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OIL PRICE UNCERTAINTY AND RENEWABLE ENERGY INNOVATION: AN INTERNATIONAL EVIDENCE

BY

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ABSTRACT

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Climate change is a significant global issue that is closely tied to efforts to decrease energy usage and increase energy efficiency. Over the last few decades, there has been a significant rise in interest regarding the development of renewable energy sources. However, despite widespread acknowledgement by researchers and policymakers of the need to shift towards renewable energy sources to address climate change, the world still relies heavily on fossil fuels. This thesis seeks to use negative binomial fixed effect model to examine how fluctuations in oil prices may affect the innovation of renewable energy technologies. Specifically, we focus on analyzing the impact of oil prices volatility on renewable energy patents count as a proxy for innovation. The study covers 80 countries over the period from 1991 to 2019. We argue that increased volatility in oil prices leads to greater innovation in renewable energy sources. Consistent with this view, we show that oil prices volatility positively impact the innovation in renewable energy.

DEDICATION

To my beloved son, who has brought immeasurable joy and meaning to my life. Your kindness, intelligence, and resilience have been a constant source of amazement and inspiration to me. This work is dedicated to you as a symbol of my endless love and, and as a reminder to never give up on your dreams and to always pursue your goals with passion and determination.

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Chapter I: Introduction

Energy has been an essential factor that covers both basic human necessities and productive activities. The industrial revolution has caused the demand for fossil fuel to increase leading to increased global output. This has contributed to raising people's income and consequently population growth. Fossil fuel and specifically oil have been the lifeblood of society. The dependence in consuming energy in 2004 which accounted for nearly 85% is dominated by fossil fuels (Sims et al., 2007), particularly crude oil, that took over coal share in the global market as the main source of energy. Oil is a major primary energy source and provides power to maintain a functioning society and economy (Guo et al., 2021; Sun et al., 2021; Zhu et al., 2021a). However, the global economy's reliance on oil-derived fuels in various sectors has left it vulnerable to several macroeconomic economic side effects. Crude oil prices are highly volatile. The economic uncertainty caused by the extreme volatility of oil prices has serious implications for the global economy. It reflects the fact that oil is the most globally traded commodity (Galyfianakis et al., 2017).

Furthermore, Price swings and market instability are exacerbated by geopolitical events and speculation surrounding oil (Eyden et al., 2019; Nouira et al., 2019). Moreover, the crude oil volatility is driven by supply-side aspects such as the inelasticity of oil supply, instability from regional conflicts, theft, and nationalization of oil companies. On the demand side, the lack of elasticity in oil demand, the political conflicts, and tensions in oil-producing regions. These factors have traditionally been the primary cause of significant fluctuations in oil prices, which have a negative impact on actual economic activity, capacity utilization rates, productivity, employment, and wages (Hamilton, 2003; Mo et al., 2019; Li et al., 2021b; Nonejad, 2021). Its widespread use has made countries, particularly importing ones, vulnerable to price shocks (Lu et al., 2019; Song et al., 2019; Wang et al., 2021a).

The widespread use of oil is raising concerns about not only price volatility, but also environmental protection (Jia et al., 2020; Smith et al., 2021). Many pollutants are produced during the oil consumption process, including carbon dioxide (CO2), which is a major source of global warming, environmental degradation, and even climate change (Mensah et al., 2019; Munir et al., 2020; Lin and Raza, 2020). The wide utilization of fossil-fuel-based material consumption and changes in consumption patterns are the primary contributors to rising GHG emissions (Fleurbaey et al., 2014). The burning of fossil fuels produced 56.6% of total anthropogenic GHG emissions (CO2) in 2004 (Rogner et al., 2007).

Limiting global warming will require massive shifts in the energy industry. This will include dramatically lowering the usage of fossil fuels, transitioning to electrical transportations, improving energy efficiency, and switching to other fuels (IPCC, 2021). A significant change in the way energy is produced and used is necessary to maintain both a sustainable economy capable of delivering necessities to people in both developed and developing countries, as well as a supporting global climate system (Nfah et al., 2007; Kankam and Boon, 2009). In recent years, technological improvements and the global search for sustainable solutions have enabled the global energy sector to transition to renewable energy sources (IPCC, 2022).

In this thesis, we advance the literature on the determinants of green innovation (e.g., Li and Shao, 2021; Zheng et al., 2021) by focusing on the role of oil price uncertainty. It also contributes to the existing literature on oil price and renewable energy (e.g., Bento et al., 2015; Cheon and Urpelainen, 2012; Go et al., 2016; Li and Shao, 2021; Liang and Fiorino, 2013; Li et al., 2022; Marin and Vona, 2021; Muhammad et al., 2022; Wang et al., 2020; Yang et al., 2019; Yuan et al., 2022; Zheng et al., 2021) by providing international evidence on the relationship between crude oil price volatility and renewable energy innovation. Specifically, we use the negative binomial fixed effect model to investigate the impact of crude oil prices volatility on renewable energy innovation in a cross-country panel consisting of 80 countries from 1991 to 2019. We expect that an increase in crude oil price volatility leads to a corresponding increase in renewable energy innovation. The intuition behind this is that higher volatile oil prices could serve as an incentive for countries to invest in alternative energy sources and reduce their dependence on fossil fuels. Our results show that renewable energy innovation is positively related to oil price volatility. Our results are robust to the use of a battery of robustness checks. Our findings have important implications for policymakers, as we show that there is a positive relationship between oil prices volatility and renewable energy innovation especially in countries that are highly dependent on oil imports. We argue that regulations are important to facilitate the adoption of renewable energy sources for countries that are more affected by oil price volatility.

Chapter 2 of this paper provides a review of the relevant literature on the relationship between crude oil prices and renewable energy innovation. We discuss the theoretical underpinnings of the relationship, as well as the empirical evidence from previous studies. Chapter 3 presents the methodology used in this study, including a description of the data and the econometric model. We also report the empirical results and discuss their implications. Finally, chapter 4 concludes the paper and provides policy recommendations based on our findings. Our results suggest that governments should implement policies that encourage investment in renewable energy technologies. By doing so, countries can reduce their dependence on fossil fuels, mitigate the risks associated with volatile oil prices, and contribute to global efforts to combat climate change. To conclude, my thesis contributes to the existing literature by providing empirical analysis derived from international evidence as our results are based on data of 80 countries. The results hold significant relevance as it offers valuable insights for policymakers and industry stakeholders striving to steer the transition towards a clean energy future.

Chapter II: Oil Prices Volatility Background

A major primary energy source and important raw material for various industries, oil plays a crucial role in enabling socioeconomic activities (Guo et al., 2021; Smith et al., 2021; Sun et al., 2021; Zhu et al., 2021a). However, the extensive use of oil has also made countries sensitive to price shocks, as noted by Lu et al. (2019), Song et al. (2019), and Wang et al. (2021a). For example, oil prices experienced significant fluctuations in 2008, rising sharply from US$90 per barrel to US$140 per barrel between January and August, before plummeting to US$40 per barrel by December of the same year. Compared to the early days of the oil industry, when prices were relatively stable and low, kerosene-driven lighting was the primary driver of oil demand. As the use of oil expanded into other sectors, such as transportation and industrial production, the demand for oil increased. The 20th century saw significant changes in the oil market, marked by the emergence of major international oil companies and the growing importance of oil as a strategic commodity (Yergin, 2006). This led to increased volatility in the oil market, as geopolitical incidents and speculative activities intensified price fluctuations and market instabilities (Eyden et al., 2019; Nouira et al., 2019). The upcoming section will discuss the factors related to oil price volatility.

2.1. Drivers of Oil Prices Volatility

Oil prices have been known to exhibit high levels of volatility, and this can be attributed to several factors, such as key characteristics of oil market fundamentals (Baumeister and Peersman, 2013; Cooper, 2003; Ellwanger et al., 2017; Hamilton, 2009; Kilian and Murphy, 2011; Murray and King, 2012; Saporta et al., 2009; Singleton, 2014), factors caused by oil derivatives market and finally factors caused by inadequate market data (Kilian and Murphy, 2011; Lipsky, 2009).

2.1.1. Oil Market Fundamentals.

The basic elements that define the fundamentals of any market are supply and demand (Kilian and Murphy, 2011). Oil market is also subject to volatility caused by supply, such as the inelasticity of oil supply (Baumeister and Peersman, 2013; Cooper, 2003; Ellwanger et al., 2017; Hamilton, 2009; Murray and King, 2012; Singleton, 2014), instability from regional conflicts, theft, and nationalization of oil companies. Moreover, the oil market is subject to demand factors such as, the lack of elasticity in oil demand (Fattouh, 2007; Jalali-Naini and Asali, 2004; Saporta et al., 2009; Tawadros, 2013), the political conflicts and tensions in oil-producing regions (Namboodiri, 1983; Triki and Affes, 2011).

2.1.1.1. Oil supply Inelasticity

There are several reasons why oil supply has become increasingly inelastic, including declining production capacity and limited discoveries of new oil fields, as well as barriers to investment in the industry (Baumeister and Peersman, 2013; Cooper, 2003; Hamilton, 2009; Kilian and Murphy, 2011; Murray and King, 2012; Singleton, 2014). For instance, in Iraq, there has been little change in infrastructure investment over the past decade due to concerns about political instability and national risks. Although unconventional oil reserves are being developed more widely, because oil producers are less able to react swiftly to price fluctuations because of their slower production rates as compared to conventional reserves (Ellwanger et al., 2017).

2.1.1.2. Oil Demand Inelasticity.

The lack of elasticity in oil demand has been mostly caused by the global economy's long-standing reliance on oil, especially in the transportation industry where oil-powered vehicles and infrastructure remain dominant despite the rise of alternative options like electric vehicles. This dependence on oil is further reinforced by the widespread subsidies for fuel consumption in non-OECD nations, which have weakened the impact of substitution and kept the demand for oil artificially high (Baumeister and Peersman, 2013; Cooper, 2003; Hamilton, 2009; Kilian and Murphy, 2011; Saporta et al., 2009; Singleton, 2014).

2.1.1.3. Regional conflicts, theft, nationalization of oil companies and Cyclicality

There are specific factors on both the supply and demand sides that exacerbate oil price volatility. On the supply side, instability from sources such as regional conflicts, theft, and nationalization of oil companies can cause significant disruptions to investment cycles and short-term supply availability, making oil supply vulnerable. For instance, global ratings agencies have highlighted the possibility of growing regulatory and investment uncertainties for companies seeking to invest in the Argentinian oil sector after the nationalization of the private oil company Yacimientos Petrolíferos Fiscales (YPF) in 2012. These factors contribute to the increasing volatility of oil prices.

Moreover, the demand for oil shows periodic changes and seasonal patterns (Jalali-Naini and Asali, 2004) which means that its relationship with real output follows the same cyclical pattern (Tawadros, 2013). This business cycle volatility can also affect oil prices. Additionally, changes in income have a greater impact on oil demand than changes in prices (Fattouh, 2007), which further strengthens the connection between oil prices and business cycles.

2.1.1.4 Role of Geopolitical Tensions

Political conflicts and tensions in oil-producing regions have traditionally been the main cause of major fluctuations in oil prices. According to (Namboodiri, 1983), the market still reacts strongly to the possibility of supply disruptions in countries experiencing political instability (Baumeister and Peersman, 2013; Cooper, 2003; Kilian, 2010; Murray and King, 2012). For example, events like the 2011 Libyan Civil

War and the ongoing tensions surrounding Iran's nuclear program have significantly increased oil prices (Triki and Affes, 2011)

2.1.2. Oil derivatives market

In response to the 1973 oil crisis, there was a consensus for the creation of effective risk management mechanisms in the oil market similar to those in foreign exchange markets. The oil derivatives market was created, offering a range of financial instruments to help oil industry players manage capital and diversify risk. Since its founding, the market for oil derivatives has grown dramatically and is now more than 14 times larger than the market for actual oil (Bruce, 2009). Advancements in technology have resulted in an increase in the number and complexity of financial instruments available to investors, leading to the development of new transaction methods and behaviors that align with market trends.

In this section, we discuss various factors contributing to oil price volatility caused by the oil derivatives market. The first factor is market inefficiencies, which are caused by non-fundamentals-based oil price volatility. The second factor is speculation as a driver of price volatility (Fattouh et al., 2013; Hamilton, 2009; Hamilton and Wu, 2011; Kilian and Murphy, 2011; Singleton, 2014), with evidence suggesting that oil prices are not solely determined by market fundamentals and can be influenced by speculative activities.

2.1.2.1. Market inefficiencies: non-fundamentals-based oil price volatility

2.1.2.1.1. Hotelling's rule

It predicts that oil prices should generally increase over time (Hotelling, 1931), but this prediction stands in contrast to the historical movement of oil prices. From 1980 to 2000, oil prices tended to decrease, with occasional bouts of volatility. It indicates that the Hotelling model's assumption of a perfectly competitive market does not accurately reflect the oil market's structural form (Livernois, 2009). The oil production quotas imposed by OPEC – the organization of exporting countries - during the 1982-1986 period, for example, significantly disrupted natural market dynamics. Additionally, OPEC's non-formulaic production ceilings further magnified market disturbance (Gault, et al., 1990). According to the WTO – the world trade organization-, the market structure of non-renewable energy resources is better characterized as imperfect (WTO, 2010). However, as the oil market becomes more transparent and less imperfect, this dynamic may change.

2.1.2.1.2. Herding behavior

In contrast to the efficient market hypothesis (EMH) proposed by Fama (1970), which suggests that the stock price reveals all relevant inside information, financial market volatility often causes investors to engage in herding behavior. Herding occurs when investors' decisions influence the market's collective behavior and cause irrational behavior, leading to market inefficiencies. Vansteenkiste (2011) argues that herding behavior and human error are creating market inefficiencies that lead to price volatility. Despite having different fundamentals, West Texas Intermediate (WTI) crude futures' cross-market correlations with the Euro Stoxx 600 and Standard and Poor's Goldman Sachs Commodity Indexes (S&P GSCI) have strengthened over the past ten years, going from almost no correlation to almost perfect correlation (Bicchetti and Maystre, 2012; Triki and Affes, 2011).

2.1.2.2. Speculation

Numerous pieces of evidence suggest that oil prices are not solely determined by market fundamentals and can be influenced by speculative activities (Fattouh et al., 2013; Hamilton, 2009; Hamilton & Wu, 2011; Kilian & Murphy, 2011; Singleton, 2014). For instance, the Persian Gulf War in 1990-1991 caused a significant increase in crude oil prices, but this did not correspond to any change in oil supply. Instead, it was due to the uncertainty created by the war. Similarly, speculative demand shocks played a crucial role in oil price volatility in 1979 (after the Iranian Revolution), 1986 (after the collapse of OPEC), and 1997-2000 (after the Asian financial crisis). Furthermore, the growing number of speculators in the crude oil market has strengthened the impact of forward-looking demand activities, which have altered the price dynamics and resulted in expectation-driven price increases (Fattouh et al., 2013).

2.1.3. Inadequate market data.

There are deficiencies in the transparency, precision, and availability of essential oil market data, such as inventories, production, stocks, and reserves, which contribute to herd behavior in oil markets (Kilian and Murphy, 2011). The imprecisions of these variables have led to the dependence on the easily accessible but relatively inadequate trends in recent oil prices as a source of investment decisions in oil price volatility (Lipsky, 2009). The Joint Organizations Data Initiative (JODI) was created in response to address the connection between OPV and the complexity of oil market data. JODI's primary goal is to increase the accuracy and accessibility of data on the oil market in order to reduce excessive price swings. Yet, despite the fact that the program has improved data openness, member nations' submission rates of data have decreased over the past three years, and the timeliness of data submissions remains irregular, adding to the uncertainty.

2.2. The Effect of OPV on the economy and the environment

Dependence on fossil fuels such as oil can have several negative impacts on the economy and the environment. One major concern is the volatility of oil prices, which can have adverse effects on the global economy. The fluctuation in oil prices can lead to inflation, increased production costs, and reduced economic growth (Kilian & Park, 2009). Moreover, the use of fossil fuels also contributes to air pollution and greenhouse gas emissions (Kartal, 2022; Lim et al., 2014; Saboori et al., 2017). This can have significant negative effects on human health and the environment. Air pollution can cause respiratory illnesses, heart disease, and even premature death. The burning of fossil fuels also contributes to the release of greenhouse gases such as carbon dioxide, which are the primary cause of global climate change (IPCC, 2014). Furthermore, fossil fuels are a finite resource, and their depletion is inevitable. As oil reserves continue to diminish, the cost of extracting oil is expected to rise, making it increasingly expensive to use (Alharthi et al., 2022; Bölük and Mert, 2014; Kilian and Park, 2009; Knight, 2018). This could lead to increased energy prices, reduced economic growth, and potential resource conflict (Rafiq et al., 2009; Duprey et al., 2017). In contrast, renewable energy sources such as wind, solar, and hydropower do not produce greenhouse gas emissions and are not subject to price volatility. Therefore, reducing dependence on fossil fuels and promoting the adoption of renewable energy sources can have significant positive impacts on the economy, the environment, and human health. Thus, the time has come to consider renewable energy as a solution.

Chapter III: Renewable energy

3.1 The Paris Agreement

Environmental concerns have grown in importance in recent years, notably in the light of the Paris Climate Accord. The agreement establishes the objective of keeping global warming well below 2°C over pre-industrial levels, with attempts to keep it under 1.5°C (UNFCCC, 2015). The goal is to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents harmful anthropogenic interaction with the climate system (UNFCCC, 1992). However, despite this goal, human activity has already resulted in a 1.1°C increase in the average global surface temperature over the pre-industrial mean, resulting in an increase in the severity and frequency of severe weather events (Allen et al., 2018)

Despite the goal set out by the Paris Agreement, current energy sector emissions patterns indicate that global temperature rise will not be contained to well below 2°C. Between 2015 and 2019, fossil fuel CO2 emissions increased by 4.6%, reaching 38 GtCO2 yr-1 and accounting for over two-thirds of yearly worldwide anthropogenic GHG emissions.

During the COVID-19 pandemic, governments imposed social isolation and lockdowns to prevent viral spread, resulting in a significant decrease in demand for fossil fuels. This forced major economic operations to a standstill, resulting in a 7.8% drop in worldwide CO2 emissions owing to a decrease in fossil fuel consumption during the first quarter of 2020 compared to the same period of 2019 (Liu et al., 2020).

3.2 Energy consumption and the environment

The Paris agreement on climate change has stimulated a growing body to examine the effect of energy consumption and environmental degradation. For instance, Lim et al. (2014) studied the relationship in the Philippines from 1965 to 2012 using Johansen cointegration and Granger-causality tests. Saboori et al. (2017) examined the nexus in three East Asian oil-importing countries for the period of 1980–2013, utilizing several tests such as the Granger causality test, Johansen cointegration test, generalized impulse response functions, and variance decompositions. Similarly, Kartal (2022) analyzed the top-five carbon-producing countries from 1965 to 2019, utilizing Multivariate Adaptive Regression Splines (MARS) to search for a similar nexus. Zhang et al. (2022) conducted a study on top carbon emitter countries and found that as the economy rapidly expands, there may be a temptation to rely on environmentally damaging energy sources to meet the growing demand for energy. This tradeoff could lead to a decline in environmental quality, as the use of non-renewable energy sources can contribute to greenhouse gas emissions and other forms of pollution.

3.3 Renewable energy as a solution

Renewable energy has emerged as a viable alternative to traditional fossil fuels such as oil in recent years (University of Surrey, 2023). Many countries have recognized the potential benefits of renewable energy and have taken steps to promote its adoption. According to a report by the International Energy Agency (IEA), the share of renewable energy in global power generation is expected to reach 30% by 2024 (IEA, 2019). The report highlights the declining costs of renewable energy technologies as a key driver for their increasing adoption. As the cost of renewable energy continues to decline, it is becoming increasingly competitive with traditional fossil fuels such as oil. Furthermore, the volatility of oil prices has led to significant uncertainty in the crude oil market. This volatility can have adverse effects on the global economy, as it affects the price of other commodities and increases the cost of production for many industries (Kilian & Park, 2009). Therefore, there is a growing need to reduce dependence on oil and promote the adoption of renewable energy sources. The adoption of renewable energy can also have positive environmental effects (Sharma et al., 2021; Zeng et al., 2017). Fossil fuels such as oil are a major contributor to greenhouse gas emissions, which are the primary cause of global climate change. Promoting the use of renewable energy sources is therefore crucial to lowering carbon intensity since they contain less carbon and are less polluting than non-renewable energy sources (Adams and Nsiah, 2019; Zeng et al., 2017). Consistent with this view, Sharma et al. (2021), using a sample from eight developing Asian countries, show that renewable energy solutions are negatively associated with ecological footprint. Sharif et al. (2020) found that increased usage of renewable energy solutions helps to reduce ecological footprint in Turkey. Inglesi-Lotz and Dogan (2018) explored the relationship between renewable energy use and CO2 emissions in Sub-Saharan Africa. They show that increases in nonrenewable energy consumption decrease pollution. Similar results were found in studies conducted by Dogan and Seker (2016) for the European Union and Bilgili et al. (2016) for 17 OECD members. Bhattacharya et al. (2017) studied the effect of institutions and renewable energy on CO2 emissions across 85 countries and found that renewable energy reduces CO2 emissions.

Transitioning to renewable energy systems can also contribute to economic growth (Bórawski et al., 2019). Inglesi-lotz (2016) shows a positive relationship between renewable energy consumption and economic growth in the OECD regions. Khobai and Roux (2017) show that renewable energy consumption has a positive impact on economic growth in South Africa. Similarly, Dees and Auktor (2018) show that renewable electricity generation has a significant and positive effect on economic growth in the MENA region.

3.4. Renewable energy types

Based on Igli´nski et al., (2022) and Algarni et al., (2023), renewable energy innovation can be based into the following renewable energy types:

3.4.1 Wind

Wind power is considered highly eco-friendly, as it doesn't emit pollutants into the air or waterways, use harmful chemicals, or pose health risks. The utilization of wind turbines to produce electricity has become cost-competitive and highly efficient, producing minimal pollutants (Zheng et al., 2017). Wind turbines harness the power of the wind to rotate a motor and generate electricity. Wind energy is considered a virtually limitless and renewable resource, and it doesn't require gasoline or damage the environment. Wind generators transform the wind's kinetic energy into various forms of energy, such as electric or internal combustion engine power (Yang et al., 2019). Windmill turbine harnesses wind power and converts it into rotational kinetic energy to power an alternator. Wind energy is one of the most rapidly expanding forms of renewable energy worldwide, obtained through relatively simple technological solutions such as wind turbines, which are part of wind power plants that convert the wind's kinetic energy into mechanical or electrical energy (Igli´nski et al., 2022).

3.4.2 Solar Energy

Solar energy is an environmentally friendly and sustainable source of electricity (Khan and Abas, 2012). As the ultimate source of all energy on Earth, the sun produces an enormous amount of energy that can be harnessed through various methods such as photosynthesis and photovoltaic (PV) electricity generation (Khan and Abas, 2012*; Shaikh et al., 2017)*. In fact, the sun accounts for approximately 99.99% of all the energy on the planet, while the remaining 0.01% is provided by the Earth (Khan et al., 2017). The potential of solar energy is enormous, with estimates suggesting that the sun could release up to 450 EJ of energy, which is equivalent to 7500 times the current global energy demand (Dinçer, 2011). Solar photovoltaics (PV) is a particularly popular choice in the energy sector, with an increasing number of countries using PV systems to generate more than 20% of their electricity (Hassan et al., 2022). The use of silicon in the production of solar cells has been a significant milestone in the development of PV technology, resulting in an efficiency increase of up to 6% in energy return (REN21, 2022). the PV industry is currently the fastest-growing industry globally, and its continued growth is essential to meet the world's increasing demand for clean and renewable energy (Hassan et al., 2022; REN21, 2022)

3.4.3 Geothermal energy

Geothermal energy is a type of renewable energy that uses the earth's internal heat to produce electricity or heat for structures. It produces 56 Megawatts of power in New Guinea using the heat and pressure of the planet (Akojwar and Kshirsagar, 2016).

Geothermal energy used to produce electricity performs better than carbon fuels in terms of pollution. Hydrothermal facilities generate much less azoth oxide pollution than fossil-fueled power stations do (Onu and Mbohwa, 2018).

3.4.4 Biomass Energy

Bioenergy power is derived from the burning of plant materials known as biomass, which is a renewable organic substance originating from both animals and plants (EIA, 2020). This includes any organic matter, whether of plant or animal origin, that can be used as fuel, such as wood, or residuals of food. Burning wood and animal waste for residential uses accounts for 11% of the world's total energy consumption; in emerging economies, this number rises to 30%. In reality, wood or briquettes are used in approximately 70% of households in developing countries for both cooking and heating (Simpson-Porco et al., 2017; Zhang et al., 2018).

3.4.5 Hydro energy

Hydropower, which involves harnessing the force exerted by water in motion to produce electricity, is commonly referred to as "hydroelectricity". Currently, it accounts for 16% of the world's power output and is expected to continue expanding at a rate of 3.1% annually, making it one of the most popular sources of clean energy. This is largely due to the fact that hydropower is a renewable energy source that is cost-effective (Algarni et al., 2023). It is the most prominent source of renewable electricity in the world and was perhaps the first renewable resource of energy on the planet (Breeze, 2018). Since its inception, hydropower has supplied the largest amount of renewable electricity worldwide. The global electricity grid system relies heavily on hydropower as a renewable energy source (Kuriqi et al., 2020). Unlike fossil fuels, hydroelectric facilities produce no pollution, which makes it an environmentally friendly alternative (Onu and Mbohwa, 2018). In addition to its use as a source of electricity, the infrastructure created for hydroelectricity also provides benefits such as the provision of water that is fit for drinking, leisure pursuits, and environmental improvements (Onu and Mbohwa, 2018)

3.5 Challenges to renewable energy

In recent years, there has been a significant push towards transitioning to renewable energy sources, such as solar, wind, and hydropower, in order to reduce greenhouse gas emissions and combat climate change. Governments, businesses, and individuals around the world are increasingly investing in renewable energy infrastructure and technology (Gielen et al., 2019; Kalair et al., 2021). One of the major challenges in this transition is the need to replace existing fossil fuel-based energy infrastructure with renewable alternatives. This requires significant investments in new infrastructure, as well as changes to existing policies and regulations to support the growth of renewable energy. Despite these challenges, many countries are making progress towards transitioning to renewable energy (Bölük & Mert, 2014; Gielen et al., 2019; Kilian & Park, 2009). In some cases, this is driven by government policies and incentives, while in others it is being driven by market forces as renewable energy becomes increasingly cost-competitive with traditional energy sources (Marro & Bertsch, 2015).

Chapter IV: Literature review and hypothesis development

4.1. Literature review

Different studies have explored the relationship between OPV and renewable energy patents (REP) activity in renewable energy technologies. Some studies have found a positive relationship between OPV and REP, indicating that periods of high oil price volatility stimulate innovation in these sectors. For example, Liang and Fiorino (2013) examined data from 1974 to 2009 in the United States and found that OPV positively affects REP applications, particularly in solar and wind power sectors. Similarly, Li et al. (2022) studied N11 countries from 1995 to 2018 and observed a positive effect of OPV on wind energy innovation (WEI). These studies suggest that increased attention and investment in renewable energy during periods of high oil price volatility contribute to innovation.

However, other studies have reported no significant relationship or even a negative relationship between OPV and REPs. Yuan et al. (2022) found no significant effect of OPV on wind energy patenting activity in China, suggesting that factors such as government policy support and technological advancements play a more significant role in wind energy innovation in China. Wang et al. (2020) studied the United States and reported a negative relationship between OPV and solar thermal patents, explaining that solar thermal technologies, being in the early stages of development and highly dependent on subsidies and incentives, are more vulnerable to fluctuations in oil prices. This section will elaborate on the relationship between OPV and REI based on previous studies.

Wind energy and solar thermal technologies have seen significant innovation and investment in recent years, and they are key components of the transition to a low-carbon economy. The development and deployment of these technologies have been driven by a range of factors, including policy support, technological advancements, and cost reductions. One potential factor that may influence innovation in wind energy and solar thermal technologies is oil prices volatility (OPV). Some studies have found evidence of a positive relationship between oil prices volatility (OPV) and renewable energy patents (REP) activity in these areas, while others have found no significant relationship or even a negative relationship (Nunes & Catalão-Lopes, 2020; Sterlacchini, 2020). To investigate the relationship between oil prices volatility (OPV) and renewable energy patents (REPs), several studies have used different datasets and methodologies. In this section, we will review some of the key empirical studies on the relationship between OPV and wind energy and solar thermal patents.

Liang and Fiorino (2013) examined the relationship between Oil Price Volatility (OPV) and REP (REP) applications in the United States. The study used data from 1974 to 2009. The study found that OPV positively affects REP applications in the United States, particularly in the solar and wind power sectors. The authors suggest that the positive effect is due to the increased attention and investment in renewable energy during periods of high oil price volatility. Similarly, Li et al. (2022) examined the relationship between OPV and Wind Energy Innovation (WEI) in N11 countries from 1995 to 2018. The study shows that OPV has a positive effect on WEI. The authors suggest that the positive effect is due to the government's increased policy support for renewable energy during periods of high oil price volatility. Kumar et al.(2020) use time-series models that examine the relationship between oil prices and REPs over time. They report a positive relationship between oil prices and REPs in the short run, but no significant relationship in the long run.

In contrast, Yuan et al. (2022) examined the relationship between OPV and wind energy patenting activity using monthly data 1973:M1 to 2021:M6. The study found no significant effect of OPV on wind energy patenting activity in China. The authors suggest that other factors, such as government policy support and technological advancements, are more important drivers of WEI in China. Another study by Wang, et al. (2020) examine the relationship between OPV and solar thermal patents in the United States. The study used patent data from the USPTO from 1975 to 2014, and oil price volatility data from the EIA over the period from 1986 to 2014. The results show a negative relationship between OPV and solar thermal patents in the United States. The authors suggest that this negative effect is due to the fact that solar thermal technologies are still in the early stages of development and are highly dependent on government subsidies and incentives. When oil prices are volatile, governments may be less likely to provide funding and incentives for these technologies, leading to a decrease in innovation activity.

Other empirical studies examine the relationship between OPV and REPs. For instance, Muhammad et al., (2022) examined the relationship between oil prices and REPs in 23 OECD countries from 1990 to 2015. The results show a positive relationship between oil prices and REPs in general, but the strength of the relationship varied across countries and renewable energy technologies. The authors suggest that government policy support, technological advancements, and market demand are important drivers of Renewable Energy Innovation (REI), and these factors may interact with OPV to influence patenting activity. Zheng et al. (2021) uses the nonlinear autoregressive distributed lag (NARDL) model, investigate the "asymmetric link between oil shocks and the carbon emission trading market in China." in China from 2013 to 2020. The results show a positive relationship between OPV and REPs in China, but the effect was weaker for solar energy patents than for wind energy patents. The authors suggest that the positive effect of OPV on REI may be due to the increased attention and investment in renewable energy during periods of high oil prices, but the effect may be weaker for solar energy technologies that are less mature and still highly dependent on government subsidies and incentives. The authors suggest that this may be due to the fact that wind energy technology is more mature and well-established in China, and therefore more able to respond quickly to changes in market conditions. By contrast, solar energy technologies are still in the early stages of development and rely heavily on government subsidies and incentives to be competitive. As such, the positive effect of OPV on solar energy innovation may be weaker in the short term but could become stronger as the technology matures and becomes more competitive.

Go et al. (2016) investigated the relationship between oil prices and solar photovoltaic (PV) patent applications in the United States. The results show that higher oil prices are associated with an increase in solar PV patent applications, suggesting that changes in the price of oil can have a positive impact on innovation in this particular technology. Similarly, Marin and Vona (2021) report a positive relationship between oil prices and wind energy patent applications in France by using data from 1997 to 2015, indicating that periods of high oil prices can stimulate innovation in wind energy. Bento et al. (2015) used a time-series model to investigate the impact of oil prices on wind energy patents in the United States from 1974 to 2008. The results show that higher oil prices were associated with an increase in wind energy patents, particularly in the early stages of wind energy development.

However, other studies do not report a positive relationship between OPV and REI. For instance, Li and Shao (2021) examine the relationship between oil prices and REPs in OECD countries from 1990 to 2018. The results show no significant relationship between oil prices and REPs, suggesting that factors other than oil prices are more important drivers of innovation in the renewable energy sector in Korea. Similarly, Yang et al. (2019) report a negative relationship between oil prices and solar energy patents, indicating that periods of low oil prices may actually stimulate innovation in the solar energy sector. The authors suggest that this may be due to the fact that low oil prices reduce the cost of energy production, making it more difficult for renewable energy technologies to compete in the market. As such, periods of low oil prices may actually stimulate innovation in the renewable energy sector by incentivizing researchers and firms to develop more cost-effective and efficient technologies. Cheon and Urpelainen (2012) used a sample from 1989 to 2007 to test the "theoretical argument against data on public R&D spending and patents in the sphere of renewable energy technologies for developed nations". The study found no significant relationship between oil prices and REPs, suggesting that other factors may be driving REI in Sweden. Similarly, a study by Sun et al. (2018) analyzed the impact of oil prices on solar thermal patents in China from 1990 to 2014. The results show a negative relationship between oil prices and solar thermal patents, suggesting that high oil prices may reduce the incentive for REI in some contexts.

Based on the discussion above, several potential mechanisms through which oil prices may influence patenting activity in the renewable energy sector. One potential mechanism is the cost of energy production (Aklin and Urpelainen, 2013).

When oil prices are high, the cost of fossil fuel energy production increases, making renewable energy technologies relatively more competitive in the market (Sims, et al., 2003). This can incentivize researchers and firms to invest more resources in developing renewable energy technologies, leading to an increase in patenting activity in this sector. Conversely, when oil prices are low, the cost of fossil fuel energy production decreases, making it more difficult for renewable energy technologies to compete in the market (Foster et al., 2017; Sims et al., 2003). This can lead to a decrease in patenting activity in the renewable energy sector.

Another potential mechanism is government policy. When oil prices are high, governments may be more inclined to support the development of renewable energy technologies as a way to reduce their dependence on imported fossil fuels and mitigate the risks associated with volatile oil prices (Poudineh, et al., 2018). This can take the form of subsidies, tax incentives, and other forms of government support for REI. These policies can help to create a more favorable environment for renewable energy research and development, leading to an increase in patenting activity in the sector. Conversely, when oil prices are low, governments may be less likely to support REI as the urgency to reduce dependence on fossil fuels may decrease (Foster et al., 2017; Poudineh et al., 2018).

According to Cheon and Urpelainen (2012), countries having established efficient innovation systems in the relevant industries are more likely to experience an increase in energy technology innovation due to global oil prices. They highlight that the traditional theories alone such as induced innovation or positive feedback are inadequate in explaining the complex dynamics of how international oil prices influence innovation in the energy sector. Rather, they argue it is contingent upon certain conditions or factors that vary across contexts.

These factors can include the presence of a strong system for sectoral innovation, prior experience with technological innovation, the capacity of political institutions to create efficient policies, and the impact of private corporations. International oil prices, which serve as exogenous price shocks, are what drive the need for new energy technology, claim Cheon and Urpelainen (2012). Energy shortages in several nations are linked to rising oil prices (Geller et al., 2006; Ikenberry, 1986). Global demand for innovative energy technology is anticipated to increase significantly as oil prices rise. Energy industry stakeholders are eager to spend money on innovative solutions that reduce prices or conserve energy.

In their study, Cheon and Urpelainen (2012) draw the conclusion that a rise in global oil prices triggers energy technology innovation within the private sector, provided that the sectoral innovation system has already reached a certain level of capability. Additionally, their findings reveal robust evidence suggesting that international oil prices also foster public funding for research and development (R&D) in new energy technologies, but again, this effect is contingent upon the sectoral innovation system having attained a certain level of capacity.

Furthermore, the impact of oil prices on REI can vary depending on the specific renewable energy technology. For example, some technologies may be more sensitive to changes in oil prices than others. Additionally, the maturity of a technology and its level of market penetration can also play a role in how it responds to changes in oil prices. For instance, as mentioned earlier, wind energy technology may be more mature and well-established in certain regions, making it more responsive to changes in market conditions than other renewable energy technologies.

In conclusion, while the empirical evidence on the relationship between OPV and REPs is mixed. The impact of oil prices on REI may depend on a variety of factors, including the specific renewable energy technology, the maturity of the technology, and the level of government support for REI. The objective of this thesis is to add to this literature by examining the impact of oil price volatility on a large sample of countries including both of OECD and non-OECD countries and using proxy for patents for different types of renewable energy technology such as solar energy, wind energy, hydro energy, geothermal energy and biomass energy.

4.2 Hypothesis Development

Our hypothesis is that oil price volatility positively influences renewable energy innovation. There are several reasons why OPV may have a positive impact on renewable energy innovation. First, Dependence on oil imports can pose significant energy security risks for oil importing countries, especially in times of geopolitical turmoil. Therefore, countries may seek to reduce their dependence on oil by promoting renewable energy sources, which can lead to increased innovation in the sector (Bórawski et al., 2019). Second, Oil prices volatility has a direct impact on three significant macroeconomic channels, namely consumption, investment, and industrial production (Başkaya et al., 2013; Bredin et al., 2011; Castillo et al., 2010; Federer, 1996; Guo and Kliesen, 2005; Rafiq et al., 2009; Sadorsky, 1999; Salim and Rafiq, 2011). And in the long run this volatility can increase inflation and unemployment (Castillo et al., 2010; Guo and Kliesen, 2005; Rafiq et al., 2009 Plante and Traum, 2012). To mitigate these issues, countries may promote renewable energy. Third, many pollutants are produced during the oil consumption process, mainly carbon dioxide (CO2), a significant contributor to climate change, environmental deterioration, and global warming (Mensah et al., 2019; Munir et al., 2020; Lin and Raza, 2020). Renewable energy is an important tool for reducing CO2 emissions and achieving carbon neutrality goals (Sarwar and Alsahhaf, 2021; Nikzad and Sedigh, 2017; Yue et al., 2021; Shan et al., 2021). Therefore, to mitigate the economic and environmental risks associated with dependence on oil and as response to institutional pressure, governments may increase their support for renewable energy innovation (Lui et al., 2021; Amores-Salvado et al., 2014; Li et al., 2022; Muhammad et al., 2022). Based on this discussion, our hypothesis states that:

H1: Oil price volatility positively impacts renewable energy innovation.

Moreover, we expect that the impact of oil price volatility on renewable energy innovation is greater in non-OECD countries compared to OECD countries. This is due to the relatively lower economic development (Feng and Zheng, 2022) and higher income elasticity of oil demand in non-OECD countries (Gately and Huntington, 2002; Dargay and Gately, 2010), which makes them more vulnerable to the effects of oil price volatility. As a result, non-OECD countries may experience a stronger drive for innovation in the renewable energy sector as a means to reduce dependence on oil and mitigate economic and environmental risks. In contrast, OECD countries, with their higher economic development and established institutional frameworks, may have greater capacity to manage and adapt to oil price volatility, leading to a relatively weaker impact on renewable energy innovation.

H2: The impact of oil price volatility on renewable energy innovation is greater in non-OECD countries compared to OECD countries.

Chapter V: Research Design and Methods

5.1. Sample and Data Sources

The study utilizes annual data from 1990 to 2019, resulting in a total of 2,212 observations, to analyze the relationship between oil price volatility and renewable energy innovation. We excluded the data for the years 2020 and 2021 that are affected by the COVID-19 pandemic. The data for the year 2022 is dropped as it is insufficient to provide post-pandemic comparison. The study includes data from 80 countries, table A1 in the appendix, shows the list of countries included in the analysis. The sources of data for the variables include the World Bank Development Indicators, Fraser Institute database, OECD Environmental Statistics, the Patent Cooperation Treaty (PCT) - OECD database, Federal Reserve Bank of St. Louis, World Bank database, and Energy Information Administration database – Sources of data for each variable is clearly presented in table A2 in the appendix.

5.2 Variables

5.2.1 Dependent Variable

We use the international renewable energy patent count obtained from the OECD database under the Patent Cooperation Treaty (PCT) as our proxy of renewable energy innovation. The count of renewable energy patents filed or authorized is commonly employed as a proxy measure for evaluating the level of innovation in the renewable energy sector (e.g., Bointner, 2014; Nesta et al., 2014; Li and Shao, 2021). To further investigate the impact of oil prices volatility on innovations in renewable energy, we categorized the renewable energy patents into four groups: wind energy, solar energy, geothermal energy, and marine energy. Solar energy encompasses solar thermal energy, solar photovoltaic (PV) energy, and solar thermal-PV hybrids.

5.2.2 Key test variable

To analyze the impact of oil prices uncertainty on renewable energy innovation, two measures of crude oil price uncertainty are utilized. The first measure, denoted as *SD_WTI*, is the annualized standard deviation of daily closing oil price for the nearest contract to maturity of West Texas Intermediate (WTI) futures. Second measure, denoted as *SD_BRENT*, is the annualized standard deviation daily returns of Brent Oil Futures oil prices. The prices are collected from Federal Reserve Bank of St. Louis database (fred) and the U.S. Energy Information Administration database (EIA), respectively. These measures have been frequently utilized in prior research (e.g., Phan et al., 2019; Sadorsky, 2008).

5.2.3 Control variables

In order to ensure the reliability of the estimation results, we control for the following variables:

- Renewable energy capacity is a useful indicator for assessing a country's potential to host innovative technologies in renewable energy (Huber, 2008). We control for renewable energy capacity using the total installed capacity of renewable electricity measured in million kilowatts (*LRECAP*), in line with Zheng et al. (2021).

- Renewable energy output. A greater demand in the renewable energy market can motivate investors and entrepreneurs to undertake renewable energy innovation projects, as they expect higher returns from successful green innovation (Herman and Xiang, 2019). We hence utilize the amount of power produced by renewable energy sources in relation to the overall power production output (*REPWR*) to capture the effect of market demand on renewable energy (Feng et al., 2019; Li and Shao, 2021) and to evaluate the effectiveness of the renewable energy innovation system (Cheon & Urpelainen, 2012), with a unit of billion kilowatt-hours.

- Economic development. We use the natural logarithm of GDP per capita (in 2015 US dollars) to measure the national level of economic development (*LGDPPC*). Economic development reflects the resources allocated to renewable energy innovation activities, which need to account for fixed costs and associated risks (Galeotti et al., 2020; Song et al., 2021; Chang et al., 2021). The adoption and utilization of renewable energy sources in developed and developing countries is positively significantly influenced by gross domestic product (GDP) (Bayale et al., 2021; Radmehr et al., 2021).

- Institutional environment. Drawing on the "Porter Hypothesis," Park and Ginarte (1997) as well as Deng and Liao (2009) that have highlighted the positive effect of institutional factors on innovation. This hypothesis posits that good institutional factors can enhance people's motivation to innovate and increase efficiency (Deng & Liao, 2009). To test this relationship, we control for three institutional factors that have been utilized in prior studies (e.g., Li and Shao, 2021). We control for several factors, including Legal and Property *(LPI*), Trade Freedom (*TFI*), and Sound Money (*SMI*). Legal and Property (*LPI)* pertains to the protection of individuals and their lawful property, which includes the rule of law and assurance of property rights. Trade Freedom (*TFI*) measures the freedom to exchange goods and services across international borders. Sound Money (*SMI*) assesses the rate of inflation and the freedom to hold foreign-currency bank accounts. All of these indices range from 0 to 10, with higher scores indicating stronger legal institutions.

- Co2 emissions (*VCO2*). The increasing realization of the impacts of global warming and the subsequent introduction of global policies aimed at reducing greenhouse gas (GHG) emissions have led to the recognition that renewable energy innovation can contribute to the reduction of CO2 emissions (Tobelmann and Wendler, 2021). Hence, we use *CO2* emissions (*VCO2*) as a control variable due to global pressure to maintain low CO2 emissions. Lui et al. (2021) argue that companies face pressure from the government and environmental groups to increase investment in renewable energy innovation to mitigate environmental damage. Therefore, we expect a positive relationship between co2 emissions and renewable energy innovation.

5.3. Empirical model

To examine the impact of oil price volatility on renewable energy, we estimate the following equations:

$$REI_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\mathrm{t}} \quad (1)$$

$$REI_{i,t} = \alpha_i + \beta_1 SD\_BRENT_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\mathrm{t}} \quad (2)$$

where *i* indicates country and *t* indicates time. *REI* is the dependent variable. It represents innovation in renewable energy technologies. *SD_WTI* is the standard deviation of West Texas Intermediate (WTI) futures daily oil prices and *SD_BRENT* is the standard deviation of Brent Oil Futures daily prices. *CONTROLS* refers to a vector including the following control variables: *LRECAP* is the logarithm of the total amount of renewable electricity that has been installed, measured in million kilowatts, *REPWR* is the proportion of the power generated from renewable sources out of the total capacity, expressed in billion kilowatt-hours, *LGDPPC* is logarithm of GDP per capita in billions of constant 2015 U.S, *LPI* is legal property rights index, *TFI* is trade freedom index, *SMI* is sound money index and *VCO2* is CO2 emissions. Moreover, we include year dummy variables to control for year fixed effects. ε captures the variability in the dependent variable that cannot be explained by the independent variables. Table A2 in the appendix provides definition and data sources of our variables.

5.4. Model specification

To construct a model suitable for analyzing the impact of uncertainty in oil prices on the innovation of renewable energy, several tests are carried out to determine the most suitable model for empirical analysis.

5.4.1. Breusch Pagan Lagrange Multiplier test

To verify the existence of a panel effect in the data, the Breusch Pagan Lagrange Multiplier test (Breusch and Pagan, 1980) was performed, which tested the null hypothesis that the data was pooled. The results of Table 1 confirmed that there was a panel effect at the 5% significance level, indicating that panel data analysis was appropriate for the study. As noted by Gujarati and Porter (2015), panel data models are ideal when information from the same cross-sectional units exists over time, as they allow for the classification of the non-observable factors that influence the dependent variable into two types: those that are constant and those that vary over time.

Table 1. Results of Breusch pagan LM test

Variables	Hypothesis	(1) Prob	(2) Result
SD_WTI	H0: There is no panel effect	0.00	reject, there is panel effect
SD_BRENT		0.00	

This table reports results of Breusch pagan LM test on REI.

5.4.2. Negative Binomial model

We consider the number of patents filed or authorized for renewable energy as a proxy for measuring innovation (as discussed in section 3.2.1.). It is important to note that the dependent variable, which we refer to as REI (Renewable Energy Innovation), exhibits a higher standard deviation compared to its average value, as shown later in summary statistics in table 3. Moreover, table 2 shows the results of the Jarque-Bera normality test which is used to assess whether the residuals (the differences between the observed and predicted values) in a regression model follow a normal distribution. In this case, the null hypothesis (H_o) is that the residuals are normally distributed.

Based on the results provided, the test statistics for both Model (1) and Model (2) are extremely large (4.0e+05), indicating a substantial deviation from normality. A significant deviation from normality suggests that the residuals do not follow a perfect normal distribution in either model.

Additionally, we observe a significant proportion of zero values in the data, indicating instances where no patents were filed or authorized for renewable energy. This excess of zeros and the overdispersion in the remaining non-zero counts can pose challenges when using traditional regression models. To address these concerns and account for the overdispersion as well as the excess zeros in the dependent variable, we employ a negative binomial model.

The negative binomial regression model is a statistical method used to analyze count data, where the dependent variable represents the number of occurrences or events. It is an extension of the Poisson regression model, which assumes that the mean and variance of the count are equal. In the negative binomial regression model, the dependent variable follows a negative binomial distribution, which allows for overdispersion, meaning that the variance can be greater than the mean. This makes it suitable for count data that exhibit extra variation or clustering beyond what is expected from a Poisson distribution (Hible, 2012).

The negative binomial regression model encompasses the Poisson distribution as a special case. In other words, when the variance equals the mean, the negative binomial distribution reduces to the Poisson distribution. The probability mass function of the negative binomial model, as represented by the equation below, it describes the likelihood of observing a specific count outcome:

$$B(z_i) = P(Z_i = z_i) = \frac{\omega(z_i + \varphi^{-1})}{\omega(z_i + 1)\omega(\varphi^{-1})}\left(\frac{\varphi^{-1}}{\varphi^{-1} + \mu_i}\right)^{\mu_i}\left(\frac{\mu_i}{\varphi^{-1} + \mu_i}\right)^{z_i}$$

μ_i =Exp$(X_i\alpha + \varepsilon_i)$ = Exp$(X_i\alpha) + Ex(\varepsilon_i)$

Where, ε_i represents the presence of variance heterogeneity, indicating that the variability in the data may differ across different observations. The parameter θ, on the other hand, is a discrete parameter that influences and characterizes the model's behavior and outcomes.

In the negative binomial regression model, the focus is on estimating the parameters that capture the relationship between the dependent variable and the independent variables. The negative binomial model is particularly suitable for count data with overdispersion and excess zeros, as it allows for a flexible and robust estimation of the relationship between variables while accommodating the observed heterogeneity in the data.

By taking into account the overdispersion in the data, where the variance exceeds the mean, this model provides a more flexible framework for analyzing count data compared to the Poisson regression model. The model estimates the relationship between the dependent variable and a set of independent variables by calculating the logarithm of the mean count as a linear combination of the independent variables. The model parameters are estimated using maximum likelihood estimation:

$$LL(z_i) = \sum_{i=1}^{n}\left\{\ln\left(\frac{\omega(z_i + \varphi^{-1})}{\omega(z_i + 1)\omega(\varphi^{-1})}\right) - (z_i + \varphi^{-1})\ln(1 + \varphi\mu_i + z_i\ln(\varphi\mu_i)\right\}$$

By utilizing the negative binomial model, we can effectively capture the impact of various independent variables on renewable energy innovation, considering both the presence of zeros and the variability in the non-zero counts (Hsiao, 2003; Chen, 2010).

Table 2. Jarque-Bera normality test

	Model (1)	Model (2)
Chi X	0	0
t-statistics	4.00E+05	4.00E+05

5.4.3. Hausman test

To choose between the fixed effects and random effects models, we used the Hausman test (Hausman, 1978) to test the null hypothesis that random effects were consistent and efficient. The results of Table 3 showed that p-value of the Hausaman test for both model is 0.000 suggesting that the fixed effects model is more appropriate for the analysis. We reject the null hypothesis that random effects model is consistent and efficient. This finding is consistent with the recommendation made by Wooldridge (2010) that fixed effects models are better suited for panel data analysis as they allow for the capture of differences between units by differences in the intercept. In particular, the negative binomial fixed effect model was selected after conducting the Hausmann test. This model accounts for potential endogeneity issues and has been shown to be more suitable for modeling count data with clustering features (Hible, 2012). By using this model, the study can better understand the impact of oil price volatility on renewable energy innovation while controlling for other relevant factors.

Table 3. Results of Hausman's test

Variables	Hypothesis	(1)	(2)
		prob	Result

SD_WTI	H0: Random effect model is appropriate	0.001	reject, fixed effect model is appropriate
SD_BRENT		0.001	

This table reports results of Hausman's test on REI.

5.5. Summary statistics

Table 4 provides an overview of the summary statistics of all variables included in our dataset. The summary statistics reported include essential measures such as the mean, median, standard deviation, and the 25th and 75th percentile values for each variable. We note that the average crude oil price uncertainty for WTI futures is 6.062% which is close to the uncertainty of Brent Oil Futures prices of 6.186%. Mean value of 0.353% for amount of power produced by renewable energy sources in relation to the overall power production capacity (*REPWR*), is low compared to targeted renewable share by the directive legislative act of the European Union (RED II, 2018). It considers a share of at least 30% by 2030 to be necessary to achieve climate targets. The mean value of CO2 emissions is 6.236 and the median is 5.59 which is slightly lower than the mean. It indicates that there may be a few countries in the sample with very high carbon dioxide emissions per capita that are skewing the average.

Table 4. Summary statistics

Variable	Mean	Median	Standard Deviation	25th percentile	75th percentile
REI	2.001	1.609	1.865	0.223	3.141
SD_WTI	6.062	5.188	5.462	2.613	6.806
SD_BRENT	6.186	5.335	5.519	2.483	7.072
LRECAP	0.817	1.051	2.163	-0.045	2.087
REPWR	0.353	0.186	0.487	0.063	0.527
LGDPPC	9.146	9.179	1.301	8.188	10.372
LPI	1.751	1.766	0.286	1.560	2.001
SMI	2.078	2.184	0.254	1.954	2.250
TFI	1.953	2.027	0.310	1.859	2.127
CO2	6.236	5.590	5.092	2.244	8.440

This table reports selected descriptive statistics of variables.

Table A3 in the appendix presents the results of the correlation analysis conducted on the variables. The analysis indicates that the majority of the variables exhibit low - significant correlation at a level of 1% which mitigate multicollinearity problem (Gujarati & Porter, 2015) as illustrated in the results of the variance inflation factor (VIF) test in table 5, except for SD_WTI and SD_BRENT are highly correlated with each other, with a correlation coefficient of 0.9931. As they are used interchangeably as the key test variables in the analysis. The results show in both Model (1) and Model (2), have a VIF less than or equal to 5, indicating low to moderate multicollinearity (O'brien, 2007). Specifically, the mean VIF for both models are 2.04, which is relatively low. This suggests that the independent variables in the models have a reasonable degree of independence and provide unique information in explaining the dependent variable.

Table 5. Results of VIF test

Model (1)			Model (2)	
Variable	VIF	1/VIF	VIF	1/VIF
LGDPPC	5.41	0.18	5.42	0.18
LPI	3.91	0.26	3.91	0.26
CO2	2.72	0.37	2.72	0.37
REPWR	2.04	0.49	2.04	0.49
LRECAP	1.81	0.55	1.81	0.55
TFI	1.62	0.62	1.62	0.62
anglo	1.49	0.67	1.49	0.67
SMI	1.36	0.73	1.36	0.74
latineurope	1.34	0.74	1.34	0.74
easteurope	1.33	0.75	1.33	0.75
latin	1.26	0.80	1.26	0.80
confucian	1.17	0.85	1.17	0.85
SD_WTI	1.02	0.98	1.03	0.97
Mean VIF	2.04		2.04	

5.6. Empirical analysis and discussion

5.6.1. Baseline results

Table 6 shows the results of impact of oil prices uncertainty on renewable energy innovation under the fixed effect negative binomial model. Model 1 uses *SD_WTI* while model 2 uses *SD_BRENT* as key test variables. The results indicate that the *SD_WTI* in model (1) is statistically significant at the 1% level, with a positive sign (0.085). This suggests that an increase in oil price volatility (as measured by *SD_WTI*) is associated with an increase in the count of renewable energy patents. The coefficient for *SD_BRENT* in the second model (2) is also statistically significant at the 1% level, with a positive sign (0.062), also suggesting a positive relationship between Brent oil price volatility and the count of renewable energy patents. These findings are consistent with the existing literature on the relationship between oil price volatility and renewable energy innovation. The literature review highlighted several factors that contribute to the positive impact of oil price volatility on renewable energy innovation (Bórawski et al., 2019; Başkaya et al., 2013; Castillo et al., 2010; Guo and Kliesen, 2005; Rafiq et al., 2009; Sadorsky, 1999; Salim and Rafiq, 2011). These factors include energy security risks, macroeconomic effects, and environmental concerns.

As for the control variables, LRECAP has a significant positive association with *REI* at a 1% level of significance in both models. This finding is consistent with Huber (2008) and Lewis and Wiser (2007) that countries that have a large market for renewable electricity generation are more likely to be home to innovative technology supplies. *LGDPPC* has a positive and statistically significant effect on the count of renewable energy patents in both models. As the adoption and utilization of renewable energy sources in developed and developing countries is significantly influenced by gross domestic product (GDP) (Bayale et al., 2021; Radmehr et al., 2021). *REPWR* has a significant and negative impact on the number of renewable energy patents. This finding is consistent with previous research by Cheon and Urpelainen (2012) and Li and Shao (2021), indicating that the innovation system for renewable energy is not effective enough. This suggests that countries which rely less on renewable energy sources may have greater prospects for innovation, particularly given the declining supply of traditional fossil fuels and the global efforts for emissions reduction.

The results also show that both *SMI* and *TFI* have a negative and statistically significant impact on the number of renewable energy patents in both models. This finding is consistent with Li and Shao's (2021) study on OECD countries, which indicates that a country's monetary policy, as measured by the *SMI*, may not be supportive of innovation in the renewable energy sector. Additionally, Nicolli and Vona (2016) propose that entry barriers can impede progress in renewable innovation. As such, it is essential to establish targeted mechanisms and favorable policies to encourage and support renewable energy innovation.

The *VCO2* variable has a positive and statistically significant effect on the count of patents in both models, suggesting that higher CO2 emissions are associated with more renewable energy innovation, consistent with Lui et al. (2021) findings.

Table 6. Regression results of the fixed-effect negative binomial model.

	(1)	(2)
VARIABLES	REI	REI
SD_WTI	0.085***	
	(12.962)	
SD_BRENT		0.062***
		(10.554)
LRECAP	0.165***	0.168***
	(7.580)	(7.688)
REPWR	-0.168***	-0.168***
	(-7.157)	(-7.078)
LGDPPC	0.129**	0.156***
	(2.498)	(3.024)
LPI	0.129	0.082
	(0.533)	(0.338)
SMI	-0.366***	-0.380***
	(-5.076)	(-5.224)
TFI	-0.331***	-0.343***
	(-3.032)	(-3.128)
CO2	0.033***	0.028**
	(2.895)	(2.481)
easteurope	0.227*	0.269**
	(1.812)	(2.173)
latin	-0.833***	-0.835***
	(-4.519)	(-4.572)
latineurope	0.082	0.047
	(0.538)	(0.315)
confucian	-0.602***	-0.571***
	(-3.213)	(-3.070)
anglo	0.201	0.194
	(1.061)	(1.039)
Observations	2,212	2,212
Number of ctry	80	80

Notes:

This table displays the results of the impact of SD_WTI and SD_BRENT on renewable energy innovation.

where REI represents renewable energy patent count, WEP represents wind energy patent, STP represents solar thermal energy patent, SPVP represents solar photovoltaic (PV) energy patent, STP_SPVPHY represents solar thermal-PV hybrids patent, GEOP represents geothermal energy patent, and all are acquired from OECD Environmental Statistics. SD_WTI represents WTI futures oil prices uncertainty and is acquired from Federal Reserve Bank of St. Louis. SD_BRENT represents Brent Oil Futures prices uncertainty and is acquired from Energy Information Administration. SD_WTI: WTI futures oil prices uncertainty. Source: Federal Reserve Bank of St. Louis. SD_BRENT: Brent Oil Futures prices uncertainty. Source: Energy Information Administration. LRECAP represents renewable energy capacity, acquired from the Patent Cooperation Treaty (PCT) - OECD database. REPWR represents renewable energy share. Source: World Bank Development Indicator, LGDPPC represents logarithm of GDP per capita, and VCO2 represents CO2 Emissions, all are acquired from the World Bank Development Indicator. LPI represents Legal & property rights, SMI represents Sound Money index and TF represents Trade Freedom index and all are acquired from Fraser Institute.

z-statistics in parentheses. ***, **, and * represent the statistical significance at 1%, 5%, and 10%, respectively.

5.6.2. Subsample analysis

In this section, we examine whether the relationship between oil price uncertainty and renewable energy innovation differs based on the level of economic development. Higher economic development typically indicates more resources, both public and private, are available for innovation (Galeotti et al., 2020). To check this, we re-run our basic regressions separately for OECD countries and non-OECD countries.

Table 7 presents the results of the regression analysis for both sub-samples. The results indicate that oil price volatility has a positive and statistically significant impact on both subsamples at a 1% significance level. However, the impact is stronger for non-OECD countries. This result is in line with Gately and Huntington (2002), Dargay and Gately (2010) and Hamilton (2009), who show that the income elasticity of oil demand is nearly 1 for non-OECD countries, which is roughly double that of OECD countries.

Table 7. Results of subsample analysis

Variables	OECD		Non-OECD	
	(1)	(2)	(1)	(2)
SD_WTI	0.072***		0.086***	
	(9.388)		(7.164)	
SD_BRENT		0.048***		0.066***
		(6.903)		(6.242)
LRECAP	0.088***	0.093***	0.214***	0.213***
	(2.750)	(2.869)	(5.857)	(5.835)
REPWR	0.035	0.045	-0.271***	-0.272***
	(0.744)	(0.954)	(-8.187)	(-8.238)
LGDPPC	0.554***	0.620***	-0.082	-0.066
	(5.415)	(6.052)	(-1.137)	(-0.925)
LPI	-1.590***	-1.797***	0.170	0.175
	(-3.153)	(-3.544)	(0.503)	(0.519)
SMI	-0.155	-0.184*	-0.358***	-0.366***
	(-1.474)	(-1.760)	(-3.375)	(-3.432)
TFI	-0.455***	-0.499***	-0.070	-0.069
	(-2.898)	(-3.171)	(-0.436)	(-0.426)
CO2	0.002	-0.002	0.076***	0.075***
	(0.148)	(-0.140)	(3.699)	(3.644)
easteurope	0.170	0.281	0.559***	0.538***
	(0.882)	(1.461)	(3.013)	(2.916)
Latin	-1.749***	-1.739***	0.446	0.423
	(-7.000)	(-7.042)	(1.597)	(1.517)
latineurope	-0.317*	-0.337*	1.056**	1.011**
	(-1.771)	(-1.903)	(2.545)	(2.467)
confucian	0.449	0.441	-0.296	-0.314
	(1.510)	(1.493)	(-1.175)	(-1.248)
Observations	1,060	1,060	1,182	1,182
Number of ctry	37	37	44	44

Notes: This table displays the results of the impact of SD_WTI and SD_BRENT on renewable energy innovation in OECD and non-OECD countries.
where REI represents renewable energy patent count, WEP represents wind energy patent, STP represents solar thermal energy patent, SPVP represents solar photovoltaic (PV) energy patent, STP_SPVPHY represents solar thermal-PV hybrids patent, GEOP represents geothermal energy patent, and all are acquired from OECD Environmental Statistics. SD_WTI represents WTI futures oil prices uncertainty and is acquired from Federal Reserve Bank of St. Louis. SD_BRENT represents Brent Oil Futures prices uncertainty and is acquired from Energy Information Administration. SD_WTI: WTI futures oil prices uncertainty. Source: Federal Reserve Bank of St. Louis. SD_BRENT: Brent Oil Futures prices uncertainty. Source: Energy Information Administration. LRECAP represents renewable energy capacity, acquired from the Patent Cooperation Treaty (PCT) - OECD database. REPWR represents renewable energy share. Source: World Bank Development Indicator, LGDPPC represents logarithm of GDP per capita, and VCO2 represents CO2 Emissions, all are acquired from the World Bank Development Indicator. LPI represents Legal & property rights, SMI represents Sound Money index and TF represents Trade Freedom index and all are acquired from Fraser Institute.
z-statistics in parentheses. ***, **, and * represent the statistical significance at 1%, 5%, and 10%, respectively.

5.6.3. Renewable energy type

We further examine how oil prices uncertainty impact renewable energy innovation for several renewable energy types. Different types of renewable energy exhibit different technological levels due to their inherent technological characteristics. According to Johnstone et al. (2010), renewable energy types have varying cost structures and levels of maturity, which leads to different responses to environmental policies. Wind and solar energy have undergone rapid development in the past few decades, while geothermal energy is mature. Nicolli and Vona (2016) oppose that wind and solar energy innovation output increased significantly after the Kyoto Protocol in 1997 (as cited in B¨ohringer et al., 2017; Hille et al., 2020).

We estimate the following equations to examine the effect of oil price volatility on renewable type:

$$WEP_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\text{t}} \quad (3)$$

$$STP_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\text{t}} \quad (4)$$

$$SPVP_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\text{t}} \quad (5)$$

$$STP\_SPVPHY_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\text{t}} \quad (6)$$

$$GEOP_{i,t} = \alpha_i + \beta_1 SD\_WTI_{i,t} + \delta CONTROLS_{i,t} + \text{Year Dummies} + \varepsilon_{i,\text{t}} \quad (7)$$

where *WEP* is wind energy patent count, *STP* is solar thermal energy patent count, *SPVP* is solar photovoltaic energy patent count, *STP_SPVPHY* is solar thermal-photovoltaic energy patent count and *GEOP* is geothermal energy patent count, and *MRINP* is marine energy patent count. The rest of the variables are as previously defined.

Table 8 and 9, reports the results of the impact of oil prices uncertainty on innovation in different renewable energy types. Table 8 and table 9 represent the variables *SD_WTI* and *SD_BRENT*, respectively. The results in both tables indicate that SD_WTI and

SD_BRENT have a positive and statistically significant impact at a 1% significance level on various types of renewable energy. The lowest effect of oil price volatility is for wind energy patents (WEP) and the highest is with the solar energy patents (SPVP) and solar thermal-PV hybrid (STP_SPVPHY). However, the magnitude of impact on all types of renewable energy is more significant when using SD_WTI as the key test variable, in line with Elder et al. (2014).

Table 8. WTI futures price fluctuation and renewable energy innovation: different renewable energy types.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	WEP	STP	SPVP	STP_SPVPHY	GEOP	MRINP
SD_WTI	0.070***	0.076***	0.098***	0.098***	0.081***	0.082***
	(8.483)	(8.511)	(12.764)	(4.712)	(4.298)	(7.446)
LRECAP	0.203***	0.046	0.203***	0.142	0.260***	0.157***
	(7.036)	(1.542)	(6.698)	(1.360)	(3.234)	(2.989)
REPWR	-0.162***	-0.130***	-0.212***	-0.328***	-0.252***	-0.213***
	(-4.342)	(-3.932)	(-6.671)	(-2.741)	(-2.734)	(-3.238)
LGDPPC	0.410***	0.203**	0.257***	0.330	-0.049	0.260**
	(5.192)	(2.518)	(3.350)	(1.311)	(-0.233)	(2.210)
LPI	-1.108***	0.065	-0.611*	-1.012	1.219	-0.692
	(-2.993)	(0.176)	(-1.704)	(-0.849)	(1.310)	(-1.218)
SMI	-0.365***	-0.298***	-0.327***	-0.278	-0.753***	-0.151
	(-3.813)	(-2.984)	(-3.274)	(-1.046)	(-3.292)	(-1.141)
TFI	-0.411***	-0.475***	-0.122	-0.346	-0.129	-0.292
	(-2.739)	(-3.091)	(-0.733)	(-0.753)	(-0.364)	(-1.551)
CO2	0.026*	0.006	0.003	-0.006	-0.012	0.018
	(1.766)	(0.356)	(0.169)	(-0.122)	(-0.323)	(0.903)
easteurope	-0.110	0.038	-0.583***	-1.945***	-0.912**	-0.332
	(-0.668)	(0.195)	(-2.927)	(-2.912)	(-2.214)	(-1.024)
latin	-0.962***	-1.330***	-2.063***	-1.776	-3.032***	-0.888**
	(-3.055)	(-4.950)	(-7.131)	(-1.366)	(-2.838)	(-2.029)
latineurope	-0.293	-0.288	-0.494**	-0.967*	-0.534	-0.691**
	(-1.373)	(-1.418)	(-2.495)	(-1.822)	(-0.989)	(-2.309)
confucian	-1.296***	-0.322	-0.898***	-1.478***	-1.720***	-0.989***
	(-6.122)	(-1.335)	(-4.287)	(-3.080)	(-3.994)	(-3.120)
anglo	-0.168	0.900***	0.165	0.089	-0.555	0.236
	(-0.697)	(2.897)	(0.689)	(0.120)	(-1.133)	(0.727)
Observations	2,212	2,168	2,122	1,489	1,450	2,039
Number of ctry	80	77	77	51	51	72

Notes: This table reports the results of the impact of WTI futures price fluctuation on renewable energy innovation of different renewable energy technologies.

where REI represents renewable energy patent count, WEP represents wind energy patent, STP represents solar thermal energy patent, SPVP represents solar photovoltaic (PV) energy patent, STP_SPVPHY represents solar thermal-PV hybrids patent, GEOP represents geothermal energy patent, and all are acquired from OECD Environmental Statistics. SD_WTI represents WTI futures oil prices uncertainty and is acquired from Federal Reserve Bank of St. Louis. SD_BRENT represents Brent Oil Futures prices uncertainty and is acquired from Energy Information Administration. SD_WTI: WTI futures oil prices uncertainty. Source: Federal Reserve Bank of St. Louis. SD_BRENT: Brent Oil Futures prices uncertainty. Source: Energy Information Administration. LRECAP represents renewable energy capacity, acquired from the Patent Cooperation Treaty (PCT) - OECD database. REPWR represents renewable energy share. Source: World Bank Development Indicator, LGDPPC represents logarithm of GDP per capita, and VCO2 represents CO2 Emissions, all are acquired from the World Bank Development Indicator. LPI represents Legal & property rights, SMI represents Sound Money index and TF represents Trade Freedom index and all are acquired from Fraser Institute.

z-statistics in parentheses. ***, **, and * represent the statistical significance at 1%, 5%, and 10%, respectively.

Table 9. Brent futures price fluctuation and renewable energy innovation: different renewable energy types.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	WEP	STP	SPVP	STP_SPVPHY	GEOP	MRINP
SD_BRENT	0.047***	0.053***	0.073***	0.078***	0.052***	0.058***
	(6.275)	(6.637)	(10.678)	(4.377)	(3.114)	(5.977)
LRECAP	0.207***	0.054*	0.211***	0.155	0.274***	0.171***
	(7.140)	(1.772)	(6.968)	(1.494)	(3.444)	(3.294)
REPWR	-0.161***	-0.134***	-0.216***	-0.328***	-0.260***	-0.215***
	(-4.317)	(-3.967)	(-6.721)	(-2.769)	(-2.844)	(-3.298)
LGDPPC	0.445***	0.234***	0.297***	0.376	0.024	0.309***
	(5.652)	(2.920)	(3.902)	(1.507)	(0.117)	(2.655)
LPI	-1.179***	0.002	-0.723**	-1.185	0.970	-0.855
	(-3.191)	(0.005)	(-2.024)	(-1.000)	(1.048)	(-1.514)
SMI	-0.375***	-0.306***	-0.341***	-0.275	-0.745***	-0.161
	(-3.912)	(-3.053)	(-3.374)	(-1.018)	(-3.254)	(-1.215)
TFI	-0.427***	-0.492***	-0.151	-0.389	-0.156	-0.310*
	(-2.847)	(-3.211)	(-0.909)	(-0.854)	(-0.442)	(-1.649)
CO2	0.020	-0.000	-0.003	-0.007	-0.024	0.013
	(1.345)	(-0.023)	(-0.189)	(-0.140)	(-0.664)	(0.653)
easteurope	-0.074	0.074	-0.521***	-1.876***	-0.865**	-0.279
	(-0.454)	(0.388)	(-2.664)	(-2.841)	(-2.120)	(-0.864)
latin	-0.990***	-1.334***	-2.026***	-1.714	-3.109***	-0.918**
	(-3.180)	(-5.000)	(-7.024)	(-1.287)	(-2.909)	(-2.147)
latineurope	-0.336	-0.310	-0.504***	-0.962*	-0.602	-0.742**
	(-1.602)	(-1.549)	(-2.592)	(-1.848)	(-1.136)	(-2.529)
confucian	-1.271***	-0.288	-0.857***	-1.431***	-1.714***	-0.987***
	(-6.042)	(-1.197)	(-4.127)	(-3.006)	(-3.999)	(-3.159)
anglo	-0.152	0.918***	0.176	0.050	-0.538	0.207
	(-0.637)	(2.992)	(0.747)	(0.069)	(-1.122)	(0.655)
Observations	2,212	2,168	2,122	1,489	1,450	2,039
Number of ctry	80	77	77	51	51	72

Notes: This table offers the results of the impact of Brent futures price fluctuation on renewable energy innovation of different renewable energy technologies.

where REI represents renewable energy patent count, WEP represents wind energy patent, STP represents solar thermal energy patent, SPVP represents solar photovoltaic (PV) energy patent, STP_SPVPHY represents solar thermal-PV hybrids patent, GEOP represents geothermal energy patent, and all are acquired from OECD Environmental Statistics. SD_WTI represents WTI futures oil prices uncertainty and is acquired from Federal Reserve Bank of St. Louis. SD_BRENT represents Brent Oil Futures prices uncertainty and is acquired from Energy Information Administration. SD_WTI: WTI futures oil prices uncertainty. Source: Federal Reserve Bank of St. Louis. SD_BRENT: Brent Oil Futures prices uncertainty. Source: Energy Information Administration. LRECAP represents renewable energy capacity, acquired from the Patent Cooperation Treaty (PCT) - OECD database. REPWR represents renewable energy share. Source: World Bank Development Indicator, LGDPPC represents logarithm of GDP per capita, and VCO2 represents CO2 Emissions, all are acquired from the World Bank Development Indicator. LPI represents Legal & property rights, SMI represents Sound Money index and TF represents Trade Freedom index and all are acquired from Fraser Institute.

z-statistics in parentheses. ***, **, and * represent the statistical significance at 1%, 5%, and 10%, respectively.

5.6.4. Robustness checks

To enhance the reliability of our findings, we conducted several robustness tests following the approach of Wen et al. (2021). We incorporated additional variables, including the inflation rate as a percentage change of the consumer price index, the percentage of gross domestic product (GDP) from exports of goods and services, and the percentage of GDP from imports of goods and services. Prior research has established that these factors can influence the performance of renewable energy innovation (Johnstone et al., 2010; Herman and Xiang, 2019). The results reported in Table 10 show that our results are robust with the introduction of additional control variables.

Furthermore, oil prices have experienced periods of volatility due to various factors including crises. To ensure that our results are not driven by crisis, we re-estimated equations 1 and 2 after excluding crisis periods (i.e., 1996, 2007, 2008, 2020). The results reported in Panel B of Table 9 show that crises do not affect our results.

Table 10. Robustness check

	(1)	(2)	(1)	(2)
VARIABLES	Panel A - including additional variables		Panel B- excluding subset periods	
SD_WTI	0.085***		0.048***	
	(13.014)		(7.808)	
SD_BRENT		0.063***		0.048***
		(10.600)		(9.025)
LRECAP	0.154***	0.159***	0.209***	0.206***
	(6.805)	(6.958)	(7.985)	(7.904)
REPWR	-0.151***	-0.152***	-0.151***	-0.151***
	(-6.284)	(-6.219)	(-5.492)	(-5.513)
LGDPPC	0.171***	0.196***	0.158***	0.148***
	(3.178)	(3.646)	(2.915)	(2.725)
LPI	0.055	0.007	0.182	0.202
	(0.223)	(0.027)	(0.701)	(0.778)
SMI	-0.373***	-0.388***	-0.253***	-0.242***
	(-5.186)	(-5.334)	(-3.856)	(-3.699)
TFI	-0.359***	-0.372***	-0.361***	-0.351***
	(-3.257)	(-3.363)	(-3.610)	(-3.512)
CO2	0.035***	0.031***	0.004	0.006
	(3.045)	(2.701)	(0.324)	(0.479)
lex	-0.010***	-0.010***	-	-
	(-3.236)	(-3.265)	-	-
lim	0.007*	0.007**	-	-
	(1.852)	(1.998)	-	-
inf	-0.009	-0.010	-	-
	(-0.575)	(-0.591)	-	-
easteurope	0.247*	0.285**	0.258*	0.226
	(1.922)	(2.253)	(1.729)	(1.511)
latin	-0.964***	-0.955***	-1.226***	-1.223***
	(-4.916)	(-4.915)	(-6.101)	(-6.061)
latineurope	0.041	0.009	0.152	0.176
	(0.269)	(0.063)	(0.843)	(0.964)
confucian	-0.445**	-0.425**	-0.565***	-0.580***
	(-2.282)	(-2.188)	(-2.633)	(-2.695)
anglo	0.140	0.133	0.769***	0.790***
	(0.741)	(0.712)	(3.066)	(3.119)
Observations	2,182	2,182	1,762	1,762
Number of ctry	79	79	80	80

Notes: This table displays the results of 2 robustness checks. Panel A uses additional variables. Panel B employs excluding periods of high volatility. We included all control variables in the regression. z-statistics in parentheses. ***, **, and * represent the statistical significance at 1%, 5%, and 10%, respectively.

Chapter VI: conclusion and policy implications

In this thesis, we investigate the impact of oil price uncertainty on renewable energy innovation using a cross-country panel that consists of 80 countries for the period 1991–2019. Our analysis employs renewable energy patent count as a proxy for renewable energy innovation. Specifically, we examine whether oil price uncertainty impacts renewable energy innovation, as well as its impact on several types of renewable energy innovations, including wind, solar, and geothermal.

Furthermore, we explore whether the relationship between oil price uncertainty and the innovation of renewable energy technologies differs between OECD and non-OECD countries. Our empirical results suggest that an increase in oil price volatility leads to an increase in renewable energy innovation, as measured by the count of patents. This implies that volatile oil prices can serve as a driver for innovation in the renewable energy sector. We found that countries with higher renewable energy generation capacity possess more resources, including human and physical capital, leading to more significant innovation in the future. We also find that Sound Money Index and the Trade Freedom Index have a negative impact on renewable energy patents. Moreover, we conclude that higher CO_2 emissions are associated with more renewable energy innovation, reflecting the increased pressure on companies from environmental groups and government entities to invest in renewable energy innovation.

Drawing from the key findings outlined earlier, we suggest the following policy recommendations:

- Use volatile oil prices as a driver for innovation in the renewable energy sector. Policymakers can leverage the impact of oil price volatility on renewable energy innovation by creating favorable policies to encourage the growth of the renewable energy sector.

- To encourage technological advancement in renewable energy, there are two key actions that policymakers should take. First, they should invest in developing human and physical capital to facilitate innovation. This is because countries with higher renewable energy generation capacity typically possess more resources, leading to more significant innovation in the future. Second, enhancing renewable energy capacity is also crucial for technological advancement. This is supported by the fact that the

The growth of renewable energy capacity installation in recent years has been significant, with the world's newly installed renewable energy capacity in 2020 increasing by more than 45% from the previous year, the largest annual increase since 1999. This trend is expected to continue, with renewable energy accounting for 90% of the total increase in global electricity generation by 2022, according to the Renewable Energy Market Update: Outlook for 2021 and 2022 released by the International Energy Agency. The potential of renewable energy to dominate global electricity production by 2022 has also been highlighted by the International Energy Agency (IEA, 2017). To achieve carbon neutrality, governments need to promote renewable energy investment, grid infrastructure, and other relevant technologies, as emphasized by Reiche (2010) and Zhao and You (2020). Therefore, building on the momentum of renewables and adopting policies that encourage greater investment in renewables, as well as in grid infrastructure and other key renewable energy technologies, is critical to the world's goal of achieving carbon neutrality and spurring technological advancement.

- Governments can promote innovation in renewable energy by implementing tax incentives, reducing trade barriers, and implementing policies to reduce carbon emissions. Countries that have lower tariff rates tend to attract more international trade and foreign investment, which can contribute to technological innovation. Foreign direct investment can bring in capital, technology, and management expertise, and can have a positive impact on the technological advancement of the host country.

- Moreover, policymakers can increase the pressure on companies to invest in renewable energy innovation as higher CO2 emissions are associated with more renewable energy innovation. This reflects the increased pressure on companies from environmental groups and government entities to invest in renewable energy innovation. Carbon constraint regulations and policies, which limit the amount of carbon emissions that companies are allowed to produce, can spur innovation in renewable energy. This is because companies are pressured to find ways to reduce their carbon emissions, which may lead them to invest in renewable energy technologies as an alternative, thus providing policymakers with additional means to encourage companies to invest in renewable energy innovation.
- Our results show that different types of renewable energy have varying responses to environmental policies, with solar energy patents being more responsive to oil price volatility than wind energy patents. Policymakers should tailor policies to the specific type of renewable energy to encourage innovation in that area.

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Appendix

Table A1. List of countries

OECD Countries		Non-OECD Countries		
Australia	Japan	Albania	Jordan	South Africa
Austria	Latvia	Algeria	Kazakhstan	Sri Lanka
Belgium	Lithuania	Argentina	Kenya	Tajikistan
Canada	Luxembourg	Bangladesh	Kuwait	Thailand
Chile	Mexico	Bulgaria	Lebanon	Tunisia
Colombia	Netherlands	Belarus	Malaysia	Ukraine
Costa Rica	New Zealand	Brazil	Moldova	UAE
Czech Republic	Norway	China	Morocco	Uruguay
Denmark	Portugal	Croatia	Pakistan	Vietnam
Estonia	Slovak Republic	Cyprus	Peru	
Finland	Slovenia	Egypt	Philippines	
France	Spain	Ethiopia	Poland	
Germany	Sweden	Georgia	Romania	
Greece	Switzerland	Hungary	Russia	
Iceland	Turkey	India	KSA	
Ireland	United Kingdom	Indonesia	Senegal	
Israel	United States	Iran	Serbia	
Italy		Iraq	Singapore	

Table A2. Variables description

Dependent variable	Description	Source
REI	renewable energy patent count.	OECD Environmental Statistics
WEP	Wind energy patent	OECD Environmental Statistics
STP	Solar thermal energy patent	OECD Environmental Statistics
SPVP	Solar photovoltaic (PV) energy patent	OECD Environmental Statistics
STP_SPVPHY	Solar thermal-PV hybrids patent	OECD Environmental Statistics
GEOP	Geothermal energy patent	OECD Environmental Statistics
MRINP	Marine energy patent	OECD Environmental Statistics
Key test variables	**Description**	**Source**
SD_WTI	WTI futures oil prices uncertainty	Federal Reserve Bank of St. Louis
SD_BRENT	Brent Oil Futures prices uncertainty	Energy Information Administration
Control Variables	**Description**	**Source**
LRECAP	Renewable energy capacity	the Patent Cooperation Treaty (PCT) - OECD database
REPWR	Renewable energy share	World Bank Development Indicator
LGDPPC	Logarithm of GDP per capita	World Bank Development Indicator
LPI	legal & property rights	Fraser Institute
SMI	Sound Money index	Fraser Institute
TF	Trade Freedom index	Fraser Institute
VCO2	CO2 Emissions	World Bank Development Indicator
Add. Control Variables	**Description**	**Source**
inf_cpi	Inflation rate as percent change of consumer price index	World Bank’s World Development Indicators Database
ex_gdp	Exports of goods and services as a percentage of GDP	World Bank’s World Development Indicators Database
im_gdp	Imports of goods and services as a percentage of GDP	World Bank’s World Development Indicators Database

Table A3. Correlation matrix

	REI	SD_WTI	SD_BRENT	LRECAP	REPWR	LGDPPC	LPI	SMI	TFI
SD_WTI	**0.12**								
SD_BRENT	**0.11**	**0.99**							
LRECAP	**0.33**	**0.07**	**0.08**						
REPWR	0.01	0.00	0.01	**0.58**					
LGDPPC	**0.21**	**0.08**	**0.08**	**0.14**	**-0.09**				
LPI	**0.18**	0.05	0.05	**0.14**	0.04	**0.76**			
SMI	**0.11**	**0.07**	**0.07**	**0.10**	0.03	**0.43**	**0.41**		
TFI	**0.08**	**0.08**	**0.08**	0.02	0.04	**0.48**	**0.55**	**0.42**	
CO2	**0.19**	0.01	0.01	-0.05	**-0.36**	**0.68**	**0.41**	**0.21**	**0.28**

Note: Bold face reports the statistical significance at 1%.