by the fact that we introduce some variables in twice lags. This way, despite some countries having missing early-year observations, all countries will have the same set of observations omitted for the pre-lags, ensuring a level of consistency in our analysis.

Table 2: Summary Statistics

Variable	Mean	Median	SD	Min	Max
Renewable %	4.354	2.754	12.348	-67.735	155.921
Energy Supply	0.525	0.587	5.061	-35.346	32.187
Renewable per Capita	7.358	4.256	23.167	-44.760	370.125
Industrial Production	2.144	2.167	5.765	-24.000	36.940
GDP per Capita	4.255	4.315	4.133	-23.288	35.100
Population	0.589	0.517	0.808	-2.541	6.199
Brent Crude Price	5.387	1.250	26.263	-47.135	60.112
Brent Volatility	23.615	-10.244	82.380	-74.822	220.433
EU ETS Membership	-	-	-	26 (Members)	11 (Non-members)
Panel details	n = 1110	N = 37	T = 30		
Balance	Unbalanced				

Note: all variables, except for EU ETS Membership, are presented in growth terms (in accordance with the steps executed for the unit root testing).

4.6 Data Visualization

4.6.1 Heterogeneity

The boxplot presented in Figure 3 illustrates the cross-sectional heterogeneity of the dependent variable before growth differencing, that is, renewable energy as a percentage of the total primary energy supply across different countries. The variability across different countries is evident from the boxplot, highlighting the diverse energy portfolios amongst the countries.

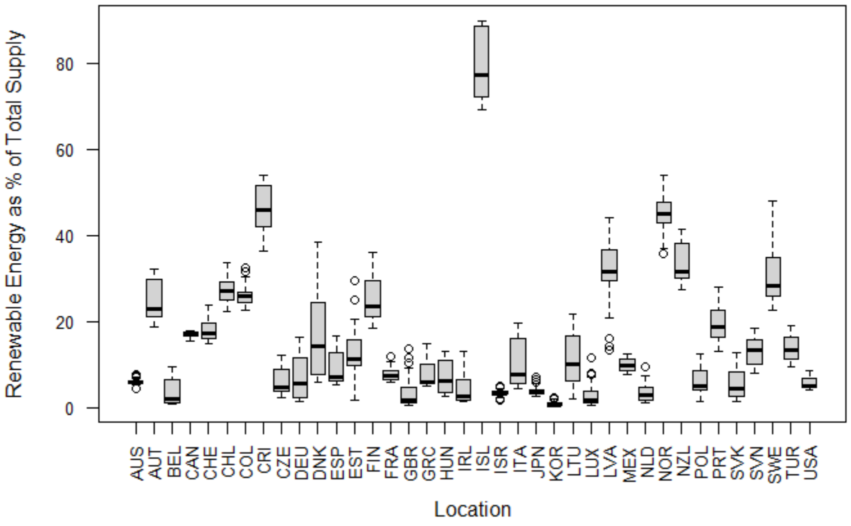

Figure 3: Boxplot of Renewable Energy Share as % of Total Supply by Location

Some countries display a high median value for renewable energy usage, indicating favor towards renewable energy sources in their energy mix. Conversely, others showcase lower median values, suggesting less reliance on renewables. Again, these unobserved characteristics can be credited to resource endowment, political will, technological advancement, or other factors. Furthermore, the box length, whiskers, and outliers in the boxplot, which represent the interquartile range, min-max range, and unusual values respectively, also vary substantially across countries. This further shows the degree of heterogeneity in the energy mix across the OECD countries.

These clear differences across countries underscore the relevance of using a fixed effects model for our analysis. Fixed effects models can control for this observed heterogeneity by allowing for country-specific effects, which are assumed to be constant over time but vary across countries. This means that the model takes into consideration the unique characteristics of each country that may affect renewable energy usage, thereby enhancing the robustness of our results.

4.6.2 Temporal Variation

Temporal variation within panel data refers to the changes of the variables over time. This type of variation is important to identify as it can impact the choice of model and its interpretation.

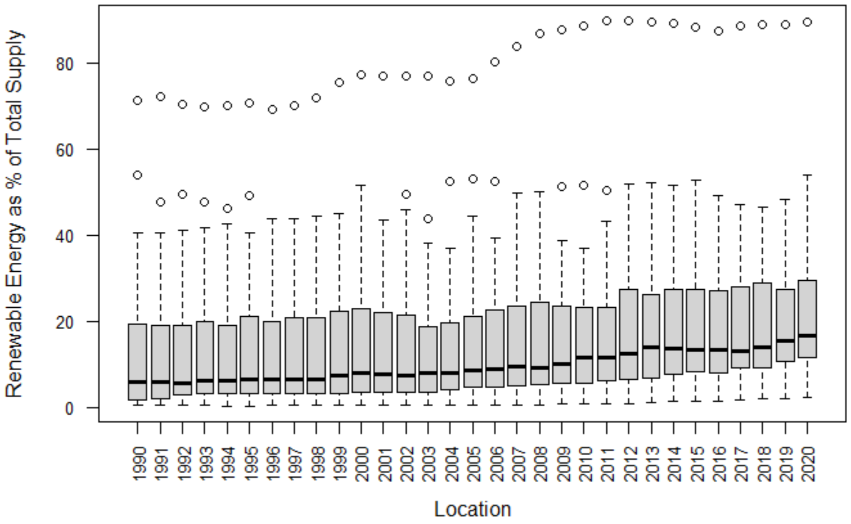

Figure 4: Boxplot of Renewable Energy Share as % of Total Supply over Time

Figure 4 presents the renewable energy share over time. The boxplot shows clear signs of a time trend, with an observable upward shift in the boxes over time. This time trend might suggest that the dependent variable increases over the years, demonstrating the existence of temporal variation.

In contrast, Figure 5 displays the growth-transformed dependent variable over time. Here, the upward trend appears to have been largely mitigated, with the plot showing much less variation. The position of the boxes and mean value over time appears with less variation compared to Figure 4. This suggests that the transformation to growth rates has effectively removed the visible time trend present in the original data.

This comparison illustrates the impact of transformation on the temporal properties of the data. The removal of the time trend in the growth-transformed data confirms our expectation about the usefulness of growth transformation in managing trends in panel data.

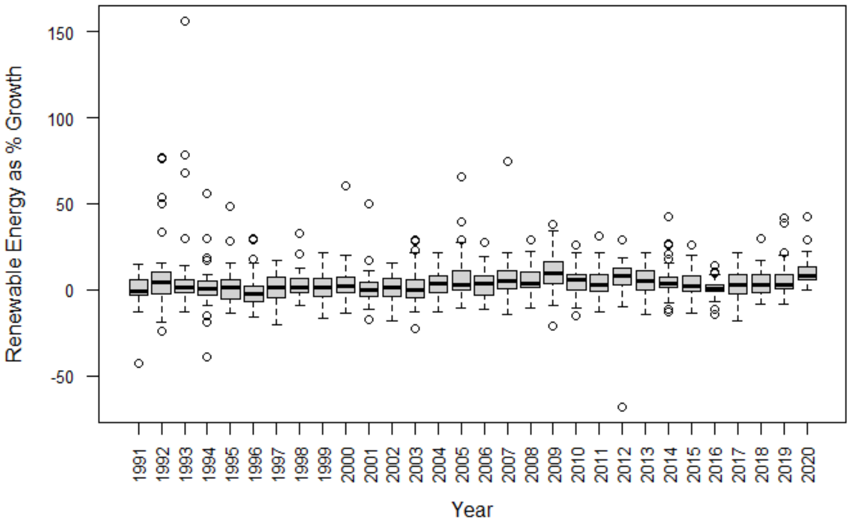

Figure 5: Boxplot of Renewable Energy Share as % of Total Supply over Time, Growth Transformed

5 Methodology

The methodology section outlines our pre-planned strategy for investigating our research question. This includes the description of the models we estimate, why these models are appropriate in our context, and also an outline of the assumptions of these models and how we test for- and deal with any violations of these assumptions.

5.1 Panel Data Regression

5.1.1 Heterogeneity

A key concept in panel data is heterogeneity. Heterogeneity refers to the difference in properties or characteristics between groups or individuals. Panel data often includes individuals or entities that are vastly different with regards to certain characteristics (Baltagi, 2013, p. 6). These characteristics may vary over time and are not observable.

5.1.2 The Fixed Effects Model

The three primary models in panel data regression: pooled OLS, random effects, and fixed effects. Their respective applications depends on the data at hand and the research question.

1. Pooled OLS: The pooled OLS panel model ignores the time-series nature of the data and treat is as a simple cross-section. This model is only applied when we are certain that there are no individual-specific effects in the data.

2. Random Effects Model: This model goes a step further and assumes that there are individual-specific effects over the temporal dimension. However, the use of this model requires the author to have strong reasons to believe that these effects are uncorrelated with the predictor variables (Brooks, 2008, p. 498).

3. Fixed Effects Model: Fixed effects models assumes that the individual-specific effects are correlated with the predictor variables. This particular model allows us to control for time-invariant, non-observable characteristics that have a significant influence on our outcome variable. In other words, we are controlling for unobserved heterogeneity (Brooks, 2008, p. 493).

Primarily, we suggests that a one-way individual fixed effects model is best suited for our research. This model enables us to control for unobserved country-specific characteristics, such as a country's resource endowment, existing energy infrastructure, regulatory environment, and geopolitical influences. We anticipate these factors to affect the share of renewable energy in a country's total energy supply, but remain "unobserved" for various reasons. Some of these factors are challenging to quantify or identify accurately. For instance, it is infeasible to translate a country's political will to transition towards greener energy sources into a measurable variable that can be observed consistently over time.

While a two-way fixed effects model, accounting for both time and individual effects, is commonly used in economic research, we argue that its application in the context of the energy transition is not entirely appropriate. The time fixed effects model helps control for unobserved factors that change over time and are common across all entities (Brooks, 2019, p. 495). We have strong reason to believe that the energy transition dynamics are specific to each country and change at different rates, influenced by the blend of a nation's policy, technological advancements, and societal attitudes towards renewables. The factors influencing the shift towards renewable energy vary greatly from country to country and aren't uniform over time. Thus, our study predominantly benefits from individual fixed effects.

The general specification of a one-way individual fixed effects model is:

$$y_{it} = \alpha + \beta x_{it} + \tau_i + \varepsilon_{it} \tag{1}$$

where:

- y_{it} is the dependent variable for individual i at time t.
- α is the overall intercept of the model.
- β is the coefficient on the independent variable x_{it}, which represents the expected change in y_{it} for a one-unit increase in x_{it}, holding all else constant.
- x_{it} is the independent or explanatory variable for individual i at time t.
- τ_i is the individual-specific effect or fixed effect. This term captures all the unobserved, time-invariant individual-specific variables that could affect y_{it}.
- ε_{it} is the error term for individual i at time t. It captures all other unobserved factors that affect y_{it} and vary over time.

5.1.3 Limitations of the Fixed Effects Model

While there are clear advantages to using a fixed effects model in our case, it also carries limitations. One significant constraint is the inability to estimate the impact of time-invariant characteristics, as they are absorbed into the individual-specific effect. For example, the inclusion of time-invariant constants representing certain characteristics could provide valuable insights. However, these are absorbed by the fixed effects, making it impossible to interpret the sign or magnitude of these individual characteristics (Hill, 2019).

To exemplify this limitation, let's consider Norway's oil reserves. These reserves could be represented as a constant because, given they are not entirely depleted over the observed timeframe, they are relatively time-invariant. However, when controlling for other unobserved factors using fixed effects estimation, this constant is absorbed into Norway's fixed effects constant, making it impossible to estimate separately.

This necessitates a compromise: while the individual fixed effects model helps us control for unobserved, individual-specific effects, it simultaneously curbs our ability to estimate the influence of observable time-invariant country characteristics. Consequently, we must rely on qualitative analysis and theoretical reasoning to interpret these effects.

Also, as previously argued, we exclude time-fixed effects from our model. While time-fixed effects certainly could capture global trends in certain contexts, we retain the argument that the potential time-varying effects in our research context is non-uniformly affecting the countries.

5.1.4 Consideration of Difference-In-Differences Estimation

After having discussed the benefits and use cases of a fixed effects model, it may be natural to consider the potential use of a difference-in-differences (DiD) estimation. Also known as event study, DiD models are great for developing a statement of causal inference. By comparing a treatment group to a control group before and after an ”event”, such as a policy change or international climate agreement, we can estimate the event’s causal effect on the outcome variable by observing the differences in outcomes between the two groups (Baltagi, 2013, p. 17).

Despite the clear benefits of DiD estimation in policy evaluation, it is not always feasible, depending on the structure of the data and whether underlying assumptions of the DiD design can be verified. The parallel trends assumption is critical to the validity of a DiD experiment, which posits that in the absence of treatment, the averages of the treatment group and control group would have followed the same trend over time (Imbens & Wooldridge, 2009). Figure 6 shows how we cannot confirm that this assumption holds true for the development of the renewable energy share.

2005, the year the EU ETS entered into force, is clearly a turning point for the renewable energy share of participants. We see a steep upwards trend for the renewable share of the energy mix, and simultaneously a delayed upward trend of Non-EU ETS members. However, Figure 6 shows that while the trends are similar in direction post 2005, they are not *parallel*. The averages converge pre-2005, and diverge in a similar fashion post 2005.

Figure 7 confirms that we cannot confirm that the parallel trends assumption is not violated when using the growth transformed mean values of the dependent variable. There is no clear parallel, and we observe that the averages converge and

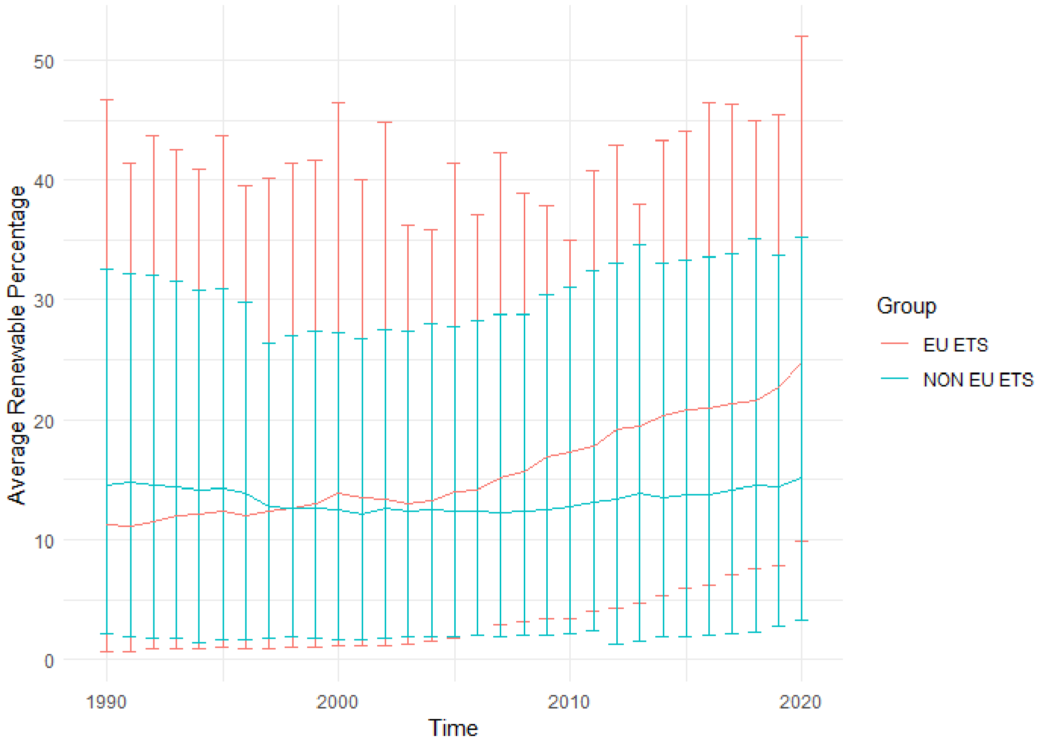

Figure 6: Average Renewable Energy Share as % of Total Supply in EU ETS Countries and Non-EU ETS Countries

diverge several times over the total time period.

The assumption of endogeneity is important in policy evaluation, as countries that choose to participate in a policy like the EU ETS are inherently different from those that opt not to (Imbens& Wooldridge, 2009). This differentiation, often influenced by economic structure, energy needs, environmental attitudes, and political dynamics, can invalidate causal comparisons of outcomes. The highly likely self-selection among EU ETS member countries present challenges in fulfilling the exogeneity assumption required for a reliable DiD design.

Because of the aforementioned, we are unable to conduct a valid DiD experimental design in this thesis. We do not want to make a statement of causal inference where the underlying assumptions might be violated. Also, the different timing of treatment for countries participating in the EU ETS and international climate agreements can also bring further complications that needs to be considered, as highlighted by Callaway & Sant'Anna (2021). Table 3 lists the sample countries and their membership status, and we can confirm that there are in fact different treatment timings. The compromised feasibility of a DiD experiment and the scope of

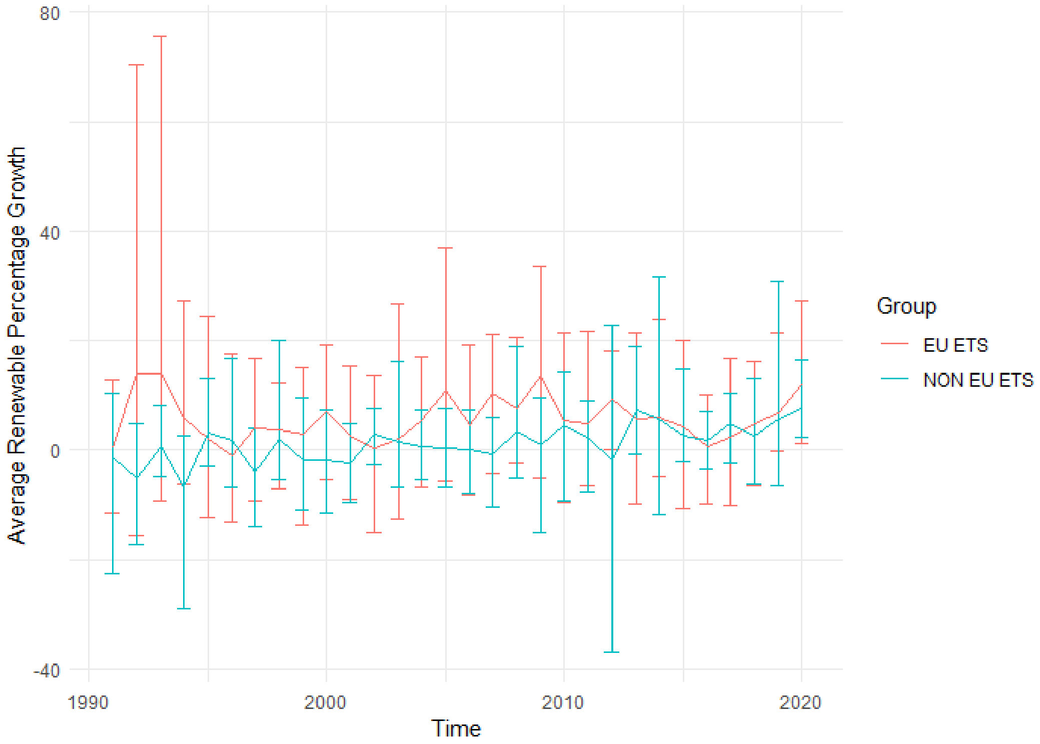

Figure 7: Average Renewable Energy Share as % of Total Supply in EU ETS, Countries and Non-EU ETS Countries, Growth Transformed

EU ETS Status	**Countries**
Joined in 2005	Austria, Belgium, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom (left 2020), Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Netherlands, Poland, Portugal, Slovakia, Slovenia, Sweden
Joined in 2008	Iceland, Norway
Never joined	Australia, Canada, Switzerland, Chile, Colombia, Israel, Japan, South Korea, Mexico, New Zealand, Turkey, United States

Table 3: EU ETS Membership Status Among Sample Countries

this thesis led us to the conclusion that a DiD design is not appropriate.

5.2 Diagnostics and OLS assumptions

In order to ensure that our panel regression models provide reliable and robust estimates, it is necessary to test for and, if necessary, address violations of the key assumptions of Ordinary Least Squares (OLS) regression. OLS assumes that errors are normally distributed, independent, have constant variance (homoskedasticity), and are uncorrelated with the independent variables (Brooks, 2008, p. 44). Violations of these assumptions can lead to biased or inefficient estimates, incorrect inference, and model miss-specification. In the following sections, we discuss these considerations in more detail and outline strategies to test for and remedy these issues.

5.2.1 Multicollinearity

One important assumption in the OLS model is that there is no perfect multicollinearity, meaning that none of the independent variables in the model are perfectly linear with any of the other independent variables. Multicollinearity inflates the variances of the parameter estimates and makes the estimates very sensitive to minor changes in the model. The presence of multicollinearity can lead to less precise estimates of the model parameters, and thus may lead to incorrect inferences about the data (Brooks, 2008, p.172).

To mitigate this potential issue during our data collection and variable selection process, we strategically tagged each variable based on the specific type of information they were intended to encapsulate. For instance, when deciding upon variables that reflect a country's wealth level, we would assign a "wealth proxy" tag to the most appropriate variable. If another potential variable was intended to capture a different aspect but showed a significant overlap with our wealth proxy, we would evaluate the importance of each variable as well as the depth of information each one could effectively capture. This process was qualitatively conducted, and we aimed to mitigate the risk of multicollinearity by making each selected variable serve a distinct and crucial role in our model.

This approach helps us not only retain variables that best represent the aspects we aim to study, but also in maintaining a data set without collinearity, thus facilitating a robust analysis. We present the outcome of a Variance Inflation Factor test in our results section to display the level of collinearity in our data.

5.2.2 Heteroskedasticity

Heteroskedasticity refers to a situation where the variability of the error term, or the 'noise' in the model, is not constant across all levels of the independent variables. In the context of panel data, we may be particularly concerned about cross-sectional heteroskedasticity, where the error variance differs across entities (e.g., countries in our case). This could arise due to differences in scale or other unobserved characteristics among the entities. If unaddressed, heteroskedasticity can lead to inefficient standard error estimates, which in turn may lead to incorrect statistical inferences (Brooks, 2008, p. 135).

To test for heteroskedasticity, we can use graphical methods, such as plotting the residuals against the predicted values or independent variables, or statistical tests such as the Breusch-Pagan test. If we detect heteroskedasticity, robust standard error estimates can be used to ensure that our statistical inference is valid.

5.2.3 Serial Correlation

Serial correlation, also known as autocorrelation in the residuals, is another diagnostic concern in panel data models. This refers to a situation where the error term for one observation is correlated with the error term for a previous observation (Brooks, 2008, p.139). This could occur, for example, if there are omitted variables that change over time in a systematic way or due to inertia in the dependent variable (i.e., it is influenced by its own past values).

The assumption of independence in OLS regression implies that there should be no autocorrelation. Violations of this assumption can lead to inefficient and biased estimates, and incorrect standard errors.

We can detect autocorrelation through visual inspection of an ACF plot of the residuals or by using statistical tests such as the Wooldridge test for autocorrelation in panel data. If autocorrelation is present, an appropriate correction is to use standard errors robust for serial correlation within a entitiy's observations.

In the following sections, we will present and discuss the preliminary regression model and conduct these diagnostic tests. This will ensure that our final model provides robust and reliable insights into the effects of the EU ETS on the renewable energy transition.

5.2.4 Clustering of Standard Errors

In panel data analysis, it is crucial to account for the potential correlation and heterogeneity present within the data. Violations of the OLS assumptions, such as homoskedasticity and independence of errors, could result in incorrect inferences, as described in the previous sections.

One common approach to address these concerns is to use clustered standard errors. Cluster-robust standard errors adjust for the fact that observations within the same cluster may not be independent and can exhibit different variances. This method offers a unified solution to when both serial correlation and heteroskedasticity are suspected to be present in panel data (Abadie et al., 2017).

When we apply clustering at the country level, we accommodate within-country error correlation, acknowledging that errors for a given country could follow a certain pattern over time. Additionally, it allows for potential differences in error variance across countries.

Therefore, to ensure our standard errors are robust and reliable, we will employ standard errors clustered at the country level in our analysis. This approach, in conjunction with the fixed effects model, allows us to address the potential pitfalls associated with panel data analysis, ensuring that our empirical findings are robust.

5.3 Model Specification

The choice of variables in our model is based on theoretical foundations and the existing literature on the energy transition. Certain variables will most likely have a lagged effect, and our lag selection was guided by employing Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) (Brooks, 2008, p. 233). Finally, we also consider interaction effects in our model, which capture the combined effect of two or more independent variables on the dependent variable. The inclusion of interaction terms allows us to explore more complex relationships and dependencies among the variables.

The final specification of our fixed effects model, including the interaction terms, can be represented by the following equation:

$$
\begin{aligned}
y_{it} = \delta\text{ETS Member}_{it} \\
&+ \beta_1\text{GDP per Capita}_{it-1} \\
&+ \beta_2\text{Primary Energy Supply}_{it} \\
&+ \beta_3\text{Renewable per Capita}_{it} \\
&+ \beta_4\text{Industrial Production}_{it-1} \\
&+ \beta_5\text{Population}_{it-2} \\
&+ \beta_6\text{Brent Crude Price}_{it-1} \\
&+ \beta_7\text{Brent Volatility}_{it} \\
&+ \gamma \cdot \text{Interaction Terms}_{it} \\
&+ \tau_i + \varepsilon_{it}
\end{aligned} \tag{2}
$$

Where:

- y_{it} is the dependent variable, representing the renewable energy share as a percentage of the total primary energy supply for country i at time t.
- δ is the coefficient for the EU ETS membership dummy variable. The dummy variable, ETS Member$_{it}$, is 1 if country i is a member of EU ETS at time t, and 0 otherwise.
- β_j are the coefficients for each corresponding independent variable.
- GDP per Capita (lag 1)$_{it}$, Primary Energy Supply$_{it}$, Renewable per Capita$_{it}$, Industrial Production (lag 1)$_{it}$, Population (lag 2)$_{it}$, Brent Crude Price (lag 1)$_{it}$, Oil Volatility$_{it}$ are the explanatory variables for country i at time t.
- $\gamma \cdot$ Interaction Terms$_{it}$ represents the interaction terms that will be estimated in the model.
- τ_i is the country-specific fixed effect. This term captures all the unobserved, time-invariant country-specific variables that could affect y_{it}.
- ε_{it} is the error term for country i at time t. It captures all other unobserved factors that affect y_{it} and vary over time.

By using a dummy variable for EU ETS membership, we can estimate the differential effect of membership in the EU ETS on the renewable energy percentage.

A positive δ would indicate that membership in the EU ETS is associated with a higher renewable energy percentage, holding other factors constant.

6 Results

In the following sections, we present the results of our regression models. It is important to note that all variables used in the following models are estimated and presented in their growth terms, both for Table 4 and Table 9. As previously stated, we apply growth terms to achieve stationary variables. However, growth terms also allow us to focus on the dynamics of the relationships between the variables, which is of particular interest in this paper.

6.1 Preliminary Fixed Effects Model Estimation

Table 4: Preliminary Fixed Effects Model Estimation

	Dependent variable:
	RE as % of Tot. Energy Supply Fixed Effects
	(1)
EU ETS Member	1.887^{**} (0.785)
GDP per Capita (lag 1)	0.134 (0.105)
Energy Supply	-0.658^{***} (0.070)
Renewable per Capita	0.221^{***} (0.016)
Industrial (lag 1)	-0.142^{*} (0.075)
Population (lag 2)	1.044 (0.802)
Brent (lag 1)	0.025^{**} (0.013)
Brent Volatility	0.002 (0.004)
Observations	973
R^2	0.279
Adjusted R^2	0.245
F Statistic	44.829^{***} (df = 8; 929)
Significance codes:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

6.2 Diagnostics Testing

To ensure the reliability of our findings, we performed diagnostics tests on the fixed effects model (1) from Table 4. The checks we perform identify potential violations of the Ordinary Least Squares (OLS) assumptions, such as heteroskedasticity and autocorrelation in the residuals. By correcting these potential issues through robust standard errors clustering, we lay a solid foundation for our subsequent analyses and interpretations.

6.2.1 Breusch-Pagan Test

Test	BP Statistic	Degrees of Freedom	p-value
Breusch-Pagan	7.3018	8	0.5044

Table 5: Breusch-Pagan Test for Homoskedasticity

As reported in Table 5, the Breusch-Pagan test results help us to assess heteroskedasticity in our preliminary model. The null hypothesis of the test is that the error variances are all equal (homoskedasticity). The p-value of 0.5044 is not statistically significant at conventional levels, suggesting we fail to reject the null hypothesis of homoskedasticity. Thus, the test results do not indicate the presence of heteroskedasticity in the model.

6.2.2 Breusch-Godfrey Test

Test	Chi-square Statistic	Degrees of Freedom	p-value
Breusch-Godfrey	30.609	19	0.04454

Table 6: Breusch-Godfrey Test for Serial Correlation

The Breusch-Godfrey test, presented in Table 6, was conducted to check for serial correlation in the residuals of our preliminary model. The null hypothesis of the test is that there is no serial correlation. A statistically significant p-value of 0.04454 leads us to reject the null hypothesis. This implies that there is evidence of serial correlation in the model. This issue may need to be addressed in further refinements of the model to ensure reliable and valid results.

However, the Autocorrelation Function (ACF) plot of the residuals from the preliminary fixed effects model, as shown in Figure 8, provides evidence against the presence of autocorrelation in our model. The black vertical lines representing autocorrelations at different lags all fall within the blue stippled lines, which indicate the confidence interval for the null hypothesis of no autocorrelation. In particular, for meaningful lags, none of the vertical lines exceed these boundaries.

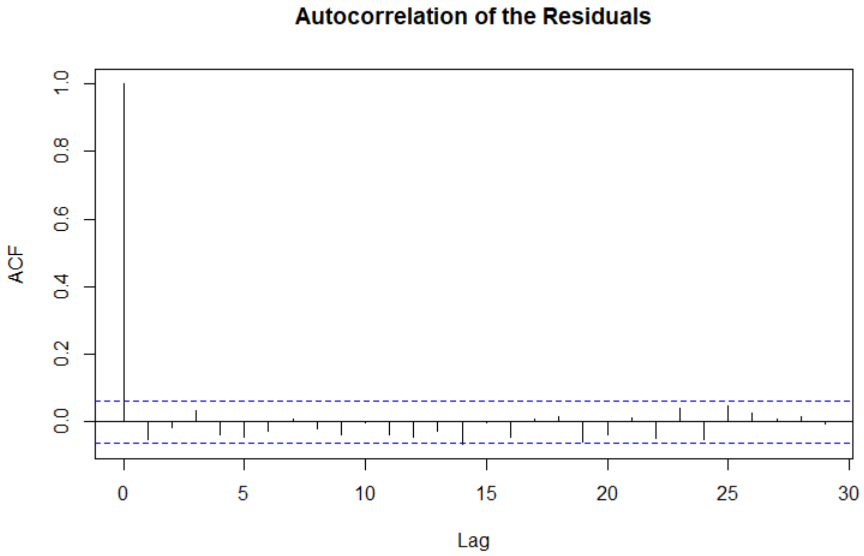

Figure 8: ACF of the Residuals

6.2.3 Variance Inflation Factors

Variable	VIF
ETS Member	1.116738
GDP per Capita (lag 1)	1.651132
Energy Supply	1.106700
Renewable per Capita	1.021781
Industrial Production (lag 1)	1.609862
Population (lag 2)	1.068927
Brent Crude Price (lag 1)	1.162510
Brent Volatility	1.076705

Table 7: Variance Inflation Factor (VIF) Test for Multicollinearity

The Variance Inflation Factors (VIF) were calculated for each explanatory variable to check for multicollinearity in our model, as displayed in Table 7. The VIF quantifies how much the variance is inflated for each coefficient, with a VIF of 1 indicating no correlation. A common rule of thumb suggests that VIFs exceeding 5 warrant further investigation. As all the VIFs in our model are close to 1, this suggests that multicollinearity is not a concern in our model, and each variable appears to contribute unique information to the prediction of the dependent variable.

6.2.4 Pesaran CD Test

Since we also wanted to confirm the presence or absence of cross-sectional dependence in our panel data, we have performed the Pesaran CD Test, the results of which

Test	z-value	p-value
Pesaran CD	0.20728	0.8358

Table 8: Pesaran CD Test for Cross-Sectional Dependence

are presented in Table 8. The null hypothesis of this test is no cross-sectional dependence, i.e., the error term of one unit does not affect that of another unit. With a p-value greater than the conventional significance levels, we fail to reject the null hypothesis, suggesting that there is no significant cross-sectional dependence in our model. This supports the appropriateness of our chosen fixed effects approach and the reliability of our analysis.

6.2.5 Concluding the Diagnostics

After conducting diagnostic tests on the preliminary model results, we found valuable information regarding our data's characteristics.

The Breusch-Pagan test revealed no signs of heteroskedasticity, suggesting a uniform variability in our errors. However, the Breusch-Godfrey test highlighted the presence of serial correlation, implying residuals in our model are not independent.

Our model showed no critical issues with multicollinearity, as evidenced by the low Variance Inflation Factor (VIF) scores. The Pesaran CD test further solidified our confidence in the fixed effects model by revealing no significant cross-sectional dependence.

The diagnostic tests, alongside the nature of our multi-period, cross-sectional data, justify the use of clustered standard errors to account for potential correlations within countries across time, yielding more accurate standard errors.

6.3 Final Results

Table 9: Fixed Effects Results

	Dependent variable:	
	RE as % of Tot. Energy Supply	
	FE without Interactions	FE with Interactions
	(2)	(3)
EU ETS Member	1.887^{**}	1.537^{*}
	(0.888)	(0.874)
GPD per Capita (lag 1)	0.134	0.060
	(0.095)	(0.085)
Energy Supply	-0.658^{***}	-0.536^{***}
	(0.078)	(0.110)
Renewable per Capita	0.221^{***}	0.222^{***}
	(0.047)	(0.047)
Industrial (lag 1)	-0.142^{**}	-0.159^{***}
	(0.056)	(0.057)
Population (lag 2)	1.044^{**}	1.016^{**}
	(0.499)	(0.492)
Brent Crude (lag 1)	0.025^{**}	0.023^{*}
	(0.012)	(0.013)
Brent Volatility	0.002	0.001
	(0.003)	(0.003)
ETS*Energy Supply		-0.277^{**}
		(0.118)
ETS*GDP per Capita		0.112
		(0.116)
GDP*Energy Supply		0.009
		(0.007)
Observations	973	973
R^2	0.279	0.283
Adjusted R^2	0.245	0.247
F Statistic	44.829^{***} (df = 8; 929)	33.150^{***} (df = 11; 926)
Significance codes:		$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$
Note:		Std. errors clustered by country

6.3.1 Multicollinearity Revisited

We briefly revisit the Variance Inflation Factors to double check if our final specification model suffer from excessive multicollinearity after having added the interaction terms. The VIF results in Table 10 is based on model (3) from Table 9.

Variable	VIF
ETS Member	2.300871
GDP per Capita (lag 1)	2.738980
Energy Supply	3.000337
Renewable per Capita	1.025088
Industrial Production (lag 1)	1.651235
Population (lag 2)	1.087666
Brent Crude Price (lag 1)	1.172072
Brent Volatility	1.091886
ETS Member*Energy Supply	2.276971
ETS Member*GDP per Capita (lag 1)	3.352771
GDP per Capita (lag 1): Energy Supply Change Percentage	1.651255

Table 10: Variance Inflation Factor (VIF) Test for Multicollinearity in the Final Model

Again, we do not exceed the threshold value of 5, indicating the we have not violated the OLS assumption of no multicollinearity.

6.4 Discussion of the Results

The final estimated results, presented in Table9, provide us with several interesting insights into the dynamics of renewable energy adoption across our sample of OECD countries between 1991 and 2020. This section includes the discussion of the model (2) and (3) results.

- **EU ETS Membership:** The coefficient for ETS membership in the fixed effects model (2) without interactions is 1.887 (p-value = 0.03386). Our results imply that ETS membership is associated with an increase in the growth rate of renewable energy adoption. When comparing the coefficient of ETS membership with the other predictors and their respective coefficient estimates, we see that participation in the scheme has the greatest magnitude by some margin.

  In terms of interpretation, a positive coefficient for the ETS member variable indicates that, all else being equal, being a member of the ETS is associated with a higher growth rate in renewable energy adoption. Specifically, according to the fixed effects model (2) without interaction terms, being a member of the ETS is associated with a 1.887 percentage points higher growth rate in renewable energy adoption compared to non-members.

Since we are estimating fixed effects models, we are able to control for time-invariant country-specific effects, assuming they could be correlated with our regressors. Even when controlling for these effects, the significance of the ETS membership is statistically significant at the 5% level for model (2). This suggests that some of the variation in renewable energy adoption growth rate attributed to ETS membership may be due to these unobserved country-specific effects. Although we can not make a statement of causality of EU ETS participation, the positive and statistically significant coefficients, at 5% and 10% for models (2) and (3) respectively, clearly suggests that membership promotes higher growth rates in renewable energy adoption, and with greater magnitude than other factors.

- **GDP per Capita (lag 1):** The coefficient for GDP per capita is positive with an estimate of 0.134 in the fixed effects model. This means that a 1 percentage point increase in GDP per capita from the previous year is associated with an estimated increase in the growth rate of renewable energy adoption 0.134 percentage points. However, this effect is not statistically significant (p-value = 0.095 model (2) and = 0.085 in model (3)), implying that we can't assert this effect within our sample of OECD countries.

  According to the theory of the Environmental Kuznets Curve (EKC), we might expect to see an initial negative effect of wealth growth on environmental quality, followed by a positive effect once a certain level of economic development is reached.

  One possible explanation for the insignificant relationship is that certain countries might have been on the left-hand side of the EKC and made the shift over to the right-hand side of the curve during the sample period, rendering us unable to make a generalized statement about the effect of wealth levels on the renewable energy share in OECD.

  Additionally, OECD countries might have mechanisms, like stringent environmental regulations or strong public support for renewable energy, which decouple economic growth from environmental degradation to some extent.

- **Energy Supply Change Percentage:** The coefficient for the energy supply change percentage is statistically significant at the 1% level in both models (2) and (3), with estimates of -0.658 and -0.536 respectively. This suggests that a 1 percentage point increase in the overall energy supply is associated with a decrease in the growth rate of renewable energy adoption by 0.658 and 0.536 percentage points in models (2) and (3) respectively.

  This indicates that, within our sample of OECD countries, expanding the overall energy supply seems to be associated with a slower growth rate of renewable energy adoption. This could be attributed to limitations in expansion of renewable energy. Compared to renewables, fossil fuels may offer easier and more rapid deployment in response to fluctuations in overall energy demand, especially when considering already installed production capacity. Expanding renewable capacity requires planning and appropriate natural resources, which can be a limiting factor. Also, when considering installed capacity, stored fossil fuels are more likely easier to deploy in response to short term demand fluctuations, since certain renewable production methods are not deployed on-demand, but rather in response to weather changes.

  However, it is important to note that this variable alone does not tell us about the composition of the energy supply change. For instance, an increase in overall energy supply could be due to a significant increase in non-renewable energy production with a simultaneously modest increase in renewable energy production, i.e., disproportional changes in either energy source. Therefore, this variable should ideally be interpreted in conjunction with other variables that provide insights into the composition of energy supply, such as the following variable.

- **Renewable Capita Change Percentage:** The coefficients for renewable capita change percentage are statistically significant at the 1% level in both estimated models (2) and (3), with positive coefficients of approximately 0.22. This suggests that, on average, a one percentage point increase in the renewable capita change percentage is associated with an approximately 0.22

percentage point increase in the growth rate of renewable energy adoption.

This positive and significant relationship aligns with our expectations based on the nature of these variables. Renewable energy per capita essentially captures the relative growth of renewable energy supply per person within a country. As this figure increases, it signifies that more renewable energy is being produced per capita, reflecting a growing commitment to renewable energy.

Consequently, it is logical that this would positively influence the growth rate of renewable energy adoption. An increase in renewable energy per capita would likely be accompanied by factors such as favorable government policies, technological advancements in renewable energy, and a positive shift in public sentiment towards renewable energy — all of which would further promote the adoption of renewable energy.

Moreover, interpreting this variable in conjunction with the energy supply change percentage sheds further light on the dynamics of energy supply within a country. While an increase in overall energy supply is associated with a decrease in the growth rate of renewable energy adoption, an increase in the renewable energy supply per capita has the opposite effect. This suggests that the composition of the energy supply change, rather than the change itself, plays a crucial role in determining renewable energy adoption rates. As countries shift towards producing more renewable energy per capita, they can counteract the negative effects of overall energy supply growth on renewable energy adoption.

- **Industrial Production (lag 1):** This variable, which represents the lagged value of industrial production, has a negative coefficient in both models (2) and (3). The coefficient is statistically significant at the 5% level in both cases.

  This suggests that a one percentage point increase in industrial production from the previous year is associated with an approximately 0.142 to 0.159 percentage point decrease in the growth rate of renewable energy adoption.

  The negative coefficient implies an inverse relationship between industrial production and the growth of renewable energy adoption. This could be attributed to the fact that industrial processes have traditionally been powered by non-renewable energy sources. So, when industrial production increases, it could lead to increased consumption of non-renewable energy, potentially crowding out or reducing the emphasis on renewable energy adoption. Another potential reason for this relationship over the sample period could be the immediate availability and affordability that fossil fuels offer. Developing both technology and infrastructure for renewable energy is costly, especially when individual industrial players might have to carry the entire cost of development themselves.

  Again, this is relationship is logical, considering that under the assumption of rationality in cost-effectiveness, governments would be harming their competitive advantage when imposing costs related to the energy transition. Thus, governments would rather leave the industrial activity to develop with the most cost-effective energy means possible with little or no intervention. This even holds true under the fact that EU ETS membership is prevalent among the majority of the sample countries, suggesting that industrial players do not contribute to shifting the energy mix in favor of a greener one.

- **Population (lag 2):** The two-year lagged population variable is statistically significant in both models, with model (2) seeing a lower level significance than model (3). In the models, a one percentage point increase in population is associated with a respectively 1.044 and 1.016 percentage points increase in the rate of growth in renewable energy adoption with a two year delay.

  This finding suggests that within the same country (holding all other factors constant), a higher population growth is associated with a subsequent increase in the growth rate of renewable energy adoption. This relationship may be due to various factors. As a population expands at a greater rate, demand for energy rises, potentially leading to increased investment in renewable energy sources. Also, with fossil fuels being depletable and having a certain capacity, renewable energy might offer a viable solution to the energy demand that follows population increases.

  While this result suggest a positive relationship between population growth and the rate of growth in renewable energy adoption, the relationship is complex and may be influenced by a range of factors, including other demographic trends, energy policies, and economic conditions.

- **Brent Crude Price (lag 1):** The Brent Crude price variable shows consistent results in models (2) and (3). In model (2), the coefficient is positive and significant at the 5% level. Model (3) retains the sign and magnitude of the coefficient, but the introduction of interaction terms makes the significance drop to a lower 10% level.

  According to these results, increases in the price of Brent Crude oil from the previous year is associated with an increase in the rate of renewable energy adoption. Specifically, a one percentage point increase in the lagged Brent Crude price is associated with a 0.025 percentage point increase in the growth rate of renewable energy adoption. This is somewhat in line with the theory of substitution effect: as the cost of oil increases, countries might look for cheaper alternatives, including renewable energy sources.

  Yet, it's important to consider the relatively small magnitude of this effect, which suggests that the price of Brent Crude is not a major driver of changes in renewable energy adoption rates within our sample. There might be several reasons behind this result. First, as mentioned in the prior analysis, oil and renewable energy are not perfect substitutes for each other. While renewables can replace oil in certain applications, there are still many uses of oil, such as in transportation and industry, where renewables currently cannot fully replace oil. Second, the impact of oil prices on renewable energy adoption may be mediated by a number of other factors, such as energy policies, technology availability, and other economic conditions. This may explain why the effect is relatively small.

- **Annual Oil Volatility:** The annual oil price volatility lacks statistical significance in the estimated models. Although both models show a weakly positive coefficient, the lack of statistical significance makes us unable to reliably infer a relationship between oil price volatility and the rate of renewable energy adoption within our sample. We had hypothesized that the volatility of oil price might introduce an element of uncertainty, thus driving countries to expand their renewable energy capacity as a hedging strategy against unpredictability in energy supply. Yet, our empirical results do not support this hypothesis for the sample.

  Several reasons could drive this result. First, countries might deploy alternative strategies to counterbalance oil price volatility, like the establishment of petroleum reserves or the diversification of energy portfolios into other fossil fuels, reducing the necessity for renewable energy as a hedge against oil price instability. Second, oil price volatility may not be influencing the decision to adopt renewable energy. The decisions related to renewable energy investments are typically long-term, taking into consideration a range of other factors such as the cost of technology, policy support, environmental considerations, and public sentiment. Considering this, oil price volatility might just be one factor amongst many, and the impact of short-term considerations, like price volatility, could be less important in light of other factors that are focused on the long-term stability of energy supply in OECD countries. Lastly, the effect of oil price volatility on renewable energy adoption may not be immediate, and our model, which incorporates only a one-year lag, may not capture this delayed effect. The consequences of oil price volatility may be present over an extended period, if at all.

Our results reveal that this relationship is not statistically significant within our sample. Future research could explore this relationship over longer time frames, different frequencies, or explore potential variations across countries based on their energy characteristics.

6.5 Results on Interaction Terms

In this section, we will discuss the interaction terms as displayed in Table 9. We will examine how the incorporation of the interaction terms changes our predictor variables, and how we interpret each interaction term's point estimate and significance.

- **ETS Member Interaction with Energy Supply:** This interaction term is statistically significant in the fixed effects model with a p-value less than 0.05. The negative coefficient indicates that for EU ETS member countries, an increase in the energy supply is associated with a less positive (or more negative) impact on the share of renewable energy. This could suggest that EU ETS member countries, with more advanced renewable energy markets, might be less sensitive to fluctuations in the total energy supply as these countries are already devoted to renewable energy transitions.

- **ETS Member Interaction with GDP per capita (lag 1):** This interaction term is not statistically significant, suggesting that being an ETS member does not change the relationship between GDP per capita and the share of renewable energy in the total energy supply.

- **Interaction of GDP per capita (lag 1) and Energy Supply:** This term is not statistically significant, implying that the interaction between GDP per capita and energy supply does not have a significant impact on the share of renewable energy in the total energy supply within our sample.

- **Changes in other predictor variables:** The incorporation of interaction terms in our models also changes the interpretation of the original predictor variables. Specifically, the coefficients on these variables now represent the effect on the share of renewable energy when the interacting variable is zero. For example, EU ETS membership now represents what impact being an EU ETS member has on the share of renewable energy when the interacting variables (i.e., GDP per capita and energy supply) are zero.

  We also note that the significance level of the Brent Crude Oil Price changes, moving from being significant at the 0.05 level to significant at the 0.1 level. This could be due to the additional complexity added by the interaction terms, which might modify the relationships between the predictors and the outcome variable.

  In conclusion, our results demonstrate that EU ETS membership changes the relationship between changes in the energy supply and the share of renewable energy. This highlights the role of emission trading schemes in influencing countries' reactions to changes in their energy supply. However, we find no significant moderating effects were found for GDP per capita. The inclusion of interaction terms provides a more nuanced understanding of these relationships, which may differ across various contexts and conditions.

6.6 Comparison with Existing Literature

Our research builds upon existing studies while offering some new perspectives on the relationships between economic and environmental factors and renewable energy consumption. This is due to our focus on renewable energy consumption as a percentage of the total energy supply, a differentiating factor that enables us to examine renewable energy consumption's development relative to a nation's total energy mix. Additionally, our research includes a broad range of factors, such as policy effects (ETS Membership), energy supply, renewable energy per capita, industrial factors, population, and crude oil prices. While including many variables contrasts the existing literature, we must also consider the fact that the discussed articles largely apply different methods from that of this paper. Nonetheless, it is interesting to see how our differentiated approach might support or contradict the existing literature.

In comparison to Sadorsky (2009a), both studies explore the relationship between economic development (income per capita) and renewable energy consumption. However, whereas Sadorsky identifies a strong positive correlation in emerging economies, our study, focusing on OECD countries, finds the GDP per capita does not significantly influence renewable energy share. The different outcomes could result from our distinctive country focus, the application of our dependent variable as a ratio, and methodological differences. Our study, for example, employs a fixed effects model approach in contrast to Sadorsky's panel cointegration methods.

Comparatively, both Sadorsky (2009b) and Apergis Payne (2014) examined the impact of oil prices on renewable energy consumption. While Sadorsky reveals considerable differences in oil price substitution effects among G7 countries, Apergis Payne affirm a positive relationship between oil price increases and renewable energy consumption in their sample of OECD countries. Our research, with a broader range of countries, echoes the latter's findings, confirming the significant positive impact of oil prices on renewable energy share. However, our observed impact magnitude may appear smaller due to our distinct dependent variable construction.

Unlike Nguyen & Kakinaka (2019), whose research supports the Environmental Kuznets Curve (EKC) hypothesis, our study doesn't find significant wealth level impact on renewable energy share. This discrepancy can be attributed to our different model application, the structuring of the dependent variable, and our exclusion of variables such as carbon dioxide emissions and economic output.

To sum up, our research brings a different perspective to the relationship between various economic-environmental factors and renewable energy consumption. Differences in methodology, data application, and the selection of dependent variables across studies have resulted in divergent conclusions.

7 Conclusion

In the pursuit of a sustainable future, understanding the dynamics of the energy mix becomes crucial. This thesis presents a comprehensive exploration of renewable energy's relationship with a diverse set of variables, offering valuable insights that may guide future policy decisions and academic research.

Our research studies the impact of EU ETS membership, GDP per capita, energy supply change, renewable capital change, industry-level factors, population dynamics, oil price, and oil price volatility on the share of renewable energy to the total energy supply. Each of these variables brought unique insights into the complex web of factors that influence renewable energy consumption.

Firstly, EU ETS membership, a variable representing a more binding and consequential form of environmental policy, was found to be positively correlated with the energy mix in favor of renewables. This bolsters the theoretical prediction that more legally binding schemes, as opposed to loose international agreements, may be better suited to mitigate the free rider problem and stimulate growth in favor of renewable energy. Secondly, GDP per capita, a common indicator of economic development, had an insignificant relationship with the renewable energy share. We found that energy supply growth and renewable energy consumption per capita growth had significant relationships with the renewable energy share, underlining the potential importance of the energy supply infrastructure and investment in renewables.

Further, our analysis also illuminated the potential influence of industrial activities and population dynamics on the energy mix. Brent oil price and oil price volatility, key components of the global energy market, were found to be significantly related to the renewable energy share. Notably, our study differs from much of the existing literature by applying a different dependent variable - renewable energy as a percentage of total energy supply. This distinctive approach allows us to focus more closely on the proportion of energy derived from renewable sources, a critical aspect of sustainable energy transition. However, a vital caveat to note is that our study is observational in nature, employing panel data models. This constrains us to make inferences only about relationships and correlations, not causal relationships.

As the world increasingly embraces renewable energy, the findings of our research suggest a positive forecast. The ongoing shift in global sentiment towards sustainability could potentially turn renewable energy investments into competitive advantages. This seems increasingly probable as demand patterns evolve due to externalities gaining prominence in utility functions of industrial players and households alike.

In summary, this thesis contributes with insights to the academic research on the energy transition. It underscores the importance of policy mechanisms, energy substitution, industrial activities, and other factors in the transition towards sustainable energy. As we collectively strive towards a more sustainable future, our study advocates for more research on the complex causal relationships. We hope that the relationships established in this thesis can serve as an inspiration for future investigations in the field of sustainable finance and the energy transition.

References

Apergis, N. & E.Payne, J. (2014). The causal dynamics between renewable energy, real gdp, emissions and oil prices: evidence from oecd countries. *Applied Economics*, *46*(36), 4519-4525. doi: 10.1080/00036846.2014.964834

Baltagi, B. H. (2013). *Econometric Analysis of Panel Data* (5th ed.). Wiley.

British Petroleum. (n.d.). *Statistical Review of World Energy 2021 — 70th edition.* https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf. (Accessed on Date 05/Jun/2023)

Brooks, C. (2019). *Introductory Econometrics for Finance* (4th ed.). Cambridge University Press.

Callaway, B. & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200-230. Retrieved from https://www.sciencedirect.com/science/article/pii/S0304407620303948 (Themed Issue: Treatment Effect 1) doi: https://doi.org/10.1016/j.jeconom.2020.12.001

Chris Brooks. (2008). *Introductory Econometrics for Finance* (2nd ed.). Cambridge University Press.

Equinor ASA. (2023). *Energy transition plan progress report 2022.* https://cdn.equinor.com/files/h61q9gi9/global/449f080ed82a58e28293f95239c5e180f9c5 energy-transition-plan-progress-report-equinor.pdf. (Accessed on 23/Mar/2023)

European Comission. (n.d.). *Eu emissions trading system (eu ets).* https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets$_{e}n.(AccessedonDate25/Jun/2023)$

Gosens, J. (2017). Natural resource endowment is not a strong driver of wind or pv development. *Renewable Energy*, *113*, 1007-1018. Retrieved from https://www.sciencedirect.com/science/article/pii/S0960148117305670 doi: https://doi.org/10.1016/j.renene.2017.06.062

Grossman, G. M. & Krueger, A. B. (1994). Economic Growth and the Environment. *NBER Working Paper Series*. Retrieved from https://www.nber.org/papers/w4634 doi: 10.3386/w4634

Hammoudeh, S. M., Ewing, B. T. & Thompson, M. A. (2008). Threshold cointegration analysis of crude oil benchmarks. *The Energy Journal*, *29*(4), 79–95. Retrieved 2023-06-04, from http://www.jstor.org/stable/41323182

Hardin, G. (1968). The tragedy of the commons: the population problem has no technical solution; it requires a fundamental extension in morality. *Science*, *162*(3859), 1243-1248. Retrieved from https://www.science.org/doi/full/10.1126/science.162.3859.1243 doi: 10.1126/science.162.3859.1243

Hicks, J. R. (1939). *Value and capital: An inquiry into some fundamental principles of economic theory*. Clarendon Press.

Hill, T. D., Davis, A. P., Roos, J. M. & French, M. T. (2019). Limitations of fixed-effects models for panel data. *Sociological Perspectives*, *63*(3), 357-369. Retrieved from https://journals.sagepub.com/doi/pdf/10.1177/0731121419863785?casa_token=7mVw-MRSI9QAAAAA:Wya4RIFiBk6-kkKwgCnA4MbODAeSJvL8PaOkOqwU6d80aOMivdhn8y9a9hVzykUUJcwlw-9YKd9JGg doi: 10.1177/0731121419863785

IEA. (n.d.). *Fuel shares in OECD total energy supply, 2020.* https://www.iea.org/data-and-statistics/charts/fuel-shares-in-oecd-total-energy-supply-2020. (Accessed on Date 04/Jun/2023)

Im, K. S., Pesaran, M. & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, *115*(1), 53-74.

Retrieved from https://www.sciencedirect.com/science/article/pii/S0304407603000927 doi: https://doi.org/10.1016/S0304-4076(03)00092-7

Imbens, G. W. & Wooldridge, J. M. (2009). Recent developments in the econometrics of program evaluation. *Journal of Economic Literature*, *47*(1), 5-86. Retrieved from http://dx.doi.org/10.1257/jel.47.1.5 doi: 10.1257/jel.47.1.5

Karacan, R., Mukhtarov, S., Barış, , İşleyen, A. & Yardımcı, M. (2021). The Impact of Oil Price on Transition toward renewable Energy Consumption? Evidence from Russia. *Energies*, *14*(2947), 1–17. doi: 10.3390/en14112947

Kuznets, S. (1955). Economic growth and income inequality. *The American Economic Review*, *45*(1), 1-28. Retrieved from https://www.jstor.org/stable/1811581

Mancur, O. (1965). *The Logic of Collective Action: Public Goods and the Theory of Groups* (1st ed.). Harvard University Press.

Murshed, M. & Tanha, M. M. (2021). Oil price shocks and renewable energy transition: Empirical evidence from net oil-importing south asian economies. *Energy, Ecology and Environment*, *6*, 183-203. Retrieved from https://link.springer.com/article/10.1007/s40974-020-00168-0 doi: https://doi.org/10.1007/s40974-020-00168-0

Nguyen, K. H. & Kakinaka, M. (2019). Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis. *Renewable Energy*, *132*, 1049-1057. Retrieved from https://www.sciencedirect.com/science/article/pii/S096014811831019X doi: https://doi.org/10.1016/j.renene.2018.08.069

Nielsen, F. & Alderson, A. S. (1997). The Kuznets Curve and the Great U-Turn: Income Inequality in U.S. Counties, 1970 to 1990. *American Sociological Review*, *62*(1), 12-33. Retrieved from https://www.jstor.org/stable/2657450

Nordhaus, W. (2015, April). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, *105*(4), 1339-70. Retrieved from https://www.aeaweb.org/articles?id=10.1257/aer.15000001 doi: 10.1257/aer.15000001

NY Times. (n.d.). *BP, in a Reversal, Says It Will Produce More Oil and Gas.* https://www.nytimes.com/2023/02/07/business/bp-oil-gas-profits.html?fbclid=IwAR0V3JS8dFtr9GIEGhnxN9jtcEWMscPwt0mAl0DhpNTSTdu1ch4qJiU0SJM. (Accessed on Date 04/Jun/2023)

OECD. (2023a). *Renewable energy.* https://data.oecd.org/energy/primary-energy-supply.htmindicator-chart. (Accessed on Date 05/Jun/2023)

OECD. (2023b). *Primary energy supply.* https://data.oecd.org/energy/primary-energy-supply.htmindicator-chart. (Accessed on Date 05/Jun/2023)

OECD. (2023c). *Industrial production.* https://data.oecd.org/industry/industrial-production.htm. (Accessed on Date 05/Jun/2023)

OECD. (2023d). *Gross domestic product (gdp).* https://data.oecd.org/gdp/gross-domestic-product-gdp.htm. (Accessed on Date 05/Jun/2023)

OECD. (2023e). *Population.* https://data.oecd.org/pop/population.htm. (Accessed on Date 05/Jun/2023)

Omri, A., Daly, S. & Nguyen, D. K. (2015). A robust analysis of the relationship between renewable energy consumption and its main drivers. *Applied Economics*, *47*(28), 2913-2923. Retrieved from `https://doi.org/10.1080/00036846.2015.1011312` doi: 10.1080/00036846.2015.1011312

Pigou, A. C. (1920). *The Economics of Welfare*. Macmillan and Co.

Pörtner, H.-O., D.C. Roberts, H. Adams, I. Adelekan, C. Adler, R. Adrian, P. Aldunce, E. Ali, R. Ara Begum, B. BednarFriedl, R. Bezner Kerr, R. Biesbroek, J. Birkmann, K. Bowen, M.A. Caretta, J. Carnicer, E. Castellanos, T.S. Cheong, W. Chow, G. Cissé, S. Clayton, A. Constable, S.R. Cooley, M.J. Costello, M. Craig, W. Cramer, R. Dawson, D. Dodman, J. Efitre, M. Garschagen, E.A. Gilmore, B.C. Glavovic, D. Gutzler, M. Haasnoot, S. Harper, T. Hasegawa, B. Hayward, J.A. Hicke, Y. Hirabayashi, C. Huang, K. Kalaba, W. Kiessling, A. Kitoh, R. Lasco, J. Lawrence, M.F. Lemos, R. Lempert, C. Lennard, D. Ley, T. Lissner, Q. Liu, E. Liwenga, S. Lluch-Cota, S. Löschke, S. Lucatello, Y. Luo, B. Mackey, K. Mintenbeck, A. Mirzabaev, V. Möller, M. Moncassim Vale, M.D. Morecroft, L. Mortsch, A. Mukherji, T. Mustonen, M. Mycoo, J. Nalau, M. New, A. Okem, J.P. Ometto, B. O'Neill, R. Pandey, C. Parmesan, M. Pelling, P.F. Pinho, J. Pinnegar, E.S. Poloczanska, A. Prakash, B. Preston, M.-F. Racault, D. Reckien, A. Revi, S.K. Rose, E.L.F. Schipper, D.N. Schmidt, D. Schoeman, R. Shaw, N.P. Simpson, C.

Singh, W. Solecki, L. Stringer, E. Totin, C.H. Trisos, Y. Trisurat, M. van Aalst, D. Viner, M.Wairiu, R.Warren, P.Wester, D.Wrathall, and Z. Zaiton Ibrahim, 2022: Technical Summary. [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. , 36-118. Retrieved from https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_TechnicalSummary.pdf doi: 10.1017/9781009325844.002.

Ricarco, D. (1817). *On the Principles of Political Economy and Taxation*. John Murray.

Sadorsky, P. (2009a). Renewable energy consumption and income in emerging economies. *Energy Policy*, *37*(10), 4021-4028. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421509003176 (Carbon in Motion: Fuel Economy, Vehicle Use, and Other Factors affecting CO2 Emissions From Transport) doi: https://doi.org/10.1016/j.enpol.2009.05.003

Sadorsky, P. (2009b). Renewable energy consumption, CO2 emissions and oil prices in the G7 countries. *Energy Economics*, *31*(3), 456-462. Retrieved from https://www.sciencedirect.com/science/article/pii/S0140988309000048 doi: https://doi.org/10.1016/j.eneco.2008.12.010

Stern, D. I. (2004). Environmental kuznets curve. In *Encyclopedia of energy* (p. 517-525). Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/B012176480X00454X doi: https://doi.org/10.1016/B0-12-176480-X/00454-X

Tidy Finance. (n.d.). *Fixed effects and clustered standard errors.* https://www.tidy-finance.org/fixed-effects-and-clustered-standard-errors.htmlclustering-standard-errors. (Accessed on Date 05/Jun/2023)

United Nations - Department of Economic and Social Affairs, Population Division. (2022). *World population prospects.* https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/900. (Accessed on Date 06/Jun/2023)

United Nations Framework Convention on Climate Change (UNFCCC). (1997). *Kyoto protocol to the united nations framework convention on climate change.* Official Text of the Kyoto Protocol. Retrieved from `https://unfccc.int/sites/default/files/resource/docs/cop3/l07a01.pdf#page=24`

US Energy Information Administration. (n.d.). *Petroleum Other Liquids.* https://www.eia.gov/dnav/pet/hist/RBRTED.htm. (Accessed on Date 05/Jun/2023)

Varian, H. R. (2014). *Intermediate Microeconomics* (9th ed.). W. W. Norton Company.

Villar, J. A. & Joutz, F. L. (2006). The relationship between crude oil and natural gas prices. *Energy Information Administration, Office of Oil and Gas.* Retrieved from `http://aceer.uprm.edu/aceer/pdfs/CrudeOil_NaturalGas.pdf`

(Apergis & E.Payne, 2014) (Baltagi, 2013) (British Petroleum, n.d.) (Chris Brooks, 2008) (Brooks, 2019) (Callaway & Sant'Anna, 2021) (?, ?) (US Energy Information Administration, n.d.) (Equinor ASA, 2023) (European Comission, n.d.) (Gosens, 2017) (Grossman & Krueger, 1994) (Hammoudeh, Ewing & Thompson, 2008) (Hardin, 1968) (Hicks, 1939) (Hill, Davis, Roos & French, 2019) (Im, Pesaran & Shin, 2003) (Imbens & Wooldridge, 2009) (Pörtner, H.-O., D.C. Roberts, H. Adams, I. Adelekan, C. Adler, R. Adrian, P. Aldunce, E. Ali, R. Ara Begum, B. BednarFriedl, R. Bezner Kerr, R. Biesbroek, J. Birkmann, K. Bowen, M.A. Caretta, J. Carnicer, E. Castellanos, T.S. Cheong, W. Chow, G. Cissé, S. Clayton, A. Constable, S.R. Cooley, M.J. Costello, M. Craig, W. Cramer, R. Dawson, D. Dodman, J. Efitre, M. Garschagen, E.A. Gilmore, B.C. Glavovic, D. Gutzler, M. Haasnoot, S. Harper, T. Hasegawa, B. Hayward, J.A. Hicke, Y. Hirabayashi, C. Huang, K. Kalaba, W. Kiessling, A. Kitoh, R. Lasco, J. Lawrence, M.F. Lemos, R. Lempert, C. Lennard, D. Ley, T. Lissner, Q. Liu, E. Liwenga, S. Lluch-Cota, S. Löschke, S. Lucatello, Y. Luo, B. Mackey, K. Mintenbeck, A. Mirzabaev, V. Möller, M. Moncassim Vale, M.D. Morecroft, L. Mortsch, A. Mukherji, T. Mustonen, M. Mycoo, J. Nalau, M. New, A. Okem, J.P. Ometto, B. O'Neill, R. Pandey, C. Parmesan, M. Pelling, P.F. Pinho, J. Pinnegar, E.S. Poloczanska, A. Prakash, B. Preston, M.-F. Racault, D. Reckien, A. Revi, S.K. Rose, E.L.F. Schipper, D.N. Schmidt, D. Schoeman, R. Shaw, N.P. Simpson, C. Singh, W. Solecki, L. Stringer, E. Totin, C.H. Trisos, Y. Trisurat, M. van Aalst, D. Viner, M.Wairiu, R.Warren, P.Wester, D.Wrathall, and Z. Zaiton Ibrahim, 2022: Technical Summary. [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]., 2022) (Karacan, Mukhtarov, Barış, İşleyen & Yardımcı, 2021) (Kuznets, 1955) (United Nations Framework Convention on Climate Change (UNFCCC), 1997) (Mancur, 1965) (Murshed & Tanha, 2021) (Nguyen & Kakinaka, 2019) (Nielsen & Alderson, 1997) (Nordhaus, 2015) (NY Times, n.d.) (OECD, 2023b) (OECD, 2023d) (OECD, 2023c) (OECD, 2023e) (OECD, 2023a) (IEA, n.d.) (Omri, Daly & Nguyen, 2015) (Pigou, 1920) (Ricarco, 1817) (Sadorsky, 2009b) (Sadorsky, 2009a) (Stern, 2004) (Tidy Finance, n.d.) (United Nations - Department of Economic and Social Affairs, Population Division, 2022) (Varian, 2014) (Villar & Joutz, 2006)